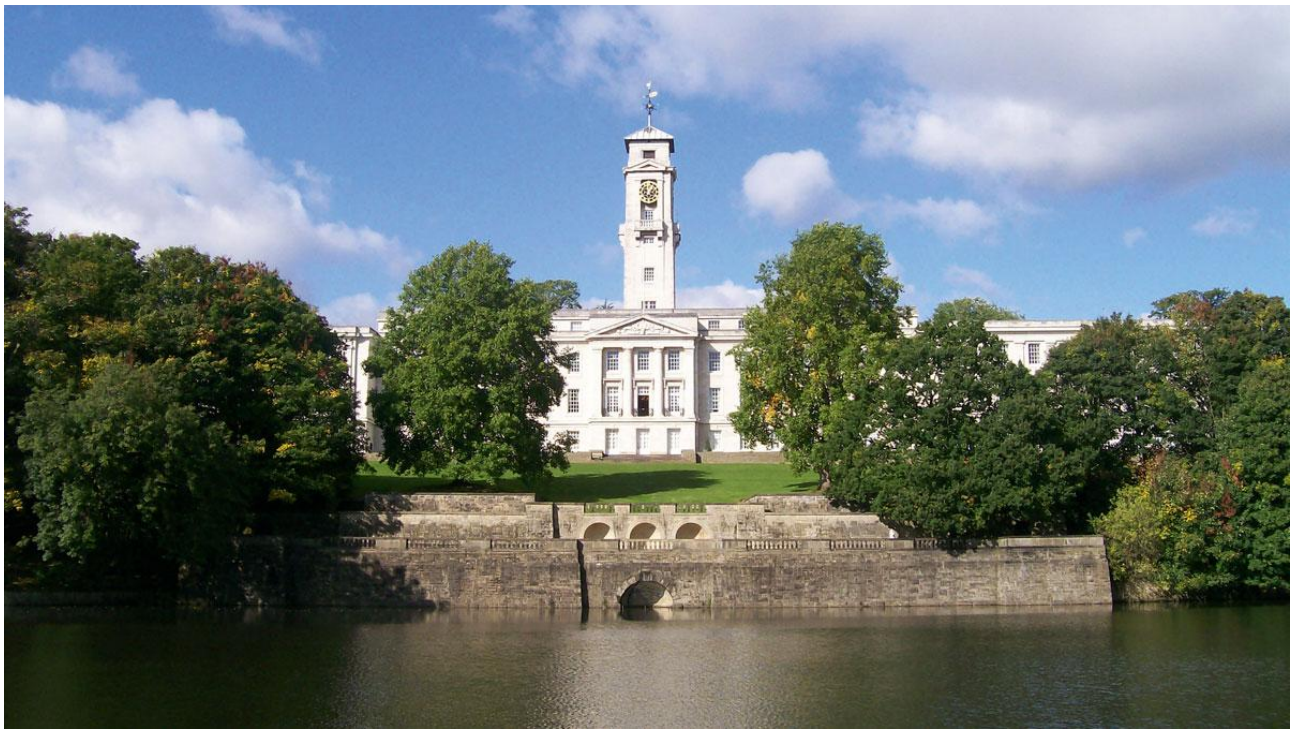
Proceedings of the 30th International Symposium on Logistics (2026)

Regenerative Supply Chains Intelligence

05-08 July 2026



Organised by

Supported by

The Institute for Advanced Manufacturing, The University of Nottingham, UK

Editors: Prof. Andrew Potter, Prof. Kulwant S Pawar, Dr Christos Braziotis, Prof. Helen Rogers and Prof. Dr. Matthias Kalverkamp

https://www.islconf.org

30th International Symposium on Logistics, 05th – 08th July 2026

ISBN-13 978-0-85358-362-2

Organised by:

The Centre for Concurrent Enterprise is a leading international authority for research in managing new product design and development, managing design teams in a global context, comparative analysis and configurations of logistics and supply chain networks and operations in different contexts, and industrial sectors in Europe, China, and India. The members of the centre conduct cutting-edge research through collaborative projects, working with companies and premier universities across the globe. It has a successful track record and experience in many national and international, multi-disciplinary, industrially applied research projects. Topics have ranged from requirements capture, assessment, benchmarking, collaborative product development, product-service systems, knowledge management, cloud manufacturing, 3D printing, analysis and modelling of supply chains, Digital Supply Chains, next generation cold supply chains, Electrical Vehicle Charging Infrastructure, performance measurement, outsourcing and analysis of logistics and supply chain operations. It also organises two annual international conferences and many workshops.

Supported by: The Institute for Advanced Manufacturing, The University of Nottingham, UK

Website: https://www.islconf.org managed by The University of Nottingham, Nottingham, UK

Registration coordination: Mejimedia.com

Front cover: University of Nottingham, United Kingdom

ISBN: ISBN-13 978-0-85358-362-2

Published by: Prof. Andrew Potter, Prof. Kulwant S Pawar, Dr. Christos Braziotis, Prof. Helen Rogers and Prof. Dr. Matthias Kalverkamp

Prepared by: Hani K. Alzahrani
Nottingham University Business School,
University of Nottingham, United Kingdom

© Copyright Nottingham University Business School, 2026

ORGANISING COMMITTEE

Prof. Kulwant S Pawar Nottingham University Business School, UK Kul.Pawar@nottingham.ac.uk	**Prof. Andrew Potter** Cardiff Business School Cardiff University, UK PotterAT@cardiff.ac.uk	**Prof. Helen Rogers** Ohm University, Germany helen.rogers@th-nuernberg.de
Dr Christos Braziotis Nottingham University Business School, UK Christos.Braziotis@nottingham.ac.uk	**Prof. Dr. Matthias Kalverkamp** Wiesbaden Business School at RheinMain UAS Matthias.Kalverkamp@hs-rm.de	**Prof. Vinh Thai** RMIT vinh.thai@rmit.edu.au
Dr. Hung Nguyen RMIT Vietnam hung.nguyen@rmit.edu.vn	**Symposium Administration** **University of Nottingham, UK** Isl21@nottingham.ac.uk	

RMIT LOCAL ORGANISERS:

Nguyen Manh Hung, Nguyen Hoang Thuan, Hiep Pham, Huyen Nguyen, Bony Pham, Trang Nguyen, Le Cao, Paul Childerhouse, Nguyen Canh Lam, Pradeepa Jayaratne, Nguyen Thi Van Anh, Anushka Siriwardana, Nguyen Thi Minh Chau, Mau Luu, Nguyen Quynh Anh, Mai Thanh Hien, Scott McDonald, Huy Truong, Nichapa Phraknoi, Dung Truong, Son Nguyen, Irfan Ulhaq, Thuy Nguyen.

ISL INTERNATIONAL ADVISORY COMMITTEE

Prof. R Accorsi, University of Bologna, Italy

Dr J Baalsrud Hauge, BIBA Germany, KTH Royal Institute of Technology, Sweden

Prof. R Banomyong, Thammasat University, Thailand

Prof. M Bourlakis, Cranfield University, UK

Prof. P. Bremer, Technical University of Applied Sciences Würzburg-Schweinfurt, Germany

Prof C Chan, University of Newcastle, Australia

Prof. HK Chan, Wenzhou-Kean University, Wenzhou, China

Prof. Y Chang, Korea Aerospace University, South Korea

Dr A Coronado, Royal Holloway U. of London, UK

Prof. S Dani, Keele University, UK

Prof. J Eschenbaecher, City University of Applied Sciences Bremen, Germany

Prof. B Gammelgaard, Copenhagen Business School, Denmark

Dr. A. Ghadge, Cranfield University, UK

Prof. C Glock, Technische Universität Darmstadt, Germany

Prof. M Goh, National University of Singapore, Singapore

Dr S Harding, Birmingham City University, Birmingham, UK

Prof. J Havenga, University of Stellenbosch, South Africa

Prof. M Y Jaber, Toronto Metropolitan University, Canada

Dr. A. Jimo, Henley Business School, UK

Prof. B Kam, RMIT, Australia

Dr P Lai, Chung Ang University, South Korea

Prof. Emeritus C Lalwani, Hull University, UK

Prof. TC Lirn, National Taiwan Ocean University, Taiwan

Prof. Dr. A Lisec, Landscape Governance College Grm Novo Mesto, Slovenia

Dr. H Lu, Newcastle University, UK

Prof. M Naim, Cardiff University, UK

Dr S O'Reilly, University College Cork, Ireland

Prof. R Pal, University of Borås, Sweden

Prof. R Pouraghabagher, CalPoly, USA

Prof. S Rahman, East West University, Bangladesh

Prof. E Sandberg, Linköping University, Sweden

Prof. J Schumacher, Fachhochschule Vorarlberg, Austria

Prof. N Subramanian, Sussex University, UK

Prof. T Takeno, Iwate Prefectural University, Japan

Prof. C Tang, UCLA Anderson School, USA

Prof. K-D Thoben, BIBA, Germany

Dr N Tipi, Open University, UK

Prof. K-M Tsai, National Kaohsiung University of Science and Technology, Taiwan

Dr J Vilko, Lappeenranta University of Technology, Finland

Prof. S Wagner, Swiss Federal Institute of Technology, Switzerland

Prof. S Woo, Chung Ang University, South Korea

Dr. A Yadlapalli, RMIT, Australia

Prof. M Zhang, Queens University Belfast, UK

Prof. X Zhao, CEIBS, China

INTRODUCTION

We are delighted to welcome our friends and colleagues, both old and new, to the 30th International Symposium on Logistics and Supply Chains. This year's event focusses on regenerative supply chain intelligence (RSCI). RSCI is increasingly important for both academic research and industry as it advances the shift from traditional efficiency-driven and sustainability-focused supply chains towards systems that actively restore, renew and enhance environmental and social dimensions while maintaining economic viability. It provides a rich interdisciplinary research domain that integrates operations management data analytics systems thinking and circular economy principles enabling the development of new theories metrics and decision-support models that move beyond 'do less harm' to 'create net positive impact'. It also opens opportunities to explore emerging technologies in enabling transparency traceability and adaptive learning within complex multi-tier supply networks. By embedding intelligence that continuously senses analyses and improves ecological and socio-economic outcomes RSCI supports firms in transitioning from linear extractive models to regenerative circular ecosystems thereby safeguarding long-term performance and legitimacy in an increasingly sustainability-conscious global economy. RSCI supports the agenda of building resilience against disruptions such as climate change geopolitical risks ensuring regulatory compliance for ethical and sustainable practices and regenerative value creation.

The organising committee, having learned from previous hybrid ISL conferences, has decided to continue with the hybrid mode this year. This format was successful during the ISL 2022, 2023, 2024 and 2025 conferences. While the hybrid mode is not ideal for networking, it is a reasonable compromise given the concerns around sustainability and the increased travel restrictions imposed by many universities.

Two categories of paper submissions were invited. The first category, 'Full Papers', is up to eight pages in length with a one-page structured abstract. These papers undergo a peer review process and are included in part 2 of the Proceedings of the Conference with an ISBN number. The second category consists of structured abstracts of 1000 words. These may be considered developmental papers representing early-stage research ideas or initial findings. Only the abstract is required for initial submission and undergoes the review process. Both full papers and structured abstracts are considered for submission to the special issue of the International Journal of Logistics Management or Computers and Industrial Engineering. The duration of in-person presentations is 30 minutes (including Q&A) while online presentations are 15 minutes during the two-day event.

The 30th International Symposium on Logistics (ISL 2026) aims to provide a forum for discussion between leading academics, researchers and practitioners specialising in logistics and supply chain management. The chosen theme is **'Regenerative Supply Chain Intelligence'**, which refers to using intelligent systems data and analytical tools to manage supply chains that actively heal, restore and enhance socio-ecological systems rather than merely minimising harm. This approach applies principles of regenerative practices inspired by natural systems to create abundance, resilience and lasting positive environmental and social impact throughout the supply network, moving beyond simple sustainability. The papers in this book of proceedings represent the latest academic thinking as well as case examples of successful implementations. The 30th ISL also presents an opportunity to engage in various discussions and debates exploring how our models concepts and findings are advancing knowledge in the area of logistics and supply chain. Equally, it is important to explore how our collective expertise can be successfully applied to develop the next generation of experts through teaching and curriculum development and to enhance the competitiveness of the industry.

As event organisers, we have applied the learnings gained from last year's online platform and combined it with our extensive experience in hosting physical events to deliver an exceptional experience for our ISL delegates. We are pleased with the success in terms of the number of submissions resulting in 95 paper presentations from authors in 31 countries. We were also fortunate to have two distinguished keynote speakers: Tran Thanh Hai, Deputy Director General, Agency of Foreign Trade, Ministry of Industry and Trade of Vietnam; Dr Dinh Huu Thanh, Co-Founder, Chairman and CEO, Bee Logistics Corporation, Vietnam; and Dr Yap Kwong Weng, CEO

of Vietnam SuperPort and Head of Strategy, Sustainability and Communications, YCH Group, Vietnam. We were equally pleased to host a workshop on 'Contextualising Supply Chain Resilience under Geopolitical Disruptions' led by Prof Kulwant S Pawar, Prof Nachiappan Subramanian, Prof Vinh Thai and Dr Hung Nguyen.

Overall, the event proved to be highly successful considering the variety of activities ranging from keynotes, paper presentations, workshops, debates, etc. These were further supported by online virtual group discussions and debates between delegates. All these activities enabled the ISL community to maintain its tradition as an informal, yet productive and knowledge-intensive event – all in all culminating in another memorable experience and successful event.

As mentioned above, and as in previous years, all abstracts and/or full papers were reviewed by two or more academic experts from the field of Logistics and Supply Chain Management. This book of proceedings containing the accepted papers, has been organised in 2 parts according to the following categories:

Part I: Abstracts

- Regenerative Supply Chains
- Supply Chain Intelligence
- Logistics Connectivity
- Smart/Digital Supply Chains
- Building Resilience for Supply Chains
- Supply Chain Analytics
- Globalisation of Supply Chains
- Humanitarian Supply Chains
- Supply Chain Skills, Training and Education

Part II: Full Papers

- Regenerative Supply Chains
- Supply Chain Intelligence
- Logistics Connectivity
- Smart/Digital Supply Chains
- Building Resilience for Supply Chains
- Supply Chain Analytics
- Globalisation of Supply Chains
- Humanitarian Supply Chains
- Supply Chain Skills, Training and Education

To date the ISL has been held in Europe, South Africa, Australia and Asia (see full list below), and the last couple of events were in hybrid mode. Last but not least, we would like to take this opportunity to express our sincere thanks to all the presenters, delegates, reviewers, Advisory Committee members, organising team, invited guest speakers, partner journals - International Journal of Logistics Management (IJLM) and Computers and Industrial Engineering (CAIE) for their valuable support and contributions. Finally, our special thanks go to the local organising committee comprising several colleagues from RMIT, Vietnam and Australia. We are equally indebted for organising the very popular industrial visit to Port of Hai Phong, Vietnam.

Prof. Andrew Potter, Prof. Kulwant S Pawar, Dr Christos Braziotis, Prof. Helen Rogers and Prof. Dr. Matthias Kalverkamp – July 2026.

PREVIOUS ISL CONFERENCES

1993 – Nottingham, UK	2011 – Berlin, Germany
1995 – Nottingham, UK	2012 – Cape Town, South Africa
1997 – Padua, Italy	2013 – Vienna, Austria
1999 – Florence, Italy	2014 – Ho Chi Minh City, Vietnam
2000 – Iwate, Japan	2015 – Bologna, Italy
2001 – Salzburg, Austria	2016 – Kaohsiung, Taiwan
2002 – Melbourne, Australia	2017 – Ljubljana, Slovenia
2003 – Seville, Spain	2018 – Bali, Indonesia
2004 – Bangalore, India	2019 – Würzburg, Germany
2005 – Lisbon, Portugal	2021 – Online
2006 – Beijing, China	2022 – Cork, Ireland (Hybrid)
2007 – Budapest, Hungary	2023 - Enschede, Netherlands
2008 – Bangkok, Thailand	2024 – Bangkok, Thailand
2009 – Istanbul, Turkey	2025 – Wiesbaden, Germany
2010 – Kuala Lumpur, Malaysia	

AUTHORS' AFFILIATION

Australia

Monash University

Queensland University of Technology

RMIT University

University of Technology Sydney

University of Wollongong

Austria

FHV- Vorarlberg University of Applied Sciences

Supply Chain Intelligence Institute Austria

University of Applied Sciences Upper Austria

Vienna University of Business and Economics

China

Chengdu University of Technology

Shanghai Business School

University of Nottingham Ningbo

Denmark

Technical University of Denmark

Egypt

German International University

Finland

Satakunta University of Applied Sciences

University of Vaasa

France

Aix-Marseille University

EDHEC Business School

NEOMA Business School

University Paris 8

Germany

BIBA University of Bremen

Cooperative State University Mannheim

Fachhochschule Südwestfalen

FH Münster

Friedrich-Alexander University Erlangen–Nürnberg (FAU)

OFFIS Institute for Information Technology

Otto-Friedrich-Universität Bamberg

Schmalenbach Institut

Technische Hochschule Deggendorf

Technische Hochschule Köln

Technische Hochschule Nürnberg Georg Simon Ohm

Technical University of Applied Sciences Würzburg-Schweinfurt

University of Applied Sciences Merseburg

Wiesbaden Business School at RheinMain University of Applied Sciences

India

C.V. Raman Global University

Indian Institute of Management Sirmaur

Indian Institute of Science Education and Research (IISER)

Indian Institute of Technology (IIT)

Sardar Patel Institute of Technology (SPIT)

Indonesia

Mulawarman University

Ireland

Technological University Dublin

Italy

Carlo Cattaneo University

Free University of Bozen-Bolzano

Politecnico di Milano

Japan

Ryutsu Keizai University

Jordan

Mutah University

Malaysia

International Islamic University Malaysia

National Defence University of Malaysia

Montenegro

University of Montenegro

Poland

Nicolaus Copernicus University in Torun

SGH Warsaw School of Economics

University of Lodz

Republic of South Korea

Incheon National University

Korea Aerospace University

Korea University

Kyungpook National University

Romania

Advanced Technology Solutions (ATS)

Saudi Arabia

King Abdulaziz University

Singapore

National University of Singapore

Slovakia

Slovak University of Technology in Bratislava

Sri Lanka

University of Moratuwa

Sweden

KTH Sweden

Linköping University

University of Borås

University of Gävle

Switzerland

ETH Zurich

Taiwan

Chia Nan University of Pharmacy and Science

Industrial Technology Research Institute

National Kaohsiung University of Science and Technology

National Taipei University of Business

National Taiwan Ocean University

Tamkang University

Thailand

Chulalongkorn University

Disaster Relief Training Center

Mahidol University

National Institute of Development Administration (NIDA)

Prince of Songkla University

Royal Thai Army Nursing College

Srinakharinwirot University

Thammasat University

United Arab Emirates

American University in the Emirates

Mamo Payments

University of Wollongong in Dubai

United Kingdom

Aston University

Cardiff University

City St George's, University of London

Cranfield University

Heriot-Watt University

Loughborough University

Royal Holloway, University of London

The Open University

University of Cambridge

University of Glasgow

University of Greenwich

University of Nottingham

University of Reading

University of Sussex

United States of America

CSCS LLC

Deloitte

Genuine Parts Company

GXO Logistics Inc

Iowa State University

Medline Industries LP

Portland State University

UNDOCKED, INC

West Virginia University

Worcester Polytechnic Institute

Vietnam

Can Tho University

CIRTech Institute, HUTECH University of Technology

Foreign Trade University

RMIT University

University of Economics Ho Chi Minh City

VinUniversity

VNU University of Economics and Business

Contents

SECTION ONE: ABSTRACTS 1

REGENERATIVE SUPPLY CHAINS 2

How Does Circularity Unfold in Agricultural Supply Chains in Developing Countries? A Systematic Literature Review; Le Khanh Nguyen, Kwok Hung Lau, Priyabrata Chowdhury. 3

Future Logistics and Supply Chain Capabilities in Retail Circular Business Models; Erik Sandberg[1], Rudrajeet Pal[2] 6

Fostering Regional SME Circular Value Chains Through Participatory Backcasting: Governance Mechanisms for Networked Sustainability Transitions; Tim Ahlheim[1], Marc Bohn[1], Tobias Hoiten[3], Jonas Kallisch[3], Matthias Kalverkamp[1], Stefan Wiesner[2] 8

From Circular to Regenerative: Coffee, Intelligence, and Exit-by-Design Supply Chain Transitions; Eunice Del Rosario Quintana-Smark, Tillmann Boehme, Thomas Birtchnell .. 11

Generating Circular Ecosystems through Refill-Return-Schemes; Nadine Leder[1], Andrew Potter[1], Jin Hooi Chan[2] 14

Regenerative Supply Chain Intelligence under Fragmentation: How Sustainability Pressures Reshape Logistics Capabilities and Performance; AKM Mohsin[1,2], Markus Gerschberger[1,2] 17

Transformation Pathways to Regenerative Supply Chains: Interplay of Organizational Unlearning and Structural Reconfiguration; Felix Naake, Julian Müller 20

Regenerative Fashion Supply Chain: Establishing A Strategic Direction for Net-Positive Industrial Transformation Via Systematic Literature Review; Huy Truong Quang[1], Rajkishore Nayak[1], Rudrajeet Pal[2,3] 23

Improving Waste-Related Reverse Logistics at Shop-Floor Level within Automotive Manufacturing; Helena Fidlerova[1], Bosko Matovic[2], Henrieta Hrablik Chovanova[1] 26

Transitioning from Sustainable to Regenerative Supply Chains: A Thematic Review and Research Agenda; Kamrul Ahsan[1], Booi Kam[1], Joseph Sarkis[2] 29

Enhancing Sustainability through the Governance of Supply Chain Network; Dinh Long Tran, Aswini Yadlapalli, Thuy Nguyen, Paul Childerhouse 33

Circular Economy Between the Tension of Theory and Practice: Re-Engineering and Innovating the Beer Distribution Game Towards Closed Loop Supply Chains; Lukas Nagel, Florian Maurer 36

What Makes Circular Economy Ventures Work? A Multi-Case Analysis of Critical Success Factors; Tillmann Boehme, Eunice Quintana-Smark, Thomas Birtchnell 38

SUPPLY CHAIN INTELLIGENCE 41

Using Game Theory to Increase the Robustness and Resilience of the Supply Chain: Rationality in the Event of Organizational Incidents; Florian Maurer[1], Daniela Tanhua[2], Katri Kesti[2] 42

Decision Efficiency as a Leading Indicator for AI-Enabled Warehouse Operations; Sathya Karuveli[1], Venkates Ramalingam[2], Krishnaveni Namasivayam[3] 46

Implications of AI-Informed Decision Making in Disrupted Supply Chains; Jannicke Baalsrud-Hauge[1], Ioana Stefan[2] 49

Drivers of Smart-Port Investment Intention Under Perceived Security Risk: Evidence from Taiwanese Ports; Muhammad Hayat, Taih-Cherng Lirn, Kuo-Chung Shang 51

Fraightmind: AI-Powered Cargo Optimization Via LLM-Driven Decision Intelligence & Interactive 3D Visualization for Real-Time "What-If" Analysis; Yoshita Singh[2], Tripti Singh[3], Dhawal Thakkar[1], Balamurugan Palaniappan[1] 53

The Role of Supplier Loyalty in Building Regenerative and Resilient Agri-Food Supply Chains; Abdulaziz Mardenli[1], Dirk Sackmann[2] Mohammad Alghababsheh[3]..... 56

Operationalizing Climate Resilience in Container Port Logistics: Evidence from European Ports; Meysam Shaverdi, Mohamed Benmerikhi 58

Quantifying the Value of Age-Information in Pharmaceutical Supply Chain Network Design: A Deterministic Model with Shelf-Life Constraints; Yukun Zhang, Chandra Irawan, Fengfeng Xie..... 60

LOGISTICS CONNECTIVITY 63

Evaluating the Impact of Logistics Service Quality on "Silver" Economy's Customer Satisfaction: A Case Study on E-Commerce in Northern Region of Vietnam; Tran Bao Huy, Nguyen Lan Anh..... 64

Determinants of Rail Transport Development in Developing Landlocked Countries: The Case of North Macedonia; Jakub Donski-Lesiuk 65

MATRA: A National Agent-Based Model for Freight System Resilience and Sustainability; Dhanan Sarwo Utomo, Philip Greening 68

Last-Mile Pharmaceutical Distribution and Spatial Demand Alignment: A Network-Based Accessibility Analysis of Elderly Populations in Taipei City; Hsien-Mei Wang[1], Hui-Chieh Li[2] 70

Characteristics of Integrated Seaport–Dry Port Systems in Hinterland Logistics: A TCCM-Based Literature Review; My Tran, Lam Nguyen, Son Nguyen 74

Forecasting Airport Parking Demand under Fixed Tariffs: A Multi-Node, Must-Serve Approach to Lunar-Holiday Capacity Preparation; Jingyu Choi, Suhyung Lee, Sein Ko, Chulung Lee 76

SMART/DIGITAL SUPPLY CHAINS 78

Digital technologies enabling efficient re-commerce logistics in secondhand fashion supply chains; Kanchana Dissanayake, Rudrajeet Pal 79

From Low-Budget Pilots to Scalable AI in Operations and Supply Chain Management: a Roadmap Built on the "Blueprints" of Implementation; Maria Ciano[1], Nicolò Saporiti[2], Rossella Pozzi[2], Mirco Peron[3] 82

Competency Framework for Smart Warehousing Managers: Expectations in the Industry 4.0 Era; Ashwini Kulkarni[1], Senthilkumar Thiyagarajan[2], Prakash Jeganathanperumal[3], Nachiappan Subramanian[4] 85

Additive Manufacturing vs. Conventional Manufacturing: A Multi-Criteria Decision Analysis Using the Analytic Hierarchy; Christos Braziotis[1], Kulwant Pawar[1], Nachiappan Subramanian[2], Ajeseun Jimo[3] 89

Infrastructure and Participation in Cargo-Bike Crowdshipping: A Discrete Choice Experiment; Sun-Ho Bang[1], Jia-Rong Chen[2], Kwang-Sup Shin[1], Mark Goh[3], Woojung Kim[1] 91

Model for Shaping Innovative Logistics Services for Supply Chains by Logistics Service Providers (LSPs, 3PLs, 4PLs); Iwona Wasielewska-Marszałkowska 93

Business-to-Business Sharing Platforms in Chinese Electronics Supply Chains: Drivers, Value Capture and Environmental Sustainability; Zhang Jiayi 96

Trust-Based Blockchain Architectures for Regenerative Food Supply Chains: A Proof-of-Trust Approach Using a Tomato Supply Chain Case; Alexandra Fiedler, Robert Schönfeld, Sven Karol, Dirk Sackmann, Richard Reinick, Merle Wilk..... 99

Blockchain Adoption Maturity for an Integrated and Regenerative Agricultural Supply Chain: A Dynamic Capability Perspective; Minh Luu, Hung Nguyen, Irfan Ul Haq 102

Decarbonising Fast-Fashion Logistics: Digital Twin Evidence to Support Sustainable UK–Sri Lanka Textile Trade; Reem Hadeed[1], Md Hanif Seddiqui[1], Rivini Mataraarachchi[2], Muhammad Azmat[1], Nandhini Mahesh[1] 106

CSR Relational Governance Mechanisms in Vietnamese Textile Supply Chains; Minh Pham[1,2], Thuy Nguyen[1], Aswini Yadlapalli[1], Paul Childerhouse[1] 109

BUILDING RESILIENCE FOR SUPPLY CHAINS 111

Feeding the Future: Vertical Integration and the Changing Face of European Food Retail; Kathrin Auer[1], Helen Rogers[2], Björn Sven Ivens[3] 112

From Crisis to Competitive Advantage: A Dynamic Capabilities Approach to Opportunity Exploitation in Maritime Supply Chain; Hang Thi Minh Hoang, Lam Canh Nguyen, Vinh Van Thai, Shahrooz Shahparvari 114

Beyond Resilience: Transilience as a means to Drive Supply Chain Transformation and Regeneration; Booi Kam, Kamrul Ahsan, Muhammad Abdulrahman 117

Future-Proofing Sustainable Columbian Coffee Supply Chain: A Stakeholder Resource-Based View; Timothy Ramjaun[1], Madeleine Pullman[2], Maneesh Kumar[3], Vasco Sanchez Rodrigues[3] 120

From Platform to Ecosystem: Orchestrating Value Co-creation in the Digital Logistics Landscape of China; Li Qing 122

Exploring The Antecedents Needed to Build Defence Supply Chain Resilient Capabilities; Zakiah Syamra' Suhaimi[1], Janet Godsell[2] 125

Sustainable Strategy in Chocolate Supply Chain in VUCA Context: A Theoretical Integration; Minh Nguyet Nguyen Luu, Anna John, Nicoleta Tipi 127

Inter-Organisational Relationships and Processor-Mediated Supply Chain Learning: A Conceptual Framework for Dynamic Capabilities in Agri-Food Supply Chains; Minh Anh Nguyen, Kwok Hung Lau, Aswini Yadlapalli 131

Supply Chain Resilience Measurement and Strategic Responses in the Volatile Environment; Mei-hui Chen[1], HsinYi Lin[2], Huiting Chih[2], Kune-muh Tsai[3] 135

How Supply Chains Can Facilitate Equitable Food Provision – Challenges & Opportunities; Emmanuel Sawyerr[1], Michael Bourlakis[2] 138

When Cities Shake: Localised Humanitarian Logistics in the 2025 Myanmar Earthquake; Nichapa Phraknoi[1], Juliana Sutanto[2], Parskorn Yasawute[3], Savangjit Kanchanakomol[4], Hung Nguyen[1] 140

Resilience-Driven Supply Chain Management: Toward a Three-Level Control Framework; Naima Rahiel, Sid Ali Addouche, Abderrahman Elmhamedi 143

SUPPLY CHAIN ANALYTICS 147

Optimal Fleet Electrification Timing Under Subsidy Phase-Out; Hui-Chieh Li 148

Evaluating Logistics Performance in ASEAN Countries: A Novel Dynamic Combined Compromise Solution (CoCoSo) Method Considering Non-Consecutive Series; Shupeng Huang[1], Andrew Potter[2], Daniel Eyers[2], Qinyun Li[2] 150

Supply Chain Intelligence for Retrofit at Scale: Diagnosing Implementation Readiness in Delivery-Sensitive Markets; Muhammad D. Abdulrahman, Priyabrata Chowdhury, Shahrooz Shahparvari, Kamrul Ahsan, Kwok Hung Lau, Vinh Thai, Priya Rajagopalan, Dmytro Ostapenko 152

Hydra-Net: Hybrid Deep Learning Based Routing and Packing Arrangement Network; Dhawal Thakkar[1], Dhanish Ahammed M V[2], Balamurugan Palaniappan[1] 155

GLOBALISATION OF SUPPLY CHAINS 160

Design Drivers for Circular Cold Chain Logistics Using Returnable Transport Items; Irina Harris, Mohammed Fakhrulddin, Dnyaneshwar Mogale, Mohamed M. Naim 161

Modern Slavery Remediation in Healthcare Supply Chains through Blockchain Implementation: A socio-technical systems perspective; Vei Yie Tan, Kamrul Ahsan, Aswini Yadlapalli.....163

When Complexity Undermines Transparency: Supply Chain Structure and Conflict-Free Mineral Sourcing; Beatrice Bais[1], Guido Orzes[2], Stephan Wagner[1] 166

Reinforcing Supply Chain Integration: A Quantitative Assessment of Textile and Garment Sector in Vietnam; Manh Kha Kieu[1], Rajkishore Nayak[1], Irfan Ulhaq[1], Tarun Panwar[2] 168

HUMANITARIAN SUPPLY CHAINS 171

Defining Humanitarian Logistics Corridors: An Anchor-Based Construct Development Approach; Ali Anjomshoae[1], Ruth Banomyong[2], Puthipong Julagasigorn[3], Paitoon Varadejsatitwong[2] 172

Inclusive Humanitarian Logistics: Addressing the Needs of Senior Citizens in Flood Response; Nichapa Phraknoi, Thuy Nguyen, Stanley Teck Lee Yap Yap, Thuan Nguyen Hoang.....175

SUPPLY CHAIN SKILLS, TRAINING AND EDUCATION..... 178

Work Engagement of Truck Drivers in a Tight Japanese Labor Market : Antecedents and Outcomes; Katsuhiko Hayashi, Sadaaki Sudo.....179

Simulation-Based Secured Assessment for Developing Procurement Judgement in Logistics and Supply Chain Education; Tram Nguyen[1], Paul Childerhouse[1], Pete Fernandes[2], Jairus Bowne[2] 182

Women Leaders in Apparel Industry: The Case of Vietnam; Aswini Yadlapalli[1], Tram Nguyen[1], Linh Tran Cam Nguyen[2] 185

SECTION TWO: FULL PAPERS..... 188

REGENERATIVE SUPPLY CHAINS 189

Unravelling Supply Chain Integration Amidst Global Uncertainty: New Evidence from an Emerging Economy; Manh Kha Kieu[1], Rajkishore Nayak[1], Irfan Ulhaq[1], Tarun Panwar[2] ..190

Systematic Review of The Agricultural Sector Decarbonization Barriers and Mitigation Strategies; Sarunyoo Kanchanasuwan[1], Suriyan Jomthanachai[1], Danuphon Tippong[1], Janya Chanchaichujit[2].....199

Not All Modularity Is Circular: A Logistics Perspective on Loop-Enabled and Loop-Blind Product Architectures; Peder Veng Søberg 207

SUPPLY CHAIN INTELLIGENCE 215

Integrating Heterogeneous Quantitative Data for Prognostic Risk Forecasting in Sea Freight: A Curriculum Learning Early Fusion MoE Framework Drawing on LongCat Flash Omni; Linus Kühl[1], Michael Dircksen[1], Stefan Lier[2], Fries Andreas[3,4], Jost Wiethölter[1] 216

Voyage-Level Arrival Delay Risk Prediction for the Port of Los Angeles–Long Beach via Fusion of AIS Trajectory Features and PortWatch Port Day Indicators; Linus Kühl[1], Michael Dircksen[1], Stefan Lier[2], Fries Andreas[3,4], Jost Wiethölter[1] 223

Configuring Digital Twin Readiness for Regenerative Supply Chain Intelligence: Evidence from Indonesia's Shrimp Supply Chain; Anggriani Profita[1,2], Lin Wu[3], Kim Tan[1].....235

Risk-Aware Capacity Contracting Under Carbon-Adjusted Transport Costs; Kannapha Amaruchkul 243

LOGISTICS CONNECTIVITY 251

Socially Responsible Consumption as a Competing Logic for Last Mile Delivery: Case of Kerala; Mohita Gangwar Sharma 252

Conceptualisation of Dry Port Logistics Service Quality; Khun Aye Han Kyu, Thananya Wasusri.....267

Greenhouse Gas Emissions and Financial Performance in Shipping Decarbonisation; Huong Le[1,2], Petri Helo[1], Khuram Shahzad[1], Vinh Thai[2], Aswini Yadlapalli[2].....274

Integrating Connectivity Design and Coordination for Sustainable Logistics: Insights from Japanese Supply Chain Innovation Award-Winners; Sara Abdalla, Siti Mariam Man, Arbaiah Abdul Razak, Wan Rohaida Wan Husain 282

Transit-Net: Mastering The Traffic-Aware Vehicle Routing Problem With Time Windows Using Multi-Stream Attention; Dhawal Thakkar, Balamurugan Palaniappan 290

From Cost Minimization to Environmental Stewardship: Transportation Trade-Offs in Supply Chains; Youssef Sayed Morsy[1], Esraa Zayed[2] 300

SMART/DIGITAL SUPPLY CHAINS 308

Bridging Information and Innovation in Green Supply Chains: The Case of Saudi Arabia; Safinaz Abourokbah, Mohammad Asif Salam, Nada Badawi.....309

Comparative Evaluation of AMR- and OHT-Based Material Transport Integrated with AS/RS in Semiconductor Manufacturing Factory; Koh Taeyoung, Chang YoonSeok 320

Automated Detection of Picking Movements with an Infrared Camera: A Technological Feasibility Study; Peik Bremer[1], Yannic Henz[1], Luca Cannava[2] 1: Technical University of Applied Sciences Würzburg-Schweinfurt, Germany; 2: Politecnico di Milano 329

Bridging the Green Gap: A Low-Cost Automation Strategy for Net-Zero Transition in Vietnamese SMEs; Dung Anh Vu[1], Kim Hua Tan[2] 340

Digital Transformation Adoption and Sustained Logistics Performance in SMEs in Vietnam: The Mediating Role Of Absorptive Capacity; My Thanh Tran Dinh, Ahmad Abareshi, Vinh V. Thai 348

The Effect of Artificial Intelligence in Hospitality Supply Chain Management; Anas Abbas, Balan Sundarakani 357

Smart Food Safety Integration Mechanisms in Emerging Market Supply Chains: Coordination for Sustainability; Linh Thi Hai Tran[1], Hiep Pham[1], An Duong Thi Binh[2], Quan Dinh Hoang[3], Huy Truong Quang[1] 364

BUILDING RESILIENCE FOR SUPPLY CHAINS 400

The Nexus Between Resilience and Sustainability in the Maritime Industry: Toward an Exploratory Theoretical Framework; Minh B. Chu[1], Vinh V. Thai[1], Canh Lam Nguyen[2] 401

Do Sustained Resilience Capabilities Lead to Sustained Competitive Advantage? - The Role of Resilience-Focused Strategic Intent and Sustained Supply Chain Performance; Doan Trinh Nguyen[1,2], Vinh Van Thai[1], Ton Hien Duc Truong[1], Priyabrata Chowdhury[1] 409

The Pursuit of Ambidexterity for Supply Chain Resilience: An Investigation of Resilience Capabilities Before, During and After Covid-19; Łukasz Marzantowicz[1], Anja Hergesell[2], Rene Bauer[3], Nils-Ole Hohenstein[4], David M. Herold[5] 417

German Carmakers Moving from Task Force Mode to Resilience Building In The 2020ff Semiconductor Supply Crisis; Peik Bremer 424

Exploring the Impact of Port Congestion on the Delivery Schedule of Food Cold Chain Companies in Ireland; Marzieh Nazemzadeh Goki, Darshak Bhatt, Hrithik Kumar Raghavendra 448

Enhancing Resource Efficiency in Regenerative Agricultural Supply Chains Using an Input-Narrowing-Focused Circularity Index; Kwok Hung Lau, Priyabrata Chowdhury 456

Revisiting Deserts, Empires, and Guilds: Historical Foundations of Frugal Supply Chains; Gilles Pache 465

Does Digital Transformation Enhance Supply Chain Resilience Capabilities? Evidence from the Vietnamese Seafood Industry; Thi Tham Tran, Vinh Van Thai, Truong Ton Hien Duc 473

SUPPLY CHAIN ANALYTICS 486

Inside The Mind of an AMR: A Demonstrator for Slam-Based Navigation in Logistics Education; Luca Reck[1], Sara Perotti[2], Luca Cannava[2], Peik Bremer[1] 487

GLOBALISATION OF SUPPLY CHAINS 500

Labor Supply Expansion and the Erosion of Social Sustainability: A System Dynamics Study of EU Trucking; Dhiraj Pal[1], Henrik Sternberg[1], Molly Hughes[2] 501

HUMANITARIAN SUPPLY CHAINS 509

CSR Legitimacy or Greenwashing? A Multi-Theoretical Framework for Analysing Corporate Social Responsibility in PNG's Extractive Industries; Alphonse Kona, David M. Herold, Erica French 510

SUPPLY CHAIN SKILLS, TRAINING AND EDUCATION..... 519

Applications and Implications of Gamification in Warehousing; Jörg M. Ries, Naoum Tsolakis.....520

SECTION ONE: ABSTRACTS

REGENERATIVE SUPPLY CHAINS

How Does Circularity Unfold in Agricultural Supply Chains in Developing Countries? A Systematic Literature Review

Le Khanh Nguyen, Kwok Hung Lau, Priyabrata Chowdhury

RMIT University, Australia

Purpose of this paper

The adverse effects of the conventional linear model on agricultural productivity and the environment have increased attention towards circular supply chain practices (CSCPs), which aim to achieve zero-waste while enhancing competitive advantage (Sahu and Choudhary, 2025). Consequently, an increasing number of studies have explored circular supply chains (CSCs) in recent years (Bathaei *et al.*, 2025). Although existing reviews have provided valuable insights into CSCs in agriculture, they largely examine key aspects in isolation, such as drivers and barriers (e.g., Mehmood *et al.* (2021)), circular economy (CE) models (e.g., Chiaraluce *et al.* (2021)), or outcomes and measurement methods (e.g., Lavelli (2021)). Limited attention has been given to integrating these elements within an explicit adoption mechanism that explains how they interact to shape CSCP adoption in practice. Moreover, much of the literature treats food waste as the primary entry point for circularity (e.g., Haque *et al.* (2023)). This focus may narrow the scope of CE and underrepresents other critical practices, including input substitution, regenerative production, and the coordination of closed- and open-loop flows.

Additionally, existing reviews predominantly focus on global or developed-country contexts, leaving developing countries relatively underexplored (Ndoka et al., 2025). This represents a critical gap, as developing economies face distinct structural and institutional constraints that fundamentally shape CSCP adoption. While some reviews acknowledge these contextual challenges (e.g., Ndoka *et al.* (2025)), they rarely explain how such conditions translate into adoption mechanisms that enable CSCPs.

Accordingly, this review aims to address these gaps by synthesising prior evidence into an integrative adoption framework that explains how developing-country contexts shape adoption mechanisms, enable CSCPs across agricultural supply chains, and generate sustainability outcomes.

Design/methodology/approach

This study adopted a systematic literature review to synthesise existing knowledge logically and systematically. The review followed the PRISMA protocol, including four stages: identification, screening, eligibility, and inclusion (Figure 1). Database searches were conducted using keywords related to CSCs and the agricultural sector. After screening and full-text assessment against predefined criteria, 68 studies were retained. These articles were examined using structured content analysis to identify key insights on contextual factors, antecedents, adoption mechanisms, CSCPs, and sustainability outcomes.

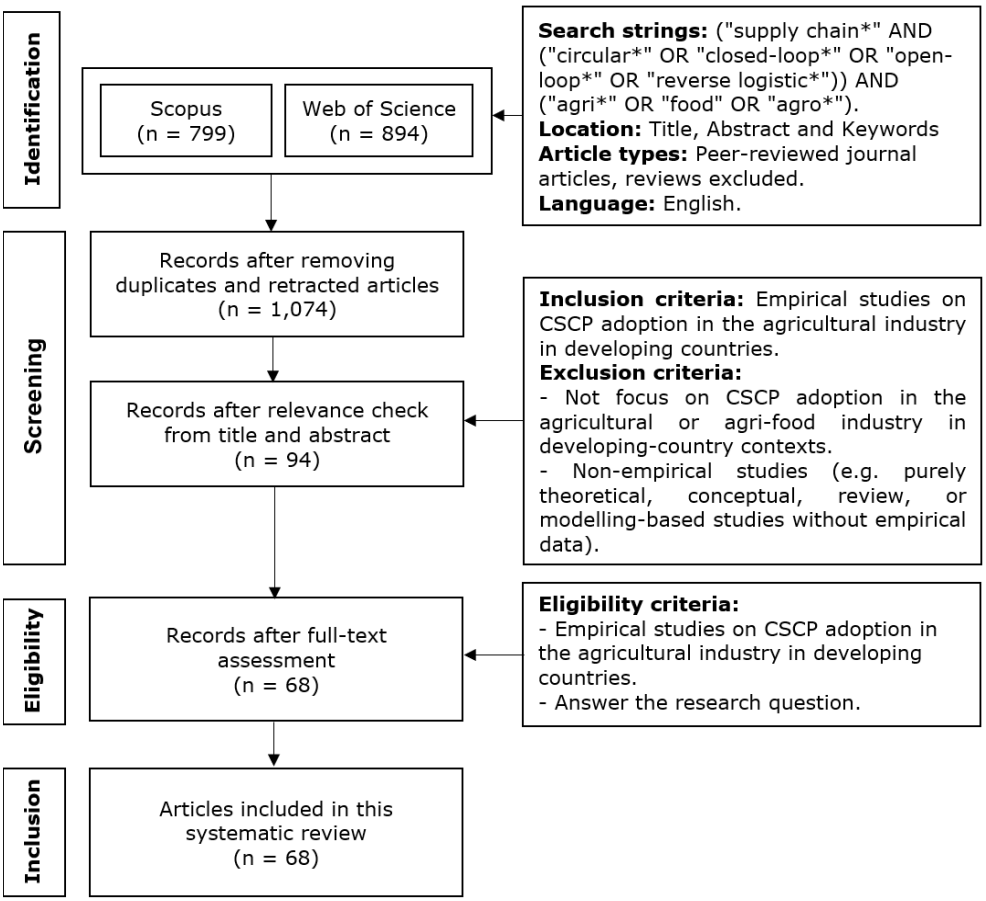


Figure 1. Review procedure

Findings

This review informed the development of an integrated conceptual framework explaining CSCP adoption as an interconnected process. *Contextual conditions* in developing countries fundamentally shape its *antecedents*. First, institutional voids, characterised by regulatory ambiguity and weak enforcement, often reduce the effectiveness of environmental regulations as drivers, unlike the stronger regulatory pressures commonly observed in developed countries (Bathaei *et al.*, 2025). Consequently, firms facing limited resources tend to prioritise short-term cost reduction and revenue generation over long-term sustainability investments, positioning economic benefits as the primary motivation for adopting CSCPs (Do *et al.*, 2022). Additionally, infrastructural gaps, such as inadequate cold chains and recycling facilities, hinder CSCP implementation at the production and post-harvest stages, whereas developed countries primarily encounter waste-related challenges at the consumption stage (Ardra and Barua, 2023). Finally, agricultural supply chains in developing countries are often fragmented and dominated by smallholders and informal actors. This fragmentation complicates the collaboration required to close resource loops, necessitating cooperative governance arrangements rather than the industrial models common in developed economies (Jayalath *et al.*, 2025, Vásquez Neyra *et al.*, 2025).

Adoption mechanisms then translate these *antecedents* into practice through partnerships, financing, training, and digital platforms, enabling *CSCP* implementation across supply chain stages from regenerative production to post-consumption resource recovery (Jayalath *et al.*, 2025). Together, these practices generate *economic, environmental, and social outcomes*, which in turn feed back into the context, gradually reshaping future adoption pathways (Vásquez Neyra *et al.*, 2025).

Value

This study moves beyond fragmented analyses of drivers, barriers, CSCPs, or outcomes by proposing an integrated framework that conceptualises CSCP adoption as an interconnected process. By linking contextual conditions, antecedents, adoption mechanisms, CSCPs, and sustainability outcomes, it clarifies how circular transitions unfold in practice within developing-country agricultural systems.

Research limitations

The findings depend on the scope and quality of the existing studies. Relevant grey and non-English literature are not included.

Practical implications

For practitioners, the study provides a roadmap for translating circular ambitions into actionable strategies in developing-country agricultural systems, supporting them in designing targeted interventions that deliver measurable benefits.

References

Ardra, S. & Barua, M. K. (2023). Inclusion of circular economy practices in the food supply chain: Challenges and possibilities for reducing food wastage in emerging economies like India. *Environment, Development and Sustainability,* 25, pp.13825-13858.

Bathaei, A., Agnusdei, L., Ardakani, Z., Streimikiene, D. & Baležentis, T. (2025). Decision support for sustainable circular food supply chain in Iran: A fuzzy multi-criteria approach. *Computers & Industrial Engineering*, pp.111403.

Chiaraluce, G., Bentivoglio, D. & Finco, A. (2021). Circular economy for a sustainable agri-food supply chain: A review for current trends and future pathways. *Sustainability,* 13, pp.9294.

Do, Q., Mishra, N., Colicchia, C., Creazza, A. & Ramudhin, A. (2022). An extended institutional theory perspective on the adoption of circular economy practices: Insights from the seafood industry. *International Journal of Production Economics,* 247.

Haque, F., Fan, C. & Lee, Y.-y. (2023). From waste to value: Addressing the relevance of waste recovery to agricultural sector in line with circular economy. *Journal of Cleaner Production*, pp.137873.

Jayalath, M. M., Perera, H. N., Ratnayake, R. C. & Thibbotuwawa, A. (2025). Harvesting sustainability: Transforming traditional agri-food supply chains with circular economy in developing economies. *Cleaner Waste Systems,* 11, pp.100264.

Lavelli, V. (2021). Circular food supply chains–Impact on value addition and safety. *Trends in Food Science & Technology,* 114, pp.323-332.

Mehmood, A., Ahmed, S., Viza, E., Bogush, A. & Ayyub, R. M. (2021). Drivers and barriers towards circular economy in agri-food supply chain: a review. *Business Strategy & Development,* 4, pp.465-481.

Ndoka, E., Alimehmeti, G., Shulla, K. & Voigt, B.-F. (2025). Transitioning to circular business models in developing countries: a systematic literature review of barriers, enablers, and future directions. *Discover Sustainability,* 6, pp.605.

Sahu, D. K. & Choudhary, D. (2025). Transitioning to Circular Economy in Agriculture Sector: An Extended Institutional Theory and Stakeholder Perspective. *Business Strategy and the Environment,* 34, pp.7180-7209.

Vásquez Neyra, J. M., Cequea, M. M. & Schmitt, V. G. H. (2025). Current practices and key challenges associated with the adoption of resilient, circular, and sustainable food supply chain for smallholder farmers to mitigate food loss. *Frontiers in Sustainable Food Systems,* 9, pp.1484933.

Future Logistics and Supply Chain Capabilities in Retail Circular Business Models

Erik Sandberg[1], Rudrajeet Pal[2]

1: Linköping University, Sweden; 2: Swedish School of Textiles, University of Borås, Sweden

Purpose of this paper

Logistics and supply chain capabilities (LSCCs) play a major role for a successful implementation of circular business models (CBMs) in the retail industry. LSCCs are concerned with the combination and coordination of resources and relationships in the supply chain that allows for improved efficiency and effectiveness in supply chain operations (Cho et al., 2008; Wu et al., 2010).

A key premise of this research is that provided the rapid development and change of retail CBMs, the LSCCs that underscore the CBMs will also need to change accordingly. From a logistics research perspective, it is therefore relevant to not only consider how current LSCCs supports CBMs, but also the characteristics of future ones. The research is guided by the following overall research question: Which LSCCs will be required for Swedish retail companies to create and operate profitable CBMs in the future?

More specifically, the study aims to identify what types of capabilities will be required in relation to the rapid development of CBMs. The study also seeks to understand why each capability will be important, which actor should possess or control the capability (the retail firm itself or another actor), and in what context the capability becomes critical, for example with respect to product type, business model, or position in the circular logistics flow (collection, sorting, recovery, or redistribution).

Design/methodology/approach

The study is based on a Delphi study approach. Although there is considerable variation in how Delphi studies are designed and conducted (Caldarelli, 2024), the method can broadly be described as a structured, iterative process in which experts assess and discuss a specific topic over several rounds, with the ambition of reaching a shared view or consensus. Where consensus cannot be achieved, divergence of opinions constitutes a relevant outcome in itself. The Delphi method is particularly suitable in contexts characterised by limited empirical evidence or where forward-looking assessments of future developments are sought.

The expert panel for this study comprises 18 participants with extensive experience of logistics, supply chain management and CBMs in a retail context. The participants represent a broad range of professional backgrounds, including retail company management, logistics service providers, technology and system providers, consultants, and researchers. Collectively, the panel covers expertise related to forward and reverse logistics, digitalisation, circular business development, governance and policy-related issues, as well as operational activities such as collection, sorting, recovery and redistribution of products. This diversity has been intentionally sought in order to capture multiple perspectives on future LSCCs requirements in retail CBMs.

The Delphi design employed in this study comprises four main steps. First, a narrative literature review was conducted to establish a baseline of currently identified LSCCs. As a finding from step one, in total nine main LSCCs were identified from the literature and further structured into three sub-capabilities each in order to clarify their scope. Second, individual semi-structured interviews, each lasting approximately 45 minutes, were conducted with all 18 participants. The purpose of these interviews was to elaborate on the literature-based LSCC framework and to adopt a forward-looking perspective, focusing on a time horizon of three to five years. Participants were encouraged to suggest revisions, clarifications, and additional capabilities. As a finding from step two, based on the interview data, the researchers revised the framework to include a total of ten LSCCs. Third, a web-based survey was distributed to the participants, with

the objective of ranking the identified LSCCs. Finally, a workshop was conducted in which the survey results were presented, discussed, and jointly interpreted by the expert panel.

Findings

As an output from second step (see methodology), the identified LSCCs were structured across three overarching categories: (1) strategy, organisation and control, (2) supply chain-wide development and governance, and (3) supply chain activities. In total, ten LSCCs were identified and elaborated.

The first category highlights capabilities related to collaboration, performance measurement, and regulatory and policy alignment. In short, these include the capability to design and manage circular logistics collaborations, share risks and profits, develop cross-industry partnerships, measure economic, social and environmental performance, conduct life cycle assessments, and align logistics operations with current and future regulatory requirements.

The second category focuses on supply chain-wide development and governance and includes data-driven traceability and transparency as well as circular competencies and flexibility in the logistics system. Key elements here involve digital monitoring and information sharing across actors, customer-oriented communication of circularity, cross-functional and digital competencies, change management, scalability, and resilience in handling both linear and circular flows.

The third category addresses operational activities in circular supply chains, including return and collection logistics, sorting and quality assessment, restoration and refurbishment, and reintroduction of products to the market. These capabilities relate to designing efficient collection systems, automated sorting and grading, value optimisation across downstream flows, organising repair and refurbishment processes, ensuring quality, and managing the timing and channels through which products are reintroduced to the market or directed towards recycling.

Value

Retailers, positioned close to end consumers, play a key role in the transformation from a linear to a circular economy. Despite this, limited research has examined LSCCs in a circular context. This study adopts a future-looking perspective on LSCC requirements in the context of retail CBMs and circular economy by providing a framework with ten LSCCs based on expert assessments. The findings offer both scholarly and practical insights into how LSCCs may support the scaling and profitability of CBMs in retail.

Research limitations/implications

The study is conducted in a Swedish retail context, which may limit direct generalisation to other national settings.

Practical implications

The findings highlight the importance of LSCCs for the future development and scaling of CBMs in retail. The study provides practitioners with a structured overview of ten key LSCC categories, elaborated and prioritised by experienced industry experts.

References

Caldarelli, G. (2024), "Expert perspectives on blockchain in the circular economy: A Delphi study with industry specialists", Journal of Cleaner Production, Vol. 465 No. 142781.

Cho, J. K. J., Ozment, J. and Sink, H. (2008), "Logistics capability, logistics outsourcing and firm performance in an e-commerce market", International Journal of Physical Distribution and Logistics Management, Vol. 38, No. 5, pp. 336-359.

Wu, S. J., Melnyk, S. A. and Flynn, B. B. (2010), "Operational capabilities: The secret ingredient", Decision Sciences, Vol. 41, No. 4, pp. 721-754.

Fostering Regional SME Circular Value Chains Through Participatory Backcasting: Governance Mechanisms for Networked Sustainability Transitions

Tim Ahlheim[1], Marc Bohn[1], Tobias Hoiten[3], Jonas Kallisch[3], Matthias Kalverkamp[1], Stefan Wiesner[2]

1: Wiesbaden Business School at RheinMain University of Applied Sciences, Germany; 2: BIBA - Bremer Institut für Produktion und Logistik GmbH at the University of Bremen, Bremen, Germany; 3: OFFIS Institute for Information Technology, Oldenburg, Germany

Purpose of this paper

The circular economy (CE) transition requires fundamental transformation from linear to circular business models to enable closed material loops and resource efficiency (Ekins et al., 2019). However, small and medium-sized enterprises (SMEs) face systemic barriers including limited access to secondary materials, rigid customer requirements, knowledge gaps, and constrained resources, particularly independent SMEs not integrated into large-scale supply chains (de Jesus & Mendonça, 2018).
Regional circular value chains offer advantages such as reduced transportation costs, trust-building through proximity and enhanced resilience (Ekins et al., 2019). However, literature provides limited guidance on governance mechanisms enabling independent SME participation, particularly regarding trust-building, data sovereignty, and neutral platform coordination (Konietzko et al., 2020; Leising et al., 2018).
This study operationalizes a "neutral platform" through non-partisan governance, a transparent non-profit model (no rent extraction), and strict data-sharing policies.
Hypothesizing that neutral governance enables collaborative circular business models, the study applies participatory backcasting to develop a strategic roadmap extending to 2035 for regional SME circular value chains, using North-West Germany as a case example.

Approach

This study integrates participatory backcasting (Quist & Vergragt, 2006) with transition management frameworks (Loorbach, 2010). Backcasting, as a normative methodology, works backward from desirable futures to identify necessary R&D activities, technological advances, and governance innovations (Robinson, 2003).
The methodology follows Quist and Vergragt's (2006) five-stage framework: strategic problem orientation, future vision construction, backcasting analysis, action agenda elaboration, and implementation planning. The regional environment is analyzed through six organizational dimensions: (1) resource management, (2) human-centric transition, (3) economic logic, (4) socio-technical innovation, (5) regional synergy , and (6) organizational agility.
Data collection employs semi-structured interviews with regional stakeholders including SMEs, industry associations, and public-private partnerships. Through qualitative coding and iterative workshops, gaps in technology, business models, and governance are identified. Comparative analysis between North-West Germany and Rhine-Main assesses transferability between regions of different economic characteristics.

Preliminary Insights

Initial stakeholder analysis reveals that governance and trust-building challenges often outweigh technical constraints.
Governance Insights: SMEs highlight data sovereignty, competitive information exposure, and power asymmetries as key challenges in circular material exchanges. Data sovereignty is viewed as a core design element for future digital CE platforms. While literature identifies ecosystem coordination importance (Konietzko et al., 2020; Leising et al., 2018), existing studies focus on

corporate-led or client-facilitated networks. This project explores neutral intermediary governance-structures that exclude profit extraction to address trust-related barriers identified in prior platform research (Konietzko et al. 2020).
Dimensional Prioritization: Workshops suggest human-centric (employee participation, culture) and governance factors (trust-building, data governance, fair value distribution) as critical preconditions, aligning with Robinson's (2003) social learning perspective.
Regional Resilience: Stakeholders perceive regional circular chains as mechanisms for reducing global supply chain dependency.
Expected Roadmap: The backcasting process will yield a prioritized R&D roadmap addressing neutral platform governance, data protocols, trust-building for SMEs, and digital coordination infrastructure. These represent expected findings from ongoing stakeholder engagement, not validated results.

Value

This research addresses gaps in CE governance literature by focusing on regional SME networks. While Konietzko et al. (2020) and Leising et al. (2018) address corporate-led contexts, our research extends participatory backcasting to independent SME circular value chains, integrating governance and data sovereignty dimensions absent from technical CE frameworks. The six-dimensional structure moves beyond techno-economic models to incorporate organizational culture and institutional trust-building as first-order circularity determinants. Neutral intermediary governance proposes innovation addressing openness-rent tension (Konietzko et al., 2020) and extends transition management theory (Loorbach, 2010) to digital platform-mediated regional circular value chains.

Research Limitations / Implications

Findings are based on qualitative interviews and initial workshops. Robinson (2003) identifies the difficulty imagining beyond current constraints ("assumption drag") as a persistent backcasting challenge. While the six-dimensional framework mitigates this, co-created visions may reflect incremental change. Quist and Vergragt (2006) note that implementation is the weakest stage in backcasting, requiring sustained engagement beyond a 12-month timeline.
Literature provides limited precedent for neutral platform operators in regional SME contexts (Konietzko et al., 2020; Leising et al., 2018), constraining theoretical grounding. Additionally, limited guidance in CE exchange platforms for SME contexts is provided for protecting competitive information while enabling transparency—requiring exploratory development (Zichichi et al., 2020; Kallisch & Wunck, 2022). Findings are contextualized to North-West Germany; broader applicability requires testing.

Practical Implications

For SMEs, this research provides a diagnostic framework for assessing circular transformation readiness across six dimensions. Industry associations gain (neutral) intermediary models for regional orchestration, while policymakers see the relevance and relation between technical infrastructure investments, governance infrastructure, and trust-building mechanisms. The resulting roadmap can help direct public research funding toward systematic steps for achieving circular future visions.

References

De Jesus, A., & Mendonça, S. (2018). Lost in transition? Drivers and barriers in the eco-innovation road to the circular economy. *Ecological Economics*, *145*, 75–89. https://doi.org/10.1016/j.ecolecon.2017.08.001

Ekins, P., Domenech, T., Drummond, P., Bleischwitz, R., Hughes, N., & Lotti, L. (2019). The circular economy: What, why, how and where. Managing Environmental and Energy Transitions for Regions and Cities, OECD. https://discovery.ucl.ac.uk/id/eprint/10093965/

Kallisch, J., & Wunck, C. (2022). Options for connecting decentralized data infrastructure to improve supply-chain decision making without giving up individual data property. *Decision Sciences Institute Annual Conference Proceedings*, 1341–1354.

Konietzko, J., Bocken, N., & Hultink, E. J. (2020). Circular ecosystem innovation: An initial set of principles. *Journal of Cleaner Production*, *253*, 119942. https://doi.org/10.1016/j.jclepro.2019.119942

Leising, E., Quist, J., & Bocken, N. (2018). Circular Economy in the building sector: Three cases and a collaboration tool. *Journal of Cleaner Production*, *176*, 976–989. https://doi.org/10.1016/j.jclepro.2017.12.010

Loorbach, D. (2010). Transition management for sustainable development: A prescriptive, complexity-based governance framework. *Governance*, *23*(1), 161–183. https://doi.org/10.1111/j.1468-0491.2009.01471.x

Quist, J., & Vergragt, P. (2006). Past and future of backcasting: The shift to stakeholder participation and a proposal for a methodological framework. *Futures*, *38*(9), 1027–1045. https://doi.org/10.1016/j.futures.2006.02.010

Robinson, J. (2003). Future subjunctive: Backcasting as social learning. *Futures*, *35*(8), 839–856. https://doi.org/10.1016/S0016-3287(03)00039-9

Zichichi, M., Contu, M., Ferretti, S., & Rodríguez-Doncel, V. (2020). *Ensuring personal data anonymity in data marketplaces through sensing-as-a-service and distributed ledger*. DEU. https://cris.unibo.it/handle/11585/752963

From Circular to Regenerative: Coffee, Intelligence, and Exit-by-Design Supply Chain Transitions

Eunice Del Rosario Quintana-Smark, Tillmann Boehme, Thomas Birtchnell

University of Wollongong, Australia

Purpose of this paper

Regenerative supply chains are often described as net-positive systems that move beyond harm reduction, yet research still lacks grounded accounts of how such systems hold together when disruption occurs in settings outside highly resourced contexts (Gualandris et al., 2024). Using spent coffee grounds (SCG) as the empirical focus, this study examines a ubiquitous, high-volume, yet operationally volatile material stream. Here, moisture, odour, contamination, and storage constraints make quality uncertain, repeatedly destabilising collection and reuse (Kourmentza et al., 2018). The analysis builds on earlier-stage findings from the broader doctoral research programme, which developed an Accidental Supply Chain (ASC) transition model with four phases: initiation, stabilisation, legitimation, and institutionalisation. This paper extends that phase model by adding a mechanism layer that explains how durability is produced and why some pathways persist while others stall.

The mechanism layer is termed Regenerative Supply Chain Intelligence (RSCI). RSCI captures four forms of intelligence that accumulate as circular recovery becomes more durable. Material intelligence is the hands-on know-how for handling volatile streams, including collection cadence, containment choices and routing decisions. Relational intelligence concerns participation and coordination work that keeps supply chain participants aligned across a recovery pathway. Institutional intelligence is visible where actors make the pathway acceptable and legible through roles, responsibility boundaries, procurement arrangements and standards. Exit-by-design intelligence completes the framework. It refers to planned handover and phase-out, so routines persist beyond short funding cycles or individual champions. In this framing, success is not the intermediary's indefinite survival. Success is the point at which coordination becomes embedded elsewhere, and the intermediary becomes less central by design.

Design/methodology/approach

The study uses an interpretive, qualitative multi-case design drawn from the broader doctoral research programme on circular economy implementation in regional Australia, complemented by comparative observations from European coffee systems. Empirical material comprises semi-structured interviews with social enterprise founders and staff, café operators, waste and logistics actors, and local government and circular economy intermediaries involved in SCG recovery and reuse. Field observations, workshop participation and document review provide additional context. Participants were recruited through purposive and snowball sampling across collection, processing and governance roles to capture variation in pathway maturity.

Analysis relies on the ASC four-phase transition model and the RSCI mechanism layer. Interview and field materials were coded iteratively to identify pathway phases, the routines that stabilise or destabilise flows, and the places where the four intelligences are produced and transferred. Evidence for RSCI was drawn from observed operating routines, role definitions, and handover artefacts such as documented protocols and continuity agreements. Memos captured decision points around ownership, incentives and stewardship, including explicit handover triggers and exit conditions. Cross-case patterning highlighted common pressure points and pathway outcomes, summarised in Figure 1.

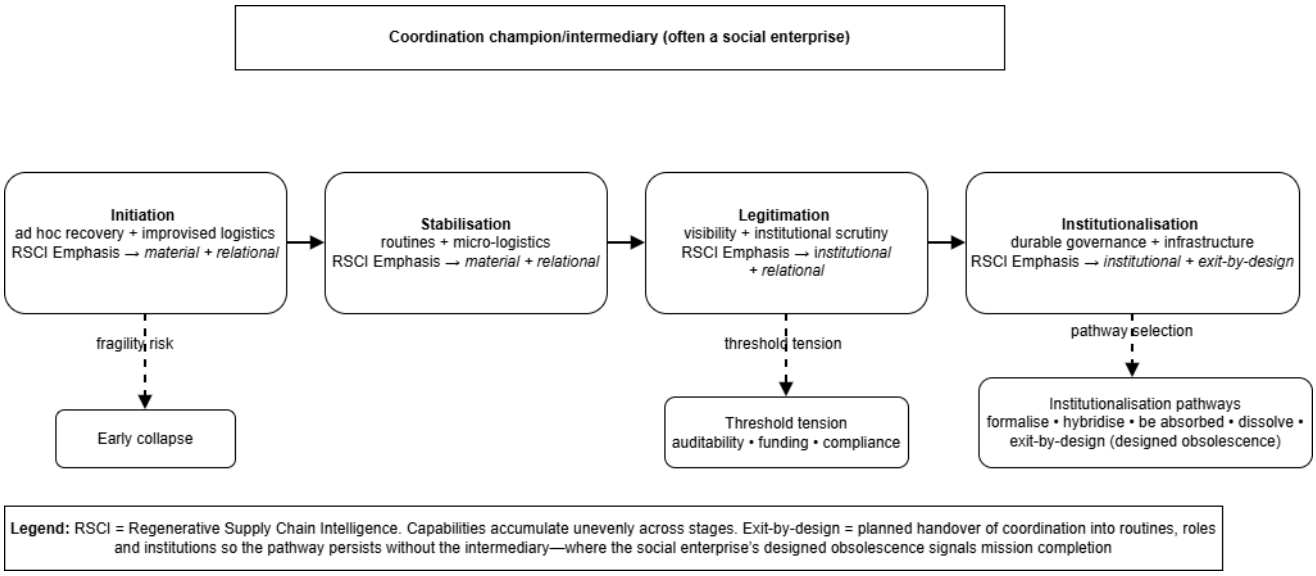
Findings

Regenerative coffee recovery rarely progresses through linear planning or technology adoption alone. It emerges through the iterative stabilisation of routines and roles. Early-stage systems commonly take the form of accidental supply chains or improvised recovery networks arising

from waste pressures and opportunistic local partnerships. In the initiation phase, SCG recovery begins through bricolage, relying on repurposed containers, improvised drop points, and informal pickups coordinated by an intermediary. In stabilisation, reliability improves when timed collection windows, sealed containers, simple quality thresholds and rapid routing rules are introduced to manage contamination and perishability (Kourmentza et al., 2018).

As pathways move into legitimation, threshold tension becomes more visible. Auditability, liability and council requirements intensify, and informal arrangements are no longer sufficient. In institutionalisation, durability hinges on exit-by-design. Systems relying on a single champion and short-term grant funding often collapse due to turnover. In contrast, pathways persist without depending on the intermediary when actors embed handover routines, such as documentation, successor roles, and continuity agreements, to transfer coordination into host organisations. Phase-out matters here as well. Reducing reversion to disposal requires deliberate withdrawal from incumbent waste routines as much as building new ones (Rogge and Johnstone, 2017).

Figure 1. Circular to Regenerative Transition Model with RSCI and exit-by-design. The model traces volatile recovery pathways (exemplified by SCG) from bricolage-based initiation and stabilisation through legitimation and institutionalisation. It highlights generalisable pressure points (early collapse, threshold tension) and pathway selection, locating where RSCI capabilities accumulate and where exit-by-design enables durability through handover and phase-out.



Value of this paper

This work contributes to ISL 2026 in three ways. First, it reframes supply chain intelligence for regenerative transitions as a socio-material capability assembled in practice rather than solely a digital optimisation problem (Gualandris et al., 2024). Second, it strengthens the ASC transition model by specifying RSCI as the mechanism layer that explains what keeps a volatile recovery pathway moving at each phase through material learning, participation building, legitimacy work and handover design. Third, it establishes exit-by-design as a durability mechanism. Planned handover and phase-out allow coordination to settle into resilient routines and institutions, so the system can survive the departure of its originators (Rogge and Johnstone, 2017). This aligns with work that treats entrepreneurial exit as part of value creation (DeTienne, 2010).

References

DeTienne, D.R. (2010) 'Entrepreneurial exit as a critical component of the entrepreneurial process', *Journal of Business Venturing*, 25(2), pp. 203–215.

Gualandris, J. *et al.* (2024) 'Unchaining supply chains: Transformative leaps toward regenerating social–ecological systems', *Journal of Supply Chain Management*, 60(1), pp. 53–67.

Kourmentza, C. *et al.* (2018) 'Spent coffee grounds make much more than waste: Advances and strategies for valorisation', *Journal of Cleaner Production*, 172, pp. 1–14.

Rogge, K.S. and Johnstone, P. (2017) 'The role of phase-out policies for low-carbon energy transitions: The German Energiewende', *Energy Research & Social Science*, 33, pp. 179–191.

Generating Circular Ecosystems through Refill-Return-Schemes

Nadine Leder[1], Andrew Potter[1], Jin Hooi Chan[2]

1: Cardiff University, United Kingdom; 2: University of Greenwich, United Kingdom

Purpose of this paper

With the transition towards a Circular Economy (CE) and the understanding that true circularity requires collective system-wide changes (e.g., Amir et al., 2020), research has increasingly adopted a circular ecosystem perspective. Within such ecosystems, independent actors collaborate to create an environment that enables coherent circular value propositions with consumers (e.g., Trevisan et al., 2022). Key partners typically include industry actors, public entities, government bodies, non-profit organisations, and research and educational institutions (e.g., Pietrulla, 2022). Despite this conceptual progress, empirical evidence on transitioning from linear business models to circular, collaborative systems remains limited (e.g., Trevisan et al., 2022).

This paper forms part of a broader research project examining circular service systems in the beverage sector. It focuses specifically on the operational and behavioural aspects of a refill-return cup scheme, analysing data on cup usage, return rates, and customer engagement. With the coffee shop industry expanding rapidly and over 2.5 billion disposable cups used annually in the UK (House of Commons, 2018), this study explores how a circular ecosystem approach can integrate consumers and businesses into circular services and promote inclusive and publicly accountable sustainable practices. In doing so, it examines return-rate patterns and user behaviour to identify factors influencing successful participation and investigates system-level interactions that enable or constrain the effectiveness of refill-based circular models.

Design/methodology/approach

The study applied a longitudinal approach, collecting data over eighteen months and structured into three phases: Pre-implementation, Implementation, and Maintenance. This design enabled continuous monitoring of the refill-return cup scheme, capturing operational and behavioural data throughout each phase to examine system performance, user engagement, and the practical requirements for setting up and sustaining the scheme.

A mixed-methods approach was employed. The primary data source was the app-based tracking system for the cups, providing metrics such as the number of cups in circulation, return rates, and timing of returns. Supplementary data were collected through short surveys with users and café staff to capture perceptions of usability, convenience, and participation barriers, allowing operational patterns to be interpreted alongside behavioural insights.

For the purposes of this study, quantitative data from the cup tracking system were analysed using descriptive statistics and trend analysis to identify patterns in return behaviour, peak usage periods, and factors influencing successful participation. Across the broader project, these data were combined with consumer survey responses and qualitative insights to triangulate findings, providing a deeper understanding of motivations, challenges, and opportunities for improvement. Where applicable, qualitative responses were coded thematically to highlight recurring behavioural patterns and key insights into user experiences.

This approach provides an evidence-based understanding of how the refill-return cup scheme functions in practice and generates actionable insights to optimise operational efficiency, enhance user engagement, and support the development of scalable, consumer-facing circular interventions for cafés, local councils, and policymakers.

Findings

Quantitative data from the app-based tracking system indicated that a majority of cups were returned within the designated timeframe, with an overall return rate of 97%, demonstrating strong user engagement. Peak usage occurred on weekdays during mid-morning and early-

afternoon periods, reflecting typical coffee purchasing behaviour. These patterns raise questions about whether refill-return schemes primarily serve commuters or leisure users, and how behavioural insights could be used to optimise participation.

Return rates varied across participating cafés, suggesting that operational factors, including staff engagement and the visibility and accessibility of cafés as return points, influenced user compliance. As this was a refill-return scheme, the data also allowed analysis of how often cups were refilled and whether they remained with a single user or circulated among multiple users. Examining the timing and frequency of returns enabled estimation of the number of cups required to maintain the scheme efficiently, helping to avoid unnecessary inventory accumulation.

This has important implications for reducing embedded CO_2 emissions associated with producing and supplying additional cups, highlighting the environmental benefits of careful operational planning. Overall, the findings demonstrate that effective management of operational and behavioural factors is key to achieving a scalable, high-performing, and environmentally sustainable refill-return system.

Overall, the findings demonstrate that a refill-return model can achieve high levels of engagement when operational requirements are clear and user experience is optimised. They also provide actionable evidence for scaling the scheme, indicating that strategic placement of return points, ongoing user communication, and staff support are critical to sustaining participation and maximising the environmental impact of consumer-facing circular interventions.

Value

This paper provides actionable insights for cafés, local councils, government bodies, and organisations within the tourism and hospitality sector seeking to support sustainable practices. By examining the operational and behavioural dynamics of a refill-return cup scheme, the study demonstrates how circular service models can reduce waste, minimise environmental impacts such as embedded CO_2 emissions, and engage consumers effectively. Unlike traditional deposit-return systems, this model allows users to borrow cups without paying upfront, increasing accessibility and inclusivity, particularly for low-income households who may otherwise be excluded from participating.

Research limitations/implications

This research is limited as the scheme was implemented within a single city, which may introduce regional bias and reflect operational and behavioural challenges that are not fully generalisable to other contexts. Within the broader project, the use of thematic analysis in interpreting qualitative data carries the potential for researcher bias in coding and interpretation, which may influence the findings. The quantitative data are derived solely from usage within participating cafés and therefore do not capture wider consumer behaviours or interactions with reuse systems beyond the scheme. As a result, the analysis may not fully account for broader patterns of participation, including the behaviours and motivations of individuals who chose not to engage.

Practical implications

The findings offer practical insights for policymakers, local authorities, and non-governmental organisations seeking to support the transition towards circular consumption practices within the tourism and hospitality sector. By evidencing how operational factors and user behaviour influence participation in refill-return systems, the study highlights the importance of scheme accessibility, return-point visibility, and stakeholder engagement in achieving high return rates. The results can inform the design and implementation of future reuse infrastructure, enabling councils and partner organisations to make evidence-based decisions regarding resource allocation, scheme configuration, and stakeholder training. In doing so, the research contributes to the development of scalable circular service models and may support the formulation of local and regional policies or legislative frameworks aimed at reducing single-use consumption and promoting inclusive, consumer-facing reuse systems.

References

Amir, S., Salehi, N., Roci, M., Sweet, S. & Rashid, A. (2022). Towards circular economy: A guiding framework for circular supply chain implementation. Business Strategy and the Environment. Available at: https://doi.org/10.1002/bse.3264

House of Commons Environmental Audit Committee, 2018. Disposable Packaging: Coffee Cups. Second Report of Session 2017–19. [Report] Ordered by the House of Commons to be printed 19 December 2017. London: House of Commons.

Pietrulla, F. (2022). Circular ecosystems: A review. Cleaner and Circular Bioeconomy, 3, 100031. Available at: https://doi.org/10.1016/j.clcb.2022.100031

Trevisan, A.H., Castro, C.G., Gomes, L.A.V. & Mascarenhas, J. (2022). Unlocking the circular ecosystem concept: Evolution, current research, and future directions. Sustainable Production and Consumption, 29, pp. 286-298. Available at: https://doi.org/10.1016/j.spc.2021.10.020

Regenerative Supply Chain Intelligence under Fragmentation: How Sustainability Pressures Reshape Logistics Capabilities and Performance

AKM Mohsin[1,2], Markus Gerschberger[1,2]

1: University of Applied Sciences Upper Austria, Austria; 2: Supply Chain Intelligence Institute Austria (ASCII)

Purpose of this paper

Global logistics systems are undergoing a profound structural transformation driven by persistent fragmentation arising from sustainability regulation, geopolitical turbulence, climate risk, and intensified stakeholder scrutiny. While much of the logistics and supply chain literature frames sustainability primarily as a matter of efficiency improvement or emissions reduction, emerging regulatory regimes increasingly demand a regenerative logic, in which logistics systems actively restore socio-ecological systems while sustaining operational viability (Matos et al., 2024; Tsvetkova & Gammelgaard, 2025). This paper addresses this gap by examining how external sustainability pressures act as a transformational driver of logistics systems, reshaping firm-level logistics capabilities and practices and, in turn, influencing operational, environmental, and financial performance. Building on dynamic capability theory (Teece, 2007), the study conceptualizes logistics not merely as a cost-minimizing function but as an intelligence-enabled adaptive system capable of sensing sustainability pressures, coordinating responses across supply networks, and translating external constraints into regenerative outcomes. Specifically, the paper pursues three objectives. First, it investigates whether sustainability pressures stimulate the development of advanced logistics capabilities, particularly integration and digitalization capabilities. Second, it examines how these capabilities enable the adoption of sustainable logistics practices under fragmented conditions. Third, it evaluates whether capability-enabled sustainable logistics practices contribute to superior performance outcomes when firms operate under high sustainability pressure environments.

Design/methodology/approach

The study adopts a multi-country firm-level panel research design, combining financial, operational, and sustainability data for logistics-intensive firms operating across Europe between 2012 and 2024. Europe provides an appropriate empirical context due to its advanced sustainability regulation, carbon pricing mechanisms, supply chain due diligence requirements, and heightened exposure to geopolitical and climate-related disruptions. Firm-level data are merged with country-year indicators capturing sustainability pressure, regulatory stringency, climate risk exposure, and geopolitical uncertainty. The analytical framework integrates the resource-based view and dynamic capability theory, conceptualizing sustainability pressure as an exogenous force that compels firms to reconfigure logistics capabilities related to integration, coordination, and digital intelligence. These capabilities enable firms to adopt sustainable logistics practices such as emissions-efficient transport, low-carbon logistics redesign, and reliability-enhancing coordination mechanisms, consistent with prior work on digital and intelligent supply chains (Le et al., 2025). Methodologically, the paper employs an Interactive Fixed Effects (IFE) panel regression model to address unobserved, time-varying global shocks that affect firms heterogeneously. Unlike conventional two-way fixed effects models, the IFE approach captures latent fragmentation forces such as energy price volatility, regulatory waves, and geopolitical shocks through unobserved common factors with firm-specific exposure. Dependent variables include logistics service reliability, sustainability-adjusted efficiency (carbon-to-serve), and financial performance (ROA). Key explanatory variables include a sustainability pressure index, logistics integration capability, digitalization capability, and a sustainable logistics practices index, alongside firm-level controls and fixed effects.

Findings

The results demonstrate that sustainability pressures play a transformational rather than peripheral role in reshaping logistics systems under fragmented global conditions. Firms exposed to higher sustainability pressure exhibit significantly stronger logistics integration and digitalization capabilities, indicating that regulatory and socio-ecological constraints actively stimulate capability development rather than merely imposing compliance costs. Further analyses reveal that logistics capabilities function as a critical enabling mechanism through which sustainability pressures are translated into operational action. Firms with stronger integration and digitalization capabilities are significantly more likely to adopt sustainable logistics practices, including emissions-efficient logistics configurations and enhanced coordination across supply networks. In contrast, firms with weaker capabilities struggle to operationalize sustainability requirements, resulting in limited performance improvements. Performance effects are heterogeneous and conditional. While sustainability pressure alone is associated with short-term efficiency trade-offs, firms with advanced logistics capabilities achieve superior logistics service reliability and improved sustainability-adjusted efficiency. Interaction effects indicate that the positive relationship between sustainable logistics practices and performance is significantly stronger at higher levels of logistics capability, highlighting the importance of intelligence-enabled coordination in regenerative logistics systems (Jayarathna et al., 2024). Financial performance results suggest that regenerative logistics transformation does not undermine profitability when supported by capability investment. Firms that embed sustainability intelligence into logistics decision-making maintain stable or improved ROA over time, even under elevated external pressure.

Value

This study makes three original contributions. First, it empirically reframes sustainability pressure as a regenerative driver of logistics capability development rather than a compliance burden. Second, it advances the concept of regenerative supply chain intelligence by showing how intelligence-enabled logistics capabilities mediate the relationship between external pressures and performance outcomes. Third, it introduces an advanced panel-data approach that explicitly accounts for latent fragmentation forces affecting global logistics systems.

Research limitations/implications

The study focuses on European firms, which may limit generalizability to regions with different institutional and regulatory contexts. Future research could extend the framework to emerging economies, humanitarian logistics, or sector-specific supply chains, and integrate micro-level or qualitative data to deepen understanding of regenerative logistics intelligence.

Practical implications

The findings indicate that regenerative logistics performance depends on intelligence-enabled capability development rather than isolated green initiatives. Managers should prioritize investments in logistics integration and digital intelligence to translate sustainability pressure into reliable, resilient, and low-carbon logistics outcomes. Policymakers can leverage sustainability regulation as a catalyst for regenerative logistics transformation by supporting capability-building initiatives.

References

Fan, M., Tang, Y., Qalati, S. A., & Ibrahim, B. (2025). Can logistics enterprises improve their competitiveness through ESG in the context of digitalization? Evidence from China. The International Journal of Logistics Management, 36(1), 196–224.

Jayarathna, C. P., Agdas, D., & Dawes, L. (2024). Perceived relationship between green logistics practices and sustainability performance: a multi-methodology approach. The International Journal of Logistics Management, 35(5), 1522–1548.

Le, T. T., Nhu, Q. P. V., & Behl, A. (2025). Role of digital supply chain in promoting sustainable supply chain performance: the mediating of supply chain integration and information sharing. The International Journal of Logistics Management, 36(5), 1439–1462.

Matos, S. V., Schleper, M. C., Hall, J. K., Baum, C. M., Low, S., & Sovacool, B. K. (2024). Beyond the new normal for sustainability: transformative operations and supply chain management for negative emissions. International Journal of Operations & Production Management, 44(13), 263–295.

Teece, D. J. (2007). Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance. Strategic Management Journal, 28(13), 1319–1350.

Tsvetkova, A., & Gammelgaard, B. (2025). Social-ecological resilience in extreme natural environments: a multiple case study of Arctic offshore supply ecosystems. International Journal of Operations & Production Management, 45(2), 463–492.

Transformation Pathways to Regenerative Supply Chains: Interplay of Organizational Unlearning and Structural Reconfiguration

Felix Naake, Julian Müller

Friedrich-Alexander University Erlangen–Nürnberg (FAU), Germany

Purpose of this paper

Escalating climate, biodiversity and social inequality crises require a paradigmatic shift from "doing less harm" to actively regenerating socio-ecological systems (Salonen, Ritala and Bocken, 2025). In supply chain management, this implies moving beyond efficiency- and mitigation-oriented models toward regenerative supply chains that restore, renew and enhance the ecosystems and communities in which they are embedded (Gualandris et al., 2024; Salonen, Ritala and Bocken, 2025). While recent literature conceptualizes regenerative supply chains and articulates guiding principles such as proportionality, reciprocity, and poly-rhythmicity, empirical insight into how such supply chains are implemented and structurally configured in practice remains limited (Gualandris et al., 2024; Hsu, Shevchenko and Yang-Sun, 2025).

Two interrelated gaps are salient. First, systematic empirical insight into how regenerative supply chains emerge under different transformation conditions remains scarce. While some supply chains are designed with regenerative intent from inception and others evolve through the transformation of legacy configurations, comparative research across such starting points is still limited. Gualandris et al. (2024) explicitly call for research examining both the purposeful creation of new regenerative supply chains and the conversion of existing ones. Hsu et al. (2025) demonstrate that regenerative practices necessitate structural changes, including larger, more *geographically dispersed supplier bases with lower interconnectedness, but how these* adaptations differ across starting conditions remains unclear.

Second, understanding of how organizational unlearning of efficiency-driven mental models enables or constrains transformations remains limited. Transitioning to regenerative supply chains requires not only redesigning physical structures but also profound shifts in mental models guiding managerial decision making (Salonen, Ritala and Bocken, 2025). Conventional supply chain management assumptions such as efficiency maximization, orientation toward scale, and linear resource flows conflict directly with regenerative principles such as reciprocity, proportionality and place-based ecological integration (Gualandris et al., 2024), with implications for supplier governance and relationship management. Established firms must simultaneously address structural reconfigurations and cognitive barriers, requiring intentional unlearning of entrenched mental models (Cegarra-Navarro and Wensley, 2019; Hsu, Shevchenko and Yang-Sun, 2025).

This study therefore examines how structural reconfigurations and processes of organizational unlearning interact in the implementation of regenerative supply chains across differing transformation starting conditions.

Design/methodology/approach

This study adopts an exploratory multiple case study design to examine how regenerative supply chain transformation unfolds across differing transformation starting conditions (Eisenhardt, 1989; Yin, 2018). The empirical strategy follows theoretical sampling and focuses on organizations that either embed regenerative principles in their supply chains from inception or engage in the transformation of established supply chain structures toward regenerative practices.

Expert interviews complement firm-level cases to provide cross-contextual insight. Data collection, currently ongoing, builds primarily on semi-structured interviews with supply chain executives, sustainability officers and founders, complemented by expert interviews (e.g., sector specialists and advisors) and archival material (including sustainability reports, strategic plans, certification audits and publicly available documents) to enable triangulation (Yin, 2018). The analysis follows the Gioia methodology for inductive concept development and subsequent cross-

case comparison. It combines sensitizing concepts from regenerative supply chain and unlearning theory with inductive first order concepts (Gioia, Corley and Hamilton, 2013; Gualandris et al., 2024; Cegarra-Navarro and Wensley, 2019).

Particular analytical attention is paid to changes at the supplier interface and to how reported unlearning processes connect to structural supply chain adaptations discussed in emerging work (Hsu, Shevchenko and Yang-Sun, 2025).

Findings

As data collection and analysis are ongoing, findings are exploratory. Preliminary observations suggest that regenerative transformation cannot be reduced to structural redesign alone. Instead, adjustments in supplier structures, governance arrangements and evaluation logics appear alongside shifts in underlying managerial assumptions. These dynamics resonate with organizational unlearning processes, understood as the intentional questioning and gradual discarding of established routines and dominant mental models (Cegarra-Navarro and Wensley, 2019).

Emerging evidence indicates that tensions arise where established performance criteria intersect with regenerative ambitions. Rather than constituting uniform barriers, such tensions appear to form part of broader adaptation processes in which decision premises are reconsidered or incrementally modified. Cross-case comparisons further suggest variation in how organizations sequence structural adaptations and how supplier relationships evolve during transformation. At this stage, these patterns remain indicative and require further empirical consolidation. Data collection is expected to be completed in February 2026, after which systematic cross-case analysis will allow more robust interpretation. The final analysis aims to specify recurring unlearning mechanisms that enable or constrain structural reconfiguration, consistent with emerging research on regenerative supply chain complexity (Hsu, Shevchenko and Yang-Sun, 2025).

Value

This paper advances regenerative supply chain research by conceptualizing transformation not only as structural reconfiguration but as a cognitive and relational change process at the supplier interface. While prior literature primarily theorizes regenerative principles (Gualandris et al., 2024; Salonen, Ritala and Bocken, 2025), this study empirically examines how such principles become embedded in supplier governance and evaluation routines.

By integrating organizational unlearning theory, the paper identifies cognitive mechanisms that help explain why regenerative implementation may progress unevenly and why established performance logics become contested during transformation (Cegarra-Navarro and Wensley, 2019). The study thus bridges regenerative supply chain scholarship and organizational change research and provides practitioners with a conceptual vocabulary for diagnosing supplier-interface tensions when moving beyond efficiency-centric supply chain models. The paper is particularly relevant for logistics and procurement leaders designing supplier governance beyond efficiency centric optimization.

Research limitations/implications

The qualitative multiple case study design favors depth and process insight over statistical generalizability, and the theoretically driven sampling cannot capture the full variety of regenerative contexts; ongoing data collection also means that all patterns remain provisional. Interview-based evidence is further shaped by retrospective sensemaking and role-specific blind spots, which triangulation and systematic Gioia-style coding can mitigate but not fully remove. Future research could employ longitudinal and mixed method designs, including dyadic buyer supplier perspectives, to test the unlearning structure link.

Practical implications

For practice, the study suggests that regenerative supply chain transformation should be approached as a coordinated change effort linking supplier relationship management routines to broader regenerative principles. Procurement and supply chain leaders may need to critically

reassess whether existing supplier selection, evaluation and governance mechanisms reinforce efficiency-centered assumptions that conflict with regenerative ambitions (Gualandris et al., 2024; Salonen, Ritala and Bocken, 2025).

References

Cegarra-Navarro, J.G. and Wensley, A. (2019) 'Promoting intentional unlearning through an unlearning cycle', Journal of Organizational Change Management, 32(1), pp. 67–79.

Eisenhardt, K.M. (1989) 'Building theories from case study research', The Academy of Management Review, 14(4), pp. 532–550.

Gioia, D.A., Corley, K.G. and Hamilton, A.L. (2013) 'Seeking qualitative rigor in inductive research: Notes on the Gioia methodology', Organizational Research Methods, 16(1), pp. 15–31.

Gualandris, J. et al. (2024) 'Unchaining supply chains: Transformative leaps toward regenerating social–ecological systems', Journal of Supply Chain Management, 60(1), pp. 53–67.

Hsu, K., Shevchenko, A. and Yang-Sun, Y.S. (2025) 'Regeneration and supply chain complexity: Insights from the forest sector', Journal of Supply Chain Management.

Salonen, K., Ritala, P. and Bocken, N. (2025) 'Emerging regenerative business paradigm: Narrative review, synthesis, and research agenda', Journal of Circular Economy.

Yin, R.K. (2018) Case study research and applications: Design and methods. 6th edn. Los Angeles: SAGE.

Regenerative Fashion Supply Chain: Establishing A Strategic Direction for Net-Positive Industrial Transformation Via Systematic Literature Review

Huy Truong Quang[1], Rajkishore Nayak[1], Rudrajeet Pal[2,3]

1: RMIT University, Vietnam; 2: University of Borås, Sweden; 3: University of Gävle, Sweden

Purpose of this paper

The purpose of this study is to understand the mechanisms that facilitate the integration of regenerative practices into fashion supply chains.

The fashion industry currently stands at a precariously unsustainable juncture, functioning as one of the primary drivers of global ecological overshoot. However, the operating environment for global fashion supply chains is undergoing an increasing seismic shift where firms engage in sustainable and circular textile practices, digitalization and social responsibility. These no longer ask firms to simply "reduce" harm but demand measurable accountability for the entire lifecycle of products (Bostancı et al., 2024).

In this context, understanding of how regeneration – beyond restoration and circularity – redefines value creation across fashion supply chains by stating that it is important to show how businesses can move from “less harm” to “doing good.” Unlike circular models that aim for a "neutral" environmental footprint, regenerative approaches aspire to a "net-positive" impact (Gualandris et al., 2024; Hsu et al., 2025). Grounded in ecological principles, regeneration seeks to align industrial activities with the capacity of the biosphere to heal and renew itself (Reslan et al., 2022). In the context of fashion, this involves a holistic transformation: from sourcing raw materials via regenerative agriculture that sequesters carbon and restores soil health, to designing production processes that run on renewable energy and return clean water to local ecosystems (Kazimierczuk et al., 2023).

Despite the compelling theoretical arguments for regenerative fashion, the path to operationalizing these concepts remains fraught with systemic barriers. The transition from a linear to a regenerative model is not merely a technical challenge; it is a profound organizational and inter-organizational undertaking (Halidu et al., 2025). Current literature on regenerative fashion is predominantly fragmented, often focusing on isolated technical innovations, such as bio-based material development or specific farming techniques, while overlooking the supply chain design required to scale these solutions.

Moving beyond the "what" of regenerative materials, this study focuses on the "how" of supply chain management, to specifically conceptualize the RFSC as a distinct systemic model and propose a strategic framework for setting future research directions through a systematic literature review.

Design/methodology/approach

To ensure a comprehensive and reproducible review of RFSC landscape, we adopted a systematic three-phase methodological framework, combining traditional bibliometric search with unsupervised machine learning techniques for topic modelling.

In phase 1 (article search and selection), data was collected by querying the Web of Science (WoS) database using a specific set of relevant keywords (e.g. regenerative, regenerative fashion). Following a set of inclusion/exclusion criteria, a final list of 348 articles was included for subsequent analysis. The literature selection process was developed according to PRISMA standards, ensuring transparency, rigor, and reproducibility of the systematic review.

In phase 2, the selected articles were classified and modelled topically using a computational approach using Python. For topic modelling, we utilized Term Frequency–Inverse Document Frequency (TF-IDF) vectorization as input for clustering algorithms. A hybrid analytical approach was applied, incorporating K-Means Clustering, Non-negative Matrix Factorization (NMF), and Louvain Community Detection on co-occurrence networks. These techniques facilitated the

generation of network graph visualizations and word clouds to identify latent themes within the literature.

The final phase focused on the semantic interpretation and validation of the computational results. The identified clusters underwent manual topic labelling to construct a preliminary causal and conceptual model.

Findings

Our preliminary analysis reveals five clusters, as strategic directions for RFSC.

Cluster 1 (Regenerative Supply Chain Management) emphasizes the central role of integrating multidimensional flows for redesigning supply chains in a sustainable-circular-regenerative direction, with the support of technology, quantitative methods and material innovation. From a flow perspective, emphasis was placed on reverse logistics and circular and closed-loop supply chains, with the growing interest in material recovery, remanufacturing, and closed-loop systems. In addition, there was strong focus on research on biomaterials – a key component of fashion regenerative manufacturing. Cluster 1's existence and effectiveness depend entirely on the symbiotic support mechanism from the other four clusters.

Cluster 2 (Sustainable production in textile ecosystems) revolves around three main pillars: (1) yarn and spinning technologies, (2) sustainable production, and (3) agriculture – biomimetic – ecosystem. Overall, the cluster reflects a trend of convergence between material innovation, production optimization, and expanding sustainable ecosystems in the textile industry – where spinning technology, sustainable agriculture, and the circular economy all play a central role in the green transition (Gualandris et al., 2024).

Cluster 3 (Material Innovation and Technical Value Creation) portrays that the textile sector is not merely a producer of commodities, but a dynamic arena for interdisciplinary convergence, employing advanced material science and digital technologies (AI) to transition from extractive production to high-value, sustainable ecosystems (Agrawal et al., 2022). This addresses value creation through material innovation in emergent areas such as "biological processes" that define "regenerative" as expanding beyond agriculture to include biomedical engineering and functional material innovation.

Cluster 4 (regenerative agriculture) reflects an integrated research stream centred on regenerative agriculture and its extension into circular and low-carbon supply-chain practices. The prominence of regenerative agriculture, regenerative development, agroforestry, and carbon sequestration indicates a strong scientific commitment to restoring ecological systems and improving soil health as foundational mechanisms for sustainable material production, particularly in cotton cultivation. Collectively, this cluster highlights a multidisciplinary convergence that positions regenerative material production, environmental impact assessment, and supply-chain optimization as interdependent pillars of contemporary sustainability research (Nazarinia et al., 2025; Oyefusi et al., 2024).

Finally, cluster 5 illustrates a research domain strongly anchored in the circular economy–driven innovation and digitally enabled manufacturing systems. Collectively, this cluster reveals a convergence of circular economy principles, digital transformation, and innovation capabilities, underscoring the systemic and interdisciplinary nature of contemporary sustainability research (Wu et al., 2025).

Value

This study develops a comprehensive theoretical and managerial framework for the RFSC by integrating insights from regenerative systems theory, circular supply chain management, and socio-technical transition literature. By doing so, this study advances theoretical clarity in the emerging regenerative discourse and provides actionable guidance for practitioners and policymakers seeking to transition fashion supply chains from extractive and linear models toward net-positive and resilient industrial ecosystems.

Research limitations/implications

The study relies primarily on secondary scientific data sources and computational text analytics to map the intellectual structure of the field. While advanced topic-modelling and semantic clustering techniques enhance objectivity and reproducibility, they may not fully capture implicit or emerging knowledge embedded in practitioner experience, unpublished frameworks, or industry-embedded innovations. The proposed framework establishes theoretical relationships and causal pathways but does not measure their statistical strength or comparative effectiveness across contexts (Nazarinia et al., 2025).

This opens scope for further research to conduct more empirical investigations, alongside ways to quantify regenerative outcomes.

Practical implications

This study offers several practical contributions for industry practitioners, policymakers, and supply chain stakeholders navigating the transition from sustainability to regenerative industrial systems. First, the proposed regenerative supply chain framework (aggregating the five clusters) provides fashion enterprises with a structured roadmap for transformation. The identification of the RFSC dimensions further equips practitioners with a diagnostic tool to evaluate readiness and implementation barriers before committing to large-scale regenerative investments.

References

Agrawal, V., Mohanty, R. P., Agarwal, S., Dixit, J. K., & Agrawal, A. M. (2022). Analyzing critical success factors for sustainable green supply chain management. Environ. Dev. Sustain. https://doi.org/10.1007/s10668-022-02396-2

Bostancı, H. B., Tanyer, A. M., & Habert, G. (2024). A multi-stakeholder engagement framework for material-building-city synergy through circular transformation. Sustain. Cities Soc., 116(105892), 105892. https://doi.org/10.1016/j.scs.2024.105892

Gualandris, J., Branzei, O., Wilhelm, M., Lazzarini, S., Linnenluecke, M., Hamann, R., Dooley, K. J., Barnett, M. L., & Chen, C.-M. (2024). Unchaining supply chains: Transformative leaps toward regenerating social–ecological systems. J. Supply Chain Manag., 60(1), 53–67. https://doi.org/10.1111/jscm.12314

Halidu, O. B., Awuah-Gyawu, M., Otchere Fianko, A., Gyamfi, B. A., & Asongu, S. A. (2025). Corporate governance and circular supply chains: Synergizing eco-adaptive organizational culture, leadership eco-innovation willingness, and perceived urgency for circularity. J. Environ. Manage., 392(126689), 126689

Hsu, K., Shevchenko, A., & Yang-Sun, Y. S. (2025). Regeneration and supply chain complexity: Insights from the Forest sector. J. Supply Chain Manag.(jscm.70005 https://doi.org/10.1111/jscm.70005

Kazimierczuk, K., Barrows, S. E., Olarte, M. V., & Qafoku, N. P. (2023). Decarbonization of agriculture: The greenhouse gas impacts and economics of existing and emerging climate-smart practices. ACS Eng. Au, 3(6), 426–442

Nazarinia, A., Pirayesh, A., Dupouët, O., & Saint-Jean, M. (2025). Circular supply chain network design: A robust probabilistic multi-objective optimisation approach. Int. J. Prod. Econ., 289(109725), 109725. https://doi.org/10.1016/j.ijpe.2025.109725

Oyefusi, O. N., Enegbuma, W. I., Brown, A., & Zari, M. P. (2024). From green to regenerative supply chain management in construction: Towards a conceptual framework. Environ. Dev., 52(101097), 101097.

Reslan, M., Last, N., Mathur, N., Morris, K. C., & Ferrero, V. (2022). Circular economy: A product life cycle perspective on engineering and manufacturing practices. Procedia Cirp, 105, 851–858. https://doi.org/10.1016/j.procir.2022.02.141

Wu, Z., Oger, R., Lauras, M., Faugère, L., & Montreuil, B. (2025). A guiding framework for hyperconnected circular supply chain implementation. J. Clean. Prod., 501(145229), 145229.

Improving Waste-Related Reverse Logistics at Shop-Floor Level within Automotive Manufacturing

Helena Fidlerova[1], Bosko Matovic[2], Henrieta Hrablik Chovanova[1]

1: Slovak University in Technology in Bratislava, Slovak Republic; 2: University of Montenegro, Montenegro

Purpose of this paper

Reverse logistics and waste management play a key role in achieving sustainability goals within industrial supply chains, particularly in the automotive industry (Govindan et al., 2015; Guide & Van Wassenhove, 2009, Zaman, 2015). Logistics processes are directly linked to several Sustainable Development Goals including SDG 12 Responsible Consumption and Production (Richnak, 2021, Nguen et al., 2020), SDG 9 Industry, Innovation and Infrastructure (Vujadinović et al., 2020), and SDG 13 Climate Action (Seuring & Müller,2008). Although environmental management systems such as ISO 14001 are widely used, evidence from practice suggests that their operational effectiveness is reduced when control mechanisms are not sufficiently implemented in daily operations (Fidlerova et al., 2025, Darnall et al. ,2008; Testa & Iraldo 2010).

The main objective of this article is to analyse and improve reverse logistics processes related to waste management in an automotive component manufacturing environment through a case study of the production hall in a selected company. The research builds on results in the research project SDG4BIZ, which focused on integrating the Sustainable Development Goals (SDGs) into business and practice, and is part of the bilateral research project SUSTLOG (APVV SK-MNE-25-0015), which focuses on developing sustainable logistics solutions for industrial companies.

The aim of the paper is to identify dominant waste streams and their cost implications, analyse waste-related reverse logistics processes at the operational level, and assess whether existing environmental management practices effectively support long-term sustainability goals in line with the SDGs.

Design/methodology/approach

The study uses a qualitative-quantitative case study methodology, suitable for examining in detail the complex processes of reverse logistics in a real production context. The research was conducted in the production hall of a company, a supplier to the automotive industry specializing in interior components. Data were collected from multiple sources to ensure robustness and triangulation: internal waste records classified according to the European Waste Catalogue, external invoices related to waste disposal and recovery, direct observations at the workplace at shop-floor level and semi-structured interviews with production, logistics and environmental management staff.

Several analytical tools were used to examine the performance of reverse logistics. First, the volumes of waste produced, and disposal costs were analysed over a multi-year period to identify dominant waste streams and cost drivers relevant for resource efficiency aimed at sustainable development goals. Secondly, a customized 5S audit focused on waste management and environmental order was conducted to evaluate workplace organization, visual management and compliance with standards. Thirdly, spaghetti diagrams were developed to quantify internal transport routes, frequencies and time requirements associated with waste handling by production and logistics workers. Finally, Ishikawa cause and effect analysis was used to structure the root causes of the identified differences. The methodological approach integrates lean logistics principles with environmental management and sustainability objectives in the context of the SUSTLOG research objectives.

Findings

The findings showed a significant concentration of waste volume and disposal costs in mixed packaging waste, indicating insufficient separation of recyclable materials, especially plastics and foils. Despite formal compliance with ISO 14001, the 5S audit revealed systematic deficiencies at the operational level, including inconsistent waste bin labelling, unannounced relocation of collection points following layout changes, and declining employee awareness of departmental rules related to waste handling. These deficiencies were confirmed by repeated complaints from external waste suppliers regarding incorrect sorting.

Spaghetti diagram analysis demonstrated that internal waste handling generates measurable time losses, both for production workers and logistics staff. On selected production lines, frequent and lengthy walking routes to waste collection points were observed, while forklift-based transport of large containers required multiple trips per shift. These activities do not add value and represent hidden logistics inefficiencies within reverse flows. Root-cause analysis indicated that the primary drivers of these problems were not technical constraints but organisational factors, including insufficient training, lack of routine audits, and the absence of an active feedback mechanism within the environmental management system. Overall, the findings show a clear discrepancy between formal environmental compliance and actual reverse logistics performance at shop-floor level.

Value

This article offers original value by combining lean logistics tools with environmental management analysis to examine reverse logistics at the operational level. Unlike many studies that focus on external recycling systems or strategic sustainability reporting extending previous transport- and sustainability-oriented studies (Lučić et al., 2025; Grdinić Rakonjac & Pajković, 2022, Huk et al., 2024), this research provides a detailed empirical view of internal waste flows, employee behaviour, and control mechanisms within the manufacturing supply chain. The integration of 5S audits, spaghetti diagrams, and root-cause analysis in the context of ISO 14001 represents a practically oriented contribution to operational-level sustainability and reverse logistics research. The findings are valuable in the field of regenerative logistics flow and sustainability, as well as for practitioners who are trying to stabilize environmental performance beyond initial certification and by stabilising waste-related reverse logistics processes.

Research limitations/implications

The presented paper is limited by its practical focus on a production floor in a selected company, which may affect the generalizability of the results. However, the results of the analysis and the identified correlations are transferable to similar automotive and manufacturing environments. Future research will focus on more studies to assess the performance after the implementation of control mechanisms, such as routine audits or visual management systems, with an emphasis on process stability and resilience.

Practical implications

The published results will allow for changes in reverse logistics processes, with a focus on waste collection layouts to reduce internal transport, standardize visual marking, strengthen employee motivation and implement simple but regular audit procedures to maintain regulatory compliance. The study demonstrates that waste-related reverse logistics represents a critical but often overlooked source of operational inefficiency, where formal environmental compliance does not automatically translate into effective shop-floor performance.

References

Darnall, N., Henriques, I., & Sadorsky, P. (2008). Do environmental management systems improve business performance in an international setting? Journal of International Management, 14(4), 364–376. https://doi.org/10.1016/j.intman.2007.09.006.

Fidlerová, H., Kuka, A., Adamczak, M., 2025. Operational aspects of sustainable reverse logistics in manufacturing enterprises. Acta Logistica 12(1),123–134. https://actalogistica.eu/issues/2025/I_2025_13_Fidlerova_Kuka_Adamczak.pdf

Guide, V. D. R., Jr., & Van Wassenhove, L. N. (2009). The evolution of closed-loop supply chain research. Operations Research, 57(1), 10–18.

Govindan, K., Soleimani, H., & Kannan, D. (2015). Reverse logistics and closed-loop supply chain: A comprehensive review to explore the future. European Journal of Operational Research, 240(3), 603–626. DOI: 10.1016/j.ejor.2014.07.012

Huk, K., Kurowski, M., Knapčíková, L. et al. Modern Mobile Infrastructure in Transport and Forwarding. Mobile Netw Appl 29, 156–165 (2024). https://doi.org/10.1007/s11036-023-02123-9

Nguyen, H., Onofrei, G., Truong, D., & Lockrey, S., 2020. Customer green orientation and process innovation alignment: A configuration approach in the global manufacturing industry. Bus. Strat. Environ. 29(6), 2498–2513. https://doi.org/10.1002/bse.2516

Lucic, M., Grdinić Rakonjac, M., Vujadinović, R., Pajković, V.R., 2025. Defining a new set of criteria for electric vehicle selection. Transp. Res. Procedia 83, 569–576, https://doi.org/10.1016/j.trpro.2025.03.027

Richnák, P., 2021. The use of progressive technologies in logistics of Slovak automotive enterprises. SHS Web Conf. 92, 04022. https://doi.org/10.1051/shsconf/20219204022

Seuring, S., Müller, M., 2008. From a literature review to a conceptual framework for sustainable supply chain management. J. Clean. Prod. 16, 1699–1710. https://doi.org/10.1016/j.jclepro.2008.04.020

Testa, F., Iraldo, F., 2010. Shadows and lights of GSCM (Green Supply Chain Management): Determinants and effects of these practices based on a multi-national study. J. Clean. Prod. 18, 953–962.

Vujadinović, R., Pajković, V., Simović, S., Damjanović, M., Nikčević, P., 2020. Experimental and numerical testing of ambient temperature impact on lifespans of cuffs of vehicles' steering systems. Appl. Sci. 10(12), 4371, https://doi.org/10.3390/app10124371

Zaman, A. U. (2015). A comprehensive review of the development of zero waste management: Lessons learned and guidelines. Journal of Cleaner Production, 91, 12–25. https://doi.org/10.1016/j.jclepro.2014.12.013

Transitioning from Sustainable to Regenerative Supply Chains: A Thematic Review and Research Agenda

Kamrul Ahsan[1], Booi Kam[1], Joseph Sarkis[2]

1: Department of Supply Chain and Logistics Management, RMIT University, Australia; 2: School of Business, Worcester Polytechnic Institute Worcester, MA, USA

Purpose of this paper

For decades, green supply chain management and sustainability initiatives have guided organisations toward minimising environmental harm, improving eco-efficiency, reducing waste, and regulatory compliance (Sarkis and Dou 2017). While these strategies have generated important progress, their predominant focus on harm reduction and incremental improvement has been criticized as producing "weak sustainability" (Demastus and Landrum 2024), insufficient for restoring ecosystems or creating net-positive environmental and social outcomes (Meyer et al. 2026).

These limitations have called for developing means to generate "strong sustainability" (Demastus and Landrum 2024). They prompted a shift toward regenerative supply chains (RSC), which integrates circular economy initiatives, regenerative design, and ecosystem restoration to refresh and strengthen natural, social, and economic systems (Bag et al. 2025; de Souza et al. 2019). Rather than solely *doing less harm*, RSCs enhance ecological systems, strengthen social well-being, and generate long-term economic value (Gualandris et al. 2023). Recent evidence suggests that regenerative practices can yield both environmental and financial benefits, including operational efficiencies, cost reductions, and improved organizational resilience (Tanveer et al. 2025)**.** Despite the possibilities, RSC research remains fragmented and provides limited conceptual clarity of how regenerative principles influence supply chain structures, governance mechanisms, and performance outcomes in practice (Hsu et al. 2025).

This study reviews the emerging literature on RSC with four objectives: (i) to identify dominant research streams and trends shaping this nascent field; (ii) to examine the core conceptual underpinnings and practical realities of regenerative supply chains; (iii) to develop a synthesizing framework that clarifies the relationships among core themes—what is being regenerated, the mechanisms enabling regeneration, and the resulting outcomes; and (iv) to provide directions for future RSC research.

Design

This integrative review adopts Denyer and Tranfield (2009) three-stage systematic literature review methodology: planning; analysis and synthesis; and reporting. The planning stage covers defining relevant search terms, selecting appropriate databases, and establishing clear inclusion and exclusion criteria, as summarised in Figure 1. The screening process resulted in a final sample of 35 articles and book chapters published between 2017 and 2026.

An inductive analytical approach was applied to examine the 35 selected articles, paying attention to their research objectives, key findings, and implications. Bibliometric data were extracted and analysed to identify publication trends. In parallel, a manual content analysis of keywords, abstracts, research questions, and stated contributions was conducted to identify core themes. The Grodal et al. (2021) data categorisation framework was employed to systematically group the articles into thematic clusters using a mutually exclusive classification scheme based on the primary focus of each article. This approach facilitated the development of a conceptual framework that elucidates the relationships among the identified themes within RSC research.

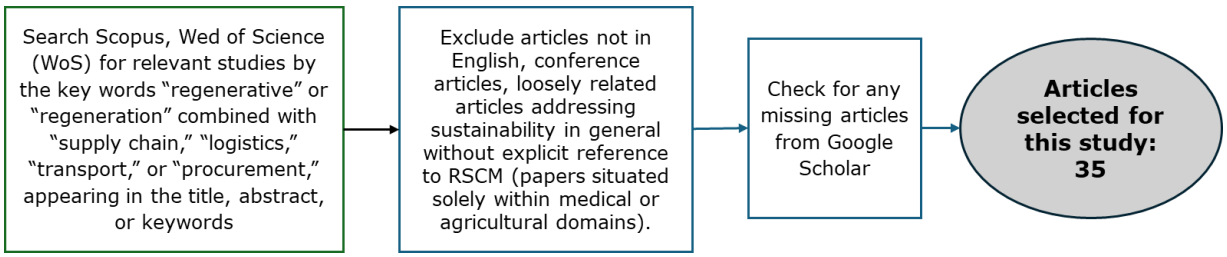


Figure 1: Article selection process

Findings

Our review shows that, despite its recency (since 2017), the state-of-the-knowledge in RSC has advanced significantly. From their publication date, the 35 papers could be divided into three major phases: foundational (2017-2020), empirical evaluation (2020-2024), and advanced applications (2025-2026). Foundational papers focused on establishing basic concepts—circular supply chain archetypes (Batista et al., 2018), regenerative design frameworks (de Souza et al. 2019), and circular economy indicators (Howard et al. 2018). Papers in the empirical evaluation period exhibit diversification into specific sectors, e.g., agri-food (Balcom et al. 2023), exploring strategies and challenges for adopting RSC (Ali 2024). Recent papers moved from "what" to "how" with advanced methodologies: deep reinforcement learning (Tseng et al. 2025) and frameworks for hyperconnectivity (Wu et al. 2025). The 2026 papers (e.g. Jadallah et al. 2026; Liu et al. 2026; Meyer et al. 2026) include applications across sectors, showing initial sign of maturity.

Substantively, our preliminary findings suggest that the core concept of RSC is encapsulated in four interconnected pillars, which center on "benefit enrichment" (Tanveer et al. 2025):

Net-positive socio-ecological outcomes: This defining goal of RSC transcends the traditional focus on minimizing negative environmental impacts (harm-reduction) to actively restoring and enhancing the social-ecological systems in which the supply chain is embedded (Gualandris et al. 2023).

Circularity and bio-inspired loops: Rooted in Circular Economy principles on closing loops for zero waste, regeneration focuses on the "quality" of those loops, enriching the systems in the process. Organic food value chains that shun pollution by sequestering greenhouse gas emissions and maintaining biodiversity, living soil, as well as clean air and water are regenerative (Roth and Zheng 2021).

Proportionality and reciprocity: Proportionality ensures resource use aligns with an ecosystem's capacity to regenerate, while reciprocity mandates that the supply chain gives back (Gualandris et al. 2023). These concepts aim to engender a mutually beneficial, ethical and structural relationship between supply chains and their host environment (both natural and social), ensuring a relationship of benefit mutuality, rather than extraction.

Strategic reconfiguration (disintermediation and reintermediation): Operationalizing the first three conceptual pillars requires a fundamental restructuring of the supply chain network, leapfrogging from gaining efficiency to creating a structurally different regeneration-enabled supply chain architecture (Hsu et al. 2025). Disintermediation leverages technology to create a direct link between producer and consumer, removing exploitative agents. Reintermediation realigns incentives by introducing new relational mechanisms, market and supply chain structures to guide demand toward restoration options, fostering regeneration (Meyer et al. 2026).

From the perspective of building operationally feasible and implementable RSCs, three key areas of concern and investigation are noted:

***Critical drivers and enablers*:** What are the critical resources (tangible & intangible) and processes needed to develop dynamic capabilities for new RSCs? What role does leadership play and what governance mechanism should be established to engender a supportive organizational culture in fostering circularity and regeneration?

Supply chain structure, coordination, and contextual realities: Across diverse sectors, establishing RSCs faces a plethora of context-specific challenges, e.g., the need to focus on soil health, biodiversity, and regenerative organic farming for short food supply chains (Balcom et al. 2023), and the importance of "designing with nature," and using biodegradable materials and modular construction to restore ecosystems in construction (Oyefusi et al. 2024). What core supply chain architectures and coordination mechanisms, e.g., coopetition, are most appropriate to deal with sector-specific practices across diverse industries?

Social-ecological embeddedness and people-centricity: A defining characteristic of RSCs is their deep integration with both natural ecosystems and human communities. How could concepts like "place focus," "social equity," and "biocentrism," be invoked to design supply chains that are embedded in and restorative of local ecosystems, foster people-centric operations, generate positive social outcomes, enhance community well-being, and ensure fair labour practices?

Value

Amid growing recognition of the limitations of harm-reduction approaches, the potential role of RSC is becoming increasingly prominent. This review is timely—it consolidates the current state of knowledge, identifies critical gaps in the literature, and outlines promising directions for future research to advance RSC development. The review offers significant opportunities and insights for prospective theorising by supporting the forward-looking development of conceptual frameworks that anticipate how systems may evolve toward restoration, renewal, and long-term resilience.

Research limitations

Based exclusively on published papers, this study requires further empirical support to validate the proposed theoretical framework.

Practical implications

Apart from proposing a research agenda to guide future theoretical and empirical investigations, this integrative review informs managerial practice by proposing a framework that highlights key drivers, enabling mechanisms, structural and organizational changes, and expected outcomes associated with regenerative transitions.

References

Ali, J. (2024) Environmental resilience: transition to regenerative supply chain management. AIMS Environmental Science 11 (2), 107-128.

Bag, S., Rahman, M. S., Routray, S. and Khurana, R. (2025) Regenerative supply chain orientation and coopetition in supply chain networks for ESG initiatives: A parallel mediation study. Journal of Business Research 201.

Balcom, R., Abebe, G. K., Yiridoe, E. K. and Hartt, C. M. (2023) Sustainable production and distribution practices in Atlantic Canadian short food supply chains: Explorative study. Frontiers in Sustainable Food Systems 7.

de Souza, V., Bloemhof-Ruwaard, J. and Borsato, M. (2019) Towards Regenerative Supply Networks: A design framework proposal. Journal of Cleaner Production 221, 145-156.

Demastus, J. and Landrum, N. E. (2024) Organizational sustainability schemes align with weak sustainability. Business Strategy and the Environment 33 (2), 707-725.

Denyer, D. and Tranfield, D. (2009) Producing a systematic review In Buchanan, D. A., Bryman, A. (editor) The Sage Handbook of Organizational Research Methods. Thousand Oaks, CA: Sage Publications Ltd 671-689.

Grodal, S., Anteby, M. and Holm, A. L. (2021) Achieving rigor in qualitative analysis: The role of active categorization in theory building. Academy of Management Review 46 (3), 591-612.

Gualandris, J., Branzei, O., Wilhelm, M., Lazzarini, S., Linnenluecke, M., Hamann, R., Dooley, K. J., Barnett, M. L. and Chen, C. M. (2023) Unchaining supply chains: Transformative leaps toward regenerating social–ecological systems. Journal of Supply Chain Management 60 (1), 53-67.

Howard, M., Hopkinson, P. and Miemczyk, J. (2018) The regenerative supply chain: a framework for developing circular economy indicators. International Journal of Production Research 57 (23), 7300-7318.

Hsu, K., Shevchenko, A. and Yang-Sun, Yang S. (2025) Regeneration and Supply Chain Complexity: Insights From the Forest Sector. Journal of Supply Chain Management.

Jadallah, N. I., Dudin, F. E. and Awwad, B. (2026) From Linear to Circular: Supply Chain Business Models for a Regenerative Economy. Technology and Innovation Towards a Future of Business Sustainability: Insights in the Digital Age. Springer. 95-110.

Liu, W., Chotia, V., Wang, L., Sharma, P., Albishri, N. and Dash, S. (2026) Intelligence by design: Large language model work integration as strategic enablers for supply chain regeneration through digital and cognitive capabilities. Technological Forecasting and Social Change 224.

Meyer, C., Luiz, J., Grutter, A. and Parker, H. (2026) Disintermediation and Reintermediation of Seafood Supply Chains for Social and Ecological Regeneration. Journal of Supply Chain Management 62 (1), 20-36.

Oyefusi, O. N., Enegbuma, W. I., Brown, A. and Zari, M. P. (2024) From green to regenerative supply chain management in construction: Towards a conceptual framework. Environmental Development 52.

Roth, A. and Zheng, Y. (2021) A Tale of Two Food Chains: The Duality of Practices on Well-being. Production and Operations Management 30 (3), 783-801.

Sarkis, J. and Dou, Y. (2017) Green supply chain management: A concise introduction. Routledge.

Tanveer, U., Hoang, Thinh G., Ishaq, S. and Howard, M. (2025) Regenerative Supply Chains in Vietnamese Agriculture: Extending Natural Resource Theory Through Collective Waste Utilization and Social Benefit. Business Strategy and the Environment 34 (8), 9993-10011.

Tseng, C. Y., Li, J., Lin, L. H., Wang, K., White Iii, C. C. and Wang, B. (2025) Deep reinforcement learning approach for dynamic capacity planning in decentralised regenerative medicine supply chains. International Journal of Production Research 63 (2), 555-570.

Wu, Z., Oger, R., Lauras, M., Faugère, L. and Montreuil, B. (2025) A guiding framework for hyperconnected circular supply chain implementation. Journal of Cleaner *Production* 501.

Enhancing Sustainability through the Governance of Supply Chain Network

Dinh Long Tran, Aswini Yadlapalli, Thuy Nguyen, Paul Childerhouse

RMIT University, Australia

Purpose of this paper

The agrifood sector is withstanding serious sustainability challenges. Due to climate change, growing conditions are harsher, and global pesticide use has increased by 16.7%. While producing food is more difficult, 1/3 of total food is lost and wasted across the production, distribution, and consumption stages of the agrifood supply chain. Nonetheless, farmers capture only 1% of the total value per output, which exacerbates instability in this sector's development. These challenges are magnified by global disruptions such as the pandemic and political unrest. Additionally, due to seasonality, perishability, and long supply chains, this leads to massive food waste and significantly high social and environmental costs from the farm to the fork (Ramos et al. 2024). With the escalating sustainability challenges, there have been calls for collective action by cross-sector stakeholders, as no single entity can solve societal challenges alone (Jia et al. 2020).

However, this collective action is extremely challenging. The core problem is the misalignment between stakeholders. It leads to differences in perceived sustainability outcomes. It is suggested that misalignment worsens the sustainability outcomes. Still, it does not adequately address how business entities can effectively interact with the cross-sector stakeholders to re-navigate their course of action and align their resources (Cole and Shirgholami 2022). Therefore, it is vital to introduce a commonly accepted language to translate differences in perceived outcomes of the involving stakeholders. Here, this study introduces the lens of value - a shared language – as the solution. By referring sustainability as sustainability value creation and capture, this study aims to reveal how the governance mechanisms of supply chain networks enhance the creation and capture of sustainability value for the supply chain network stakeholders. To achieve the research purpose, the following objectives are indicated:

- Identify the types of sustainability values that are created and captured by supply chain network stakeholders.
- Explore the governance mechanisms that promote greater sustainability value creation for supply chain network stakeholders.
- Explore alternative governance mechanisms that best align with supply chain network stakeholders to capture their share of sustainability value creation.

Design/methodology/approach

The theoretical scope of the paper is grounded in the Relational View. The Relational View is built on four main pillars: relation-specific assets, knowledge-sharing routines, complementary resources and capabilities, and effective governance (Dyer and Singh 1998). This theoretical lens is utilized to explain how the engagement of multiple stakeholders in the supply network can enhance sustainability value. Complementary resources and capabilities, knowledge-sharing routines, and relationship-specific assets can facilitate sustainability, value creation and capture. Additionally, an appropriate selection of governance mechanisms is a safeguard for inter-organizational relationships. It can drive effective coordination and alignment. It can promote greater sustainability outcomes for the overall network's stakeholders.

This research adopts a qualitative single case study approach combined with abductive reasoning. Case research is identified as the "best fit" for this study because it is particularly appropriate for exploring and examining socially constructed, complex realities, such as those found in multi-stakeholder supply chains. This method is ideal for answering "what" and "why" questions and seeking new insights into the unique settings of multiple realities (Yin 2018). Additionally, the choice of abductive reasoning is strategic; it allows the research to link and

contrast insights derived from empirical data with existing literature, facilitating a rigorous exploration of the subject matter (Dubois and Gadde 2002).

The coffee supply chain in the Central Highlands of Vietnam is selected as the research context. One-on-one interviews with representatives across three groups of stakeholders will be utilized for data collection, including firms, non-governmental organizations, and government agencies. Data collected from interviews will be recorded, transcribed, and analyzed. The interviews will be conducted in the Vietnamese language and then translated into English for further analysis. Data will be analyzed using NVivo 15 (Licensed by RMIT University) through coding cycles, including first-cycle and second-cycle coding (Miles et al. 2014).

Expected Findings

The value created by supply chain network stakeholders is various, including economic, social, and environmental forms (Schenkel et al. 2015). However, the capture of created value can be heterogeneous among stakeholders.

It is expected that the complementarity of both contractual and relational governance mechanisms can drive greater value creation and capture for supply chain network stakeholders. While the contractual mechanisms will provide the initial foundation for the relationship between stakeholders, the relational mechanisms might determine the effectiveness of the relationship in terms of sustainability, value creation, and capture.

Value

This study introduces the lens of value to clarify and unify differences in agendas and motivations, as well as in perceived sustainability outcomes, across stakeholder groups, including firms, non-governmental organizations, and government agencies. By fostering mutual understanding of sustainability from different stakeholder perspectives, it facilitates greater sustainability outcomes, including value creation and capture, for supply chain network stakeholders. Additionally, this study cultivates a holistic approach to discuss governance, sustainability, and value creation and capture from the perspectives of various stakeholder groups in the supply chain network. By adopting a holistic approach, stakeholders can successfully coordinate their sustainability activities.

Research limitations/implications

The qualitative and explorative characteristics of this study provide enriched analysis and insight into the discussion of governance, sustainability, and value creation and capture. However, this approach is constrained by generalizability. Future empirical research will help further increase the capability to generalize the outcomes of this research.

Practical implications

The research has two prospective practical impacts for the stakeholders involved. First, by suggesting a shared language as 'value', different stakeholders can gain mutual understanding regarding the expected benefits of each other. Second, this study is expected to benefit cross-sector cooperation by providing a set of best practices for stakeholders to better align their capabilities and resources, especially in sustainability-related projects.

References

Cole R and Shirgholami Z (2022) 'The outlook for modern slavery in the apparel sector in a post-lockdown economy', Supply Chain Management: An International Journal, 27(4):526–537, https://doi.org/10.1108/SCM-06-2020-0245

Dubois A and Gadde LE (2002) 'Systematic Combining: An Abductive Approach to Case Research', Journal of Business Research, 55(7): 553–560, https://doi.org/10.1016/S0148-2963(00)00195-8

Dyer JH and Singh H (1998) 'The Relational View: Cooperative Strategy and Sources of Interorganizational Competitive Advantage', The Academy of Management Review, 23(4):660–679. https://doi.org/10.2307/259056

Jia F, Peng S, Green J, Koh L and Chen X (2020) ‘Soybean supply chain management and sustainability: A systematic literature review’, Journal of Cleaner Production, 255:120254, https://doi.org/10.1016/j.jclepro.2020.120254

Miles MB, Huberman MA and Saldana J (2014) 'Qualitative Data Analysis: A Methods Sourcebook', 3rd ed, Thousand Oaks, CA: Sage Publications.

Ramos E, Rabiee M, Tarei PK, Chavez M & Coles PS (2024) ‘A diverse, unbiased group decision-making framework for assessing drivers of the circular economy and resilience in an agrifood supply chain’, Production Planning & Control, 1–21, https://doi.org/10.1080/09537287.2024.2370988

Schenkel M, Krikke H, Caniëls MJ and van der Laan E (2015) ‘Creating integral value for stakeholders in closed loop supply chains’, Journal of Purchasing & Supply Management, 21:155-166, http://dx.doi.org/10.1016/j.pursup.2015.04.003

Yin RK (2018) 'Case Study Research and Applications: Design and Methods', 6th ed, Thousand Oaks, CA: Sage Publications.

Circular Economy Between the Tension of Theory and Practice: Re-Engineering and Innovating the Beer Distribution Game Towards Closed Loop Supply Chains

Lukas Nagel, Florian Maurer

Vorarlberg University of Applied Sciences, Austria

Purpose of this paper

The purpose of this paper is to further investigate to an observation made during the execution of the MIT's Beer Distribution Game. It was played within the Erasmus+ project SMARTER to teach and train international students about Supply Chain Management. The Beer Distribution Game, a pedagogical experiential learning tool for real-time simulation of phenomena in a supply chain, does not yet cover the current state of theory with regard to the concept of the circular economy. It simply represents a chain – ranging from the raw material producer to the end customer. Therefore, the full paper addresses the topic of circularity in supply chain management. A supply chain is generally considered to be a linear, end-to-end process. (Jockel & Femerling, 2025, p. 35). However, this take, make, use and dispose approach with resources, also known as cradle to grave, contradicts circular economy (Kreutzer, 2024, p. 10), a theory that focus on waste management, product life extension, and material recovery (recycling) in a long-term perspective (Hansen & Revellio, 2020, p. 1250). It is characterized by eliminating waste and pollution, circulate products and materials at their highest value, and regenerating nature (Ellen MacArthur Foundation, 2026). This paper is based on the research question of how a circularity-based Beer Distribution Game for supply chain can look like and which adaptations and changings of the game's rules need to be engineered.

Design/methodology/approach

This paper adheres to the design sciences methodology. It combines preliminary observations, the findings obtained from the execution of the Beer Distribution Game in the Erasmus+ project SMARTER, and a rigorous literature review on theories relating to supply chains in combination with the circular economy to highlight the state-of-art in supply chain management. The results are incorporated into design study, which is carried out in the form of a case study. In this case study, expert interviews with managers and decision-makers in the field of food supply chain and its B2B consumers will be used to determine how the circular economy is implemented in practice. The knowledge gained will support in the re-engineering and further development of the Beer Distribution Game toward circularity and closed-loop supply chains (Zeballos et al., 2016). The results of two workshops with test users are used to continuously evaluate and validate the extended version of the Beer Distribution Game and further improve it.

Findings

The research findings contribute to supply chain management theory and practice. In the theoretical part the status quo of circular economy and if the term supply chain is longer appropriate or an alternative must be found like "supply network planning" are discussed. Moreover, the drives and the motivation of circular economy are treated. The practical part provides a case study, how the circular economy works concrete at a local brewery with its B2B customers. It examines which goods are in circularity and identifies, why is it possible with these goods. With the findings of the theoretical and practical parts the BDG of the Erasmus+ project SMARTER is examined with the current state of knowledge on circular economy and as much knowledge as possible is integrated into the BDG. Management simulations, such as the BDG, have the advantage that theoretical knowledge can be put into practice in a laboratory setting and the effects of decisions become immediately apparent. Further findings will be gained from two trials of the circular economy-based version of the Beer Distribution Game. The final result is a proven, circular economy-based version of the beer distribution game as a pedagogical experiential learning tool for lecturers, students, professionals, and prospective in the field "Supply Chain Management in combination Circular Economy".

Value

The originality of this paper lies on the integration of the theoretical and practical view of circular economy in the management simulation Beer Distribution Game. Moreover, the status quo of circular economy and an example of a local brewery with its customers are analysed.

The target group of this paper are lecturers, students, professionals and prospective in the field Supply Chain Management in combination with Circular Economy. It also serves to motivate stakeholders to be proactive in the circular economy of the beer industry. Furthermore, scholars and lecturers can build on the findings do address the limitations of this work like to adapt other management simulations to the current status or observe the practical part in other regions etc.

Practical implications

With this paper, we address the limitations of the linear, end-to-end supply chain approach. We present a refined model of the Beer Distribution Game the responds to the closed-loop supply chains, demanded by politics, business, and industry. Moreover, relevant factors for a circular economy perspective are identified by means of a literature review and a practical case study. The final outcome is a circular economy-based version of the BDG as a pedagogical experiential learning tool.

References

Ellen MacArthur Foundation. (2026). Circular economy introduction. https://www.ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview

Hansen, E. G., & Revellio, F. (2020). Circular value creation architectures: Make, ally, buy, or laissez-faire. Journal of Industrial Ecology, 24(6), 1250–1273. https://doi.org/10.1111/jiec.13016

Jockel, O., & Femerling, J. C. (2025). Logistik und Supply Chain Management: Grundlagen – Übungen – Fallbeispiele. Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-48243-5

Kreutzer, R. T. (2024). Kreislaufwirtschaft. WiSt - Wirtschaftswissenschaftliches Studium, 53(9), 10–17. https://doi.org/10.15358/0340-1650-2024-9-10

Zeballos, L. J., Méndez, C. A., & Barbosa-Povoa, A. P. (2016). Design and Planning of Closed-Loop Supply Chains: A Risk-Averse Multistage Stochastic Approach. Industrial & Engineering Chemistry Research, 55(21), 6236–6249. https://doi.org/10.1021/acs.iecr.5b03647

What Makes Circular Economy Ventures Work? A Multi-Case Analysis of Critical Success Factors

Tillmann Boehme, Eunice Quintana-Smark, Thomas Birtchnell

University of Wollongong, Australia

Purpose of this Paper

Despite growing policy attention and investment, many circular economy (CE) initiatives struggle to progress beyond pilot projects or grant-funded demonstrations. While the circular economy is frequently framed as a sustainability or waste management challenge, comparatively little empirical research has examined the organisational, technical, and structural conditions that enable CE ventures to achieve operational viability and scale. Existing literature tends to emphasise macro-level policy instruments or high-level principles, offering limited insight into how CE ventures create and capture value in practice. The purpose of this paper is to identify and theorise the critical success factors (CSFs) that influence the viability and scalability of circular economy ventures. Specifically, the study seeks to answer the following research question: What configurations of structural, organisational, and process-related factors enable circular economy ventures to transition from waste recovery activities to sustainable business models? By adopting an exploratory, multi-case research design, the paper aims to move beyond normative prescriptions and provide empirically grounded insights into how CE ventures operate across different organisational forms.

Design/Methodology/Approach

The study employs a qualitative multiple case study methodology to explore CE venture dynamics within real-world organisational contexts. A case study approach is well suited to investigating complex, contemporary phenomena embedded in their institutional and operational environments, particularly where causal mechanisms are not yet well theorised. Four circular economy ventures were selected using opportunity sampling, reflecting both access considerations and relevance to the research objectives. The cases comprise two commercially oriented B-certified social enterprises and two non-governmental organisations (NGOs). This configuration enabled comparative analysis across organisational forms while maintaining a shared focus on waste valorisation and circular business models. All cases operated in close geographic proximity to their primary waste streams, allowing for examination of supply dynamics and operational embeddedness.

Data collection followed a multi-source triangulation strategy, incorporating semi-structured interviews, direct observations, email correspondence, and archival materials such as patents, consulting reports, and publicly available policy documents. Semi-structured interviews served as the primary data source and were conducted with key organisational decision-makers. Interviews lasted approximately two hours and followed a common interview guide, enabling consistency while allowing for the exploration of emergent themes. Where feasible, interviews were conducted on-site, facilitating contextual verification through observation of operational processes. Data analysis adopted an iterative, multi-method qualitative approach, integrating within-case analysis and cross-case comparison. Method triangulation and investigator triangulation were used to enhance analytical rigour and reduce bias. The analytical process focused on identifying recurring patterns related to value creation mechanisms, organisational structure, supply chain configuration, and scaling dynamics. From this analysis, a set of critical success factors was inductively derived and synthesised into a conceptual model explaining CE venture viability and scalability.

Findings

The findings reveal that successful circular economy ventures are shaped by a layered configuration of interdependent factors, rather than by environmental intent or waste recovery alone. Six interrelated themes emerged across the cases.

First, proximity to waste generation sites was identified as a foundational operational condition. All cases operated in close geographic proximity to their primary waste streams, reducing transport costs and enabling timely access to feedstock. However, proximity alone was insufficient. Supply continuity emerged as a critical determinant of operational efficiency. Ventures with reliable, controllable access to waste inputs were better positioned to stabilise production processes and meet market demand. In contrast, cases exposed to contested or inconsistent waste supplies experienced increased risk and reduced efficiency. Second, successful ventures approached circular economy challenges as engineering problems, prioritising process innovation over basic material recovery. The commercially successful cases invested in developing proprietary processing techniques that enabled the extraction of high-value outputs from waste streams. This engineering-led approach shifted the business model from low-margin recycling activities toward differentiated production, enhancing value capture. Ventures lacking defensible process innovation struggled to generate sufficient margins, even when environmental benefits were clear.

Third, intellectual property (IP) played a central role in supporting competitive advantage. Patented or otherwise protected processing methods enabled ventures to appropriate value from innovation and reduced vulnerability to imitation. IP functioned not only as a technical asset but also as a signalling mechanism, supporting legitimacy and partnership formation. Fourth, organisational form significantly influenced long-term viability. NGO-led ventures demonstrated strong social and environmental commitment but faced persistent challenges related to grant dependence and policy-driven demand. These constraints limited strategic flexibility and hindered scaling efforts. In contrast, B-certified social enterprises combined mission-driven objectives with commercial discipline, enabling reinvestment in innovation and market development. Fifth, capital-based partnerships emerged as a key enabler of scale. Successful ventures formed partnerships with established industrial actors, gaining access to infrastructure, finance, and market channels. These partnerships also enabled ventures to bridge regulatory and policy gaps by aligning commercial operations with government objectives and global supply chain requirements. Finally, end-to-end supply chain control distinguished viable CE ventures from those that struggled. The successful cases exhibited high levels of control across sourcing, processing, and demand creation. By utilising digital platforms and retail channels, these ventures reduced reliance on intermediaries, stabilised revenue streams, and synchronised supply with demand. Together, these findings suggest that CE success depends on the alignment of foundational conditions, value creation mechanisms, organisational enablers, and market control strategies. Environmental intent alone was insufficient to ensure viability.

Value/Originality

This paper makes several original contributions to the circular economy and entrepreneurship literature. First, it reframes circular economy ventures as engineering-led value creation systems rather than waste management initiatives. By foregrounding process innovation and IP, the study challenges dominant narratives that equate circularity with recycling or material diversion alone. Second, the paper introduces a multi-layer conceptual model of critical success factors that integrates supply conditions, innovation mechanisms, organisational form, partnerships, and market control. This model advances CE theory by explaining why ventures operating under similar environmental and policy conditions experience divergent outcomes. Third, the study provides rare empirical insight into organisational form within CE contexts, demonstrating the structural limitations of grant-dependent NGO models and the relative resilience of commercially oriented hybrid enterprises. Fourth, the findings contribute to entrepreneurship research by extending push–pull and institutional perspectives to circular economy contexts, highlighting the role of necessary but not sufficient background conditions and the importance of value capture mechanisms.

Research Limitations/Implications

The study is subject to several limitations. First, the use of opportunity sampling and a small number of cases limits generalisability. The findings are intended to support theory building rather than statistical inference. Second, the cases are geographically bounded, and institutional conditions may differ in other contexts. Third, the study focuses on early-stage and mid-stage ventures; long-term performance outcomes were not observable. These limitations suggest

several avenues for future research. Quantitative studies could test the proposed propositions across larger samples and diverse institutional contexts. Longitudinal research could examine how critical success factors evolve over time, particularly as waste streams become contested. Further research could also explore the role of policy design in supporting engineering-led CE innovation rather than short-term pilots.

Practical Implications

For practitioners, the findings suggest that successful circular economy ventures should prioritise engineering-led process innovation, defensible IP, and integrated supply chain control rather than relying on environmental narratives alone. Proximity to waste sources and supply continuity should be treated as strategic considerations, not operational afterthoughts. For policymakers, the results indicate that grant-funded pilots, while valuable for experimentation, are insufficient to support long-term CE outcomes. Policy frameworks should incentivise capital partnerships, infrastructure investment, and value-added processing capabilities. Supporting hybrid organisational forms may offer a more effective pathway to scaling circular solutions. For investors and industry partners, the study highlights the importance of CE ventures that demonstrate control over supply, processing, and demand, as well as clear mechanisms for value capture.

SUPPLY CHAIN INTELLIGENCE

Using Game Theory to Increase the Robustness and Resilience of the Supply Chain: Rationality in the Event of Organizational Incidents

Florian Maurer[1], Daniela Tanhua[2], Katri Kesti[2]

1: Vorarlberg University of Applied Sciences, Austria; 2: Satakunta University of Applied Science, Finland

Keywords

Supply Chain Robustness & Resilience, Decision Theory, Transport Logistics Providers, Coping with Organizational Risks and Hazards

Past and ongoing events, both: man-made risks and environmental-caused hazards, have shown the vulnerability of global supply chains and supply chain networks. Since the COVID-19 crisis, the notions of robustness and resilience moved into the center of attention in the management of supply chains and extended enterprise networks. And in fact, nearby events such as global conflicts, false promises, taxes and tariffs, etc., the engineering of robustness-increasing measures and resilient-increasing measures into (global) supply chains are more relevant than ever (i.e., World Economic Forum (2013)).

Both concepts – the concept of organizational robustness and the concept of organizational resilience – are about a system's reliability in withstanding and coping with hazardous disruption. The notion of robustness, in addition, adresses the organization's stability: it is the organizational ability being either insensitive (Gremyr & Hasenkamp, 2011) and/or strong and sturdy to deviations (Christopher & Rutherford, 2004), to withstand risks (Wieland & Wallenburg, 2012), resist disruptions (Vlajic et al., 2012), prevent undesirable impacts (Roy, 2010) as well as retaining the system's structures and funcitons intact (i.e., Meepetchdee & Shah (2007), Vlajic et al. (2012), unchanged, or nearly unchanged (i.e., Wieland & Wallenburg (2013), Klibi et al. (2010)). It is about sustaining operations when a major disruption hits (Scholten et al., 2014), continuing operations, and remaining effective for all plausible futures (i.e., Wieland & Wallenburg (2012)). Under the (realistic) assumption that not all risks, hazards, and events can be prevented, a system is requested to develop routines for organizational responses (Lengnick-Hall & Beck, 2005): to survive, adapt, and grow in unforeseen events, even in catastrophic incidents (Fiksel et al., 2014), thus to be resilient. The notion of resilience is about the system's capability to evolve out of organizational hazards and crises without adverse effects. Colloquially: bouncing back (Sheffi & Rice, 2005) through anticipation and adjustment to trends, capacity to change (Välikangas & Hamel, 2003), self-renewal, adaptations, and continuous innovation (Ponomarov & Holcomb, 2009), (encouraging) entrepreneurial behavior (Reinmoeller & van Baardwijk, 2005) – under certain and uncertain environments (inherent resilience versus adaptive resilience (Ponomarov & Holcomb, 2009)).

Within this paper, we consider the concept of robustness as a resource-based property of an organization: it is about the maintenance of organizational performance, its monitoring, and measurements toward the right product, in the right quantity, to the right price, in the right time, and with the expected quality. In the center are, for example, risk anticipation and mitigation measures, such as organizational risk management and business continuity planning. In contrast, we consider the concept of resilience as a capability-based property of an organization: it represents an organizational governance framework for learning and knowledge, renewal, change, and innovation, orchestrating and mediating between organizational robustness and the organization’s ability to be flexible and agile towards renewal, change, and innovation.

We consider the concept of robustness and resilience as an organizational process of active decision-making.

Therefore, we connect the concepts of robustness and resilience to decision theory – especially to the Theory of Games. Game Theory can be traced to v. Neumann (1928) and v. Neumann & Morgenstern (1944), who established Game Theory as an academic discipline. Game Theory investigates real-life, interactive situations wherein opponents (minimum: two actors) compete for a strategic resource. Under the assumption of rational behavior, the actors have to decide among strategies (minimum: two strategies) to leverage the best, self-interested possible outcome. Related to the game's conditions, the decision-making of the actors can lead to a payoff equilibrium between the players, an asynchronous payoff equilibrium between the players (i.e., one actor is satisfied by the outcome, the other actor is disgruntled), or a dysfunctional payoff equilibrium. Scholars and academics have further developed the theory and introduced important solution concepts to mediate conflicts and cooperation. Solution concepts include, for example, the Minimax Theorem (v. Neumann & Morgenstern, 1944) intoducing safety and security in decision-making; the Nash equilibrium (Nash, 1950a, 1950b) introducing stable cooperation in decision-making; the Shapley value (i.e., Shapley (1953), Hart (1987)) introducing fairness and cooperation in decision-making; the »sure-thing-principle« introducing the concept of strict dominance (Diekmann, 2009).

We turn our focus to rationality in decision-making for the increase of organizational robustness and resilience in times of organizational prosperity and organizational adversity. The leading research question investigates »how managers can decide rationally towards increased organizational robustness and resilience in systems and among ecosystem thus to better respond to and act on organizational dynamics, risks, uncertainties, and crises?«. In responding to the research question, we make use of four business cases. These business cases, elaborated with three Transport Logistics Providers from Austria, Germany, and Switzerland, allow us to connect challenges in rational decision-making with the concepts of organizational robustness and resilience. By transforming the cases into a game, we make use of the Game Theory's 2x2 payoff matrix. In doing so, we include the important aspects of the situation and exclude the unimportant ones (Samuelson, 2016).

At the current state, the paper’s audience is scholars and students within the fields of Supply Chain Management and (*Transport*) Logistics. After the active integration of the paper at hand into a lecture entitled “Supply Chain Resilience” (*5 ECTS course, organized on the 17-19th March 2026 at the Satakunta University of Applied Science (Finland)*), its demonstration by making use of the MIT’s Beer Distribution Game and the discussion of the results with staff and students, the paper shall be reworked and submitted to an academic journal. The audience then is both academia (i.e., scholars, scientists, students) and practitioners (i.e., managers and organizational decision-makers) within the field.

Acknowledgements

This work is supported by the Interreg Alpine Space Project: Apollo – territoriAl corPOrate weLfare through digitaLization and cOoperation. The authors wish to thank the funding authority and people involved in the project and paper for their support and collaboration in making this research possible.

References

Christopher, M., & Rutherford, C. (2004). Creating Supply Chain Resilience Through Agile Six Sigma. http://www.sclgme.org/shopcart/Documents/critical_eye.pdf

Diekmann, A. (2009). Spieltheorie: Einführung, Beispiele, Experimente (Game theory: introduction, examples, experiments) (4th ed.). Rowohlt Taschenbuch.

Fiksel, J., Polyviou, M., Croxton, K. L., & Pettit, T. (2014). From Risk to Resilience: Learning to Deal With Disruption. MIT Sloan Management Review, (Winter 2015). http://sloanreview.mit.edu/article/from-risk-to-resilience-learning-to-deal-with-disruption/

Hart, S. (1987). The New Palgrave: A Dictionary of Economics (Shapley value) (J. Eatwell, M. Milgate, & P. Newmann, Eds.). The Macmillan Press Limited.

Ida Gremyr & Torben Hasenkamp. (2011). Practices of robust design methodology in practice. The TQM Journal, 23(1), 47–58. https://doi.org/10.1108/17542731111097489

Klibi, W., Martel, A., & Guitouni, A. (2010). The design of robust value-creating supply chain networks: A critical review. European Journal of Operational Research, 203(2), 283–293. https://doi.org/10.1016/j.ejor.2009.06.011

Lengnick-Hall, C. A., & Beck, T. E. (2005). Adaptive Fit Versus Robust Transformation: How Organizations Respond to Environmental Change. Journal of Management, 31(5), 738–757. https://doi.org/10.1177/0149206305279367

Nash, J. F. (1950a). Equilibrium points in n-person games. Proceedings of the National Academy of Sciences, 36(1), 48–49. https://doi.org/10.1073/pnas.36.1.48

Nash, J. F. (1950b). The Bargaining Problem. Econometrica, 18(2), 155–162. https://doi.org/10.2307/1907266

Reinmoeller, P., & van Baardwijk, N. (2005). The Link Between Diversity and Resilience. MIT Sloan Management Review, (Sumer 2005). http://sloanreview.mit.edu/article/the-link-between-diversity-and-resilience/

Rick Edgeman & Joseph A. Williams. (2014). Enterprise self-assessment analytics for sustainability, resilience and robustness. The TQM Journal, 26(4), 368–381. https://doi.org/10.1108/TQM-01-2014-0012

Roy, B. (2010). Robustness in operational research and decision aiding: A multi-faceted issue. European Journal of Operational Research, 200(3), 629–638. https://doi.org/10.1016/j.ejor.2008.12.036

Samuelson, L. (2016). Game Theory in Economics and Beyond. Journal of Economic Perspective, 30(4), 107–130. http://dx.doi.org/10.1257/jep.30.4.107

Scholten, K., Sharkey Scott, P., & Fynes, B. (2014). Mitigation processes – antecedents for building supply chain resilience. Supply Chain Management: An International Journal, 19(2), 211–228. https://doi.org/10.1108/SCM-06-2013-0191

Serhiy Y. Ponomarov & Mary C. Holcomb. (2009). Understanding the concept of supply chain resilience. The International Journal of Logistics Management, 20(1), 124–143. https://doi.org/10.1108/09574090910954873

Shapley, L. S. (1953). A Value for n-Person Games. In H. W. Kuhn & A. W. Tucker (Eds.), Contributions to the Theory of Games (AM-28), Volume II (pp. 307–318). Princeton University Press. https://www.degruyter.com/document/doi/10.1515/9781400881970-018/html

Sheffi, Y., & Rice, J. B. (2005). A Supply Chain View of the Resilient Enterprise. MIT Sloan Management Review, (Fall 2005). http://sloanreview.mit.edu/article/a-supply-chain-view-of-the-resilient-enterprise/

v. Neumann, J. (1928). Zur Theorie der Gesellschaftsspiele (On the theory of parlor games). Mathematische Annalen, 100(1), 295–320. https://doi.org/10.1007/BF01448847

v. Neumann, J., & Morgenstern, O. (1944). Theory of Games and Economic Behavior. Princeton University Press.

Välikangas, L., & Hamel, G. (2003). The Quest for Resilience. Harvard Business Review, (September 2003). https://hbr.org/2003/09/the-quest-for-resilience

Vlajic, J. V., van der Vorst, J. G. A. J., & Haijema, R. (2012). A framework for designing robust food supply chains. International Journal of Production Economics, 137(1), 176–189. https://doi.org/10.1016/j.ijpe.2011.11.026

Wieland, A., & Wallenburg, C. M. (2012). Dealing with supply chain risks. International Journal of Physical Distribution & Logistics Management, 42(10), 887–905. https://doi.org/10.1108/09600031211281411

Wieland, A., & Wallenburg, C. M. (2013). The influence of relational competencies on supply chain resilience: A relational view. International Journal of Physical Distribution & Logistics Management, 43(4), 300–320. https://doi.org/10.1108/IJPDLM-08-2012-0243

World Economic Forum. (2013). Building Resilience in Supply Chains. An Initiative of the Risk Response Network in collaboration with Accenture [Industry Agenda]. World Economic Forum. www.weforum.org; http://www3.weforum.org/docs/WEF_RRN_MO_BuildingResilienceSupplyChains_Report_2013.pdf

Yongyut Meepetchdee & Nilay Shah. (2007). Logistical network design with robustness and complexity considerations. International Journal of Physical Distribution & Logistics Management, 37(3), 201–222. https://doi.org/10.1108/09600030710742425

Decision Efficiency as a Leading Indicator for AI-Enabled Warehouse Operations

Sathya Karuveli[1], Venkates Ramalingam[2], Krishnaveni Namasivayam[3]

1: Deloitte; 2: GXO Logistics Inc; 3: CSCS LLC

Purpose of this paper

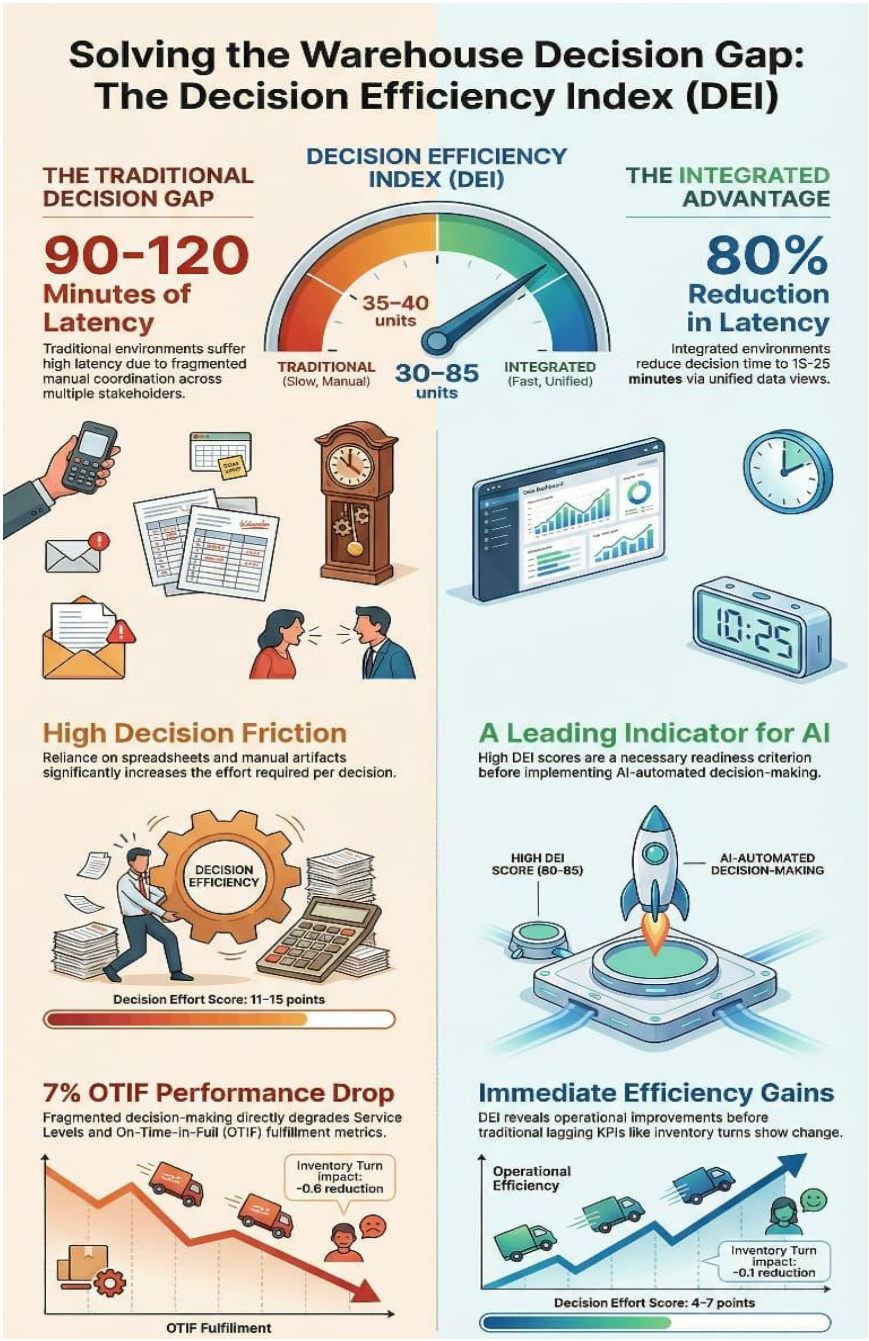
This paper addresses a fundamental constraint in modern warehouse and logistics operations: performance is increasingly limited not by physical execution capacity but by slow, fragmented operational decision-making. While Warehouse Management Systems (WMS) and Transportation Management Systems (TMS) have optimized transactional throughput, the decisions that govern how operations respond to disruptions inbound delays, labor constraints, order volatility remain manual, reactive, and dispersed across multiple systems and stakeholders. This fragmentation introduces decision latency, increases human effort, and produces variable responses to similar disruptions, directly degrading service levels, inventory performance, and fulfillment reliability.

The paper pursues three aims: First, to introduce Decision Efficiency as a measurable organizational capability that quantifies how effectively operations convert signals into timely, low-friction actions. Second, to propose a practical Decision Efficiency Index (DEI) that positions decision-making capability as a leading indicator of operational performance, moving before traditional KPIs reveal change. Third, to establish DEI as a readiness criterion for AI adoption, arguing that organizations must achieve baseline decision efficiency before AI-assisted or automated decision-making can succeed. While demonstrated through warehouse operations, the DEI construct is designed as a general framework applicable to any function or industry facing time-critical decisions under uncertainty.

Design/Methodology/Approach

The research develops DEI as a productivity-style index for operational decisions, structured as outcome quality divided by decision friction. For warehouse operations, outcome quality is operationalized as the product of Service Level and Inventory Turns, reflecting the dual imperatives of customer fulfillment and capital efficiency. Decision friction combines two measurable components: Decision Latency (average elapsed time from signal recognition to committed action) and Decision Effort (human work required per decision). Decision Effort is quantified using a simple, observable formula based on three counts per decision instance: number of systems accessed, people involved, and manual artifacts created. This yields: Effort = $w_1 \cdot$Systems + $w_2 \cdot$People + $w_3 \cdot$Artifacts, where weights can be set to one in the simplest case.

The study employs scenario-based simulation comparing two decision environments responding to a critical inbound delay threatening outbound on-time-in-full (OTIF) performance in a consumer packaged goods warehouse. The Traditional Environment requires navigating multiple systems (WMS, TMS, labor management, yard management), coordinating across four to six stakeholders via email and calls, and creating manual artifacts such as spreadsheets and reconciliation reports. The Integrated Decision Environment provides a unified operational view centered on the disruption, pre-assembles relevant constraints and affected orders, and surfaces recommended actions for human review and confirmation. Both environments face identical operational conditions; only information availability and decision support structure differ. Decision latency, effort components, DEI, and resulting impacts on OTIF and inventory turns are measured and compared across the two environments.



Findings

The simulation demonstrates three principal findings. First, decision efficiency improves substantially and immediately when information integration and decision support are introduced, while traditional KPIs improve more gradually. In the Traditional Environment, average decision latency ranged from ninety to one hundred twenty minutes, with effort scores of eleven to fifteen (typically four to five systems, four to six people, three to four artifacts per decision). DEI measured thirty-five to forty relative units. The Integrated Environment reduced decision latency to fifteen to twenty-five minutes and effort to four to seven (one to two systems, two to three people, zero to one artifacts), yielding DEI of eighty to eighty-five units more than doubling decision efficiency. OTIF impact declined from negative seven percent in the Traditional Environment to negative one percent in the Integrated Environment, while inventory turns degradation improved from negative zero point six to negative zero point one.

Second, information integration primarily affects the DEI denominator before influencing the numerator. Unified views and embedded decision logic do not instantly alter demand patterns,

network design, or physical capacity. Their immediate effect is reducing the number of systems, people, and artifacts required per decision and shortening elapsed decision time. This denominator reduction raises DEI even before service and inventory performance materially shift, positioning DEI as a leading indicator of operational improvement.

Third, DEI reveals decision-making improvements that traditional monthly KPI reports often miss during transition periods. Organizations implementing new decision support tools can observe declining latency and effort evidence of strengthened capability before structural constraints allow full KPI improvement to manifest.

Value

This paper makes three original contributions. First, it introduces a general-purpose framework for quantifying decision efficiency that is theoretically grounded yet operationally practical, requiring only basic observation and system timestamps rather than specialized measurement tools. Second, it positions decision efficiency as a prerequisite capability for AI adoption rather than treating AI as a direct solution to fragmented decision-making. Third, it provides warehouse and logistics managers with a concrete leading indicator that bridges information system investments and operational outcomes, enabling proactive management of decision quality before lagging KPIs signal deterioration. The framework offers value to operations managers, technology leaders guiding AI deployment, and researchers exploring links between information systems and performance.

Research Limitations/Implications

The study relies on scenario-based simulation rather than empirical field data from multiple warehouse sites. Future research should empirically measure DEI longitudinally across warehouses and apply the framework in other operational contexts with appropriate outcome metrics.

Practical Implications

Organizations should adopt DEI measurement alongside traditional KPIs. Warehouse leaders can identify high-latency decisions where integration delivers maximum impact. For AI adoption, use DEI to distinguish decisions ready for assistance from those requiring fundamental improvement first.

References

Holweg, M. (2007). The genealogy of lean production. *Journal of Operations Management*, 25(2), 420-437.

Waller, M. A., & Fawcett, S. E. (2013). Data science, predictive analytics, and big data. *Journal of Business Logistics*, 34(2), 77-84.

Choi, T. M., Wallace, S. W., & Wang, Y. (2018). Big data analytics in operations management. *Production and Operations Management*, 27(10), 1868-1883.

Implications of AI-Informed Decision Making in Disrupted Supply Chains

Jannicke Baalsrud-Hauge[1], Ioana Stefan[2]

1: KTH Royal Institute of Technology, Sweden; 2: Advanced Technology Solutions, Romania

Purpose of this paper

This paper investigates how the usage of AI-assisted decision-making may affect the overall resilience of a supply chain. This paper presents work-in-progress results and discusses the outcome of a structured literature review on the limitations and the opportunities of using AI as decision-support tools to increase the resilience of a supply chain. We specifically analysed the time-to-react and if the literature reported success cases.

Design/methodology/approach

The objective of this study is to analyse the current state of the art in terms of how AI-informed decisions in the supply chain affects the supply chain resilience. The methodological approach for the systematic literature review (SLR) is based on [1,2]. The search string used was "decision making supply chain using AI AND resilience". The search was time-bound to only publications from 2021 to 2026. To further rectify, the relevance search has been limited to articles written in English. With the automatic exclusion of non-relevant topics (titles and skimming through abstracts), the latest search (dated Feb. 23, 2026) resulted in 76 titles in PRIMO, of which 43 (will be updated when we have read all full papers) are included in this paper. The analysis of this part is presented in section three.

Findings

Based on only reading the abstracts, the preliminary findings are that the literature indicates that AI-informed decision making improves the sustainability [3], but that the quality of the decisions depends much on the data availability as well as the transparency in the supply chain. The examined papers (at the current stage) show how Data analytics and AI techniques (mainly machine learning, natural language processing) help in improving resilience, but also how other digital technologies (Internet of Things, Robotics and Cloud computing) have a positive effect [4,5]. A main challenge is related to ethics and privacy.

Value

This paper provides an overview of current state-of-the art

Research limitations/implications

Fast changing environment, very fast technology development.

Practical implications

Will be elaborated when we have read all papers and not only screened the abstracts.

References

[1] Chandra, V. (2018). Research methodology (A. Hareendran, Ed.; 1st edition.). Noida, Uttar Pradesh, India: Pearson India Education Services.

[2] Säfsten, K. (2020). Research methodology: for engineers and other problem-solvers (M. Gustavsson & R. Ehnsiö, Eds.). Studentlitteratur AB.

[3] Singh, D., Sharma, A., Singh, R. K., & Rana, P. S. (2025). Augmenting supply chain resilience through AI and big data. Business Process Management Journal, 31(2), 631–657. https://doi.org/10.1108/BPMJ-04-2024-0260

[4] Samuels, A. (2025). Digital transformation in supply chains: improving resilience and sustainability through AI, Blockchain, and IoT. Frontiers in Sustainability (Lausanne), 6, Article 1584580. https://doi.org/10.3389/frsus.2025.1584580

[5] Kazancoglu, Y., Mangla, S. K., Luthra, S., & Agarwal, M. R. (2025). Role of emerging technologies for empowering resilience and transparency in supply chains. Annals of Operations Research, 353(3), 977–1018. https://doi.org/10.1007/s10479-025-06741-2

Drivers of Smart-Port Investment Intention Under Perceived Security Risk: Evidence from Taiwanese Ports

Muhammad Hayat, Taih-Cherng Lirn, Kuo-Chung Shang

National Taiwan Ocean University, Taiwan

Purpose of this paper

Although smart-port technologies are becoming essential to the operations of modern seaports, organizational capabilities, regulatory pressures, environmental expectations, and growing cybersecurity concerns all influence investment decisions. The purpose of this study is to explain why port decision-makers want to invest in smart-port technologies by looking at how attitudes and intentions are influenced by regulatory pressure, environmental concerns, and IT infrastructure readiness. It also looks at how perceived security risk could reduce the impact of attitudes on intentions.

Theoretical Framework

The Theory of Planned Behavior (TPB) serves as the foundation for the model. The following are listed as external antecedents of attitude toward smart-port investment: regulatory pressure, environmental concern, and IT infrastructure readiness. It is anticipated that regulatory pressure and IT readiness may both directly and indirectly affect intention through attitude, while environmental concern will only affect intention through attitude. The proximal determinant of intention is represented as attitude, and the relationship between attitude and intention is moderated by perceived security risk.

Methodology

Port authorities, terminal operators, and logistics service providers are among the important decision-makers in Taiwanese port operations who will be provided a structured questionnaire. In order to determine the relative significance of environmental, regulatory, and technological drivers as well as to estimate direct, mediated, and moderated relationships, data will be analyzed using Partial Least Squares Structural Equation Modeling (PLS-SEM).

Expected Findings

It is anticipated that the research will demonstrate that regulatory pressure and IT infrastructure readiness have both direct and attitude-mediated effects on investment intention, whereas environmental concern primarily shapes a favorable attitude toward smart-port investment. Additionally, the positive effect of attitude on intention is expected to be significantly reduced by perceived security risk, emphasizing cybersecurity as a significant barrier even in the presence of favorable environmental and regulatory conditions.

Originality / Value

This study incorporates technological, institutional, and environmental factors into a logical behavioral framework for smart-port investment by modeling both full and partial mediation at the same time as a cybersecurity-related moderation. With an emphasis on Taiwanese ports, it provides policymakers and port managers with new ideas on how to create cybersecurity, infrastructure, and regulatory plans that efficiently facilitate smart-port digitalization.

References

Alziady, A. A. D. J., & Enayah, S. H. (2019). Studying the effect of institutional pressures on the intentions to continue green information technology usage. Asian Journal of Sustainability and Social Responsibility, 4(1). https://doi.org/10.1186/s41180-018-0023-1

Chen, M. F., & Tung, P. J. (2014). Developing an extended Theory of Planned Behavior model to predict consumers' intention to visit green hotels. International Journal of Hospitality Management, 36, 221–230. https://doi.org/10.1016/j.ijhm.2013.09.006

Driafish, A. A., Alziady, J., & Enayah, S. H. (2019). Studying the effect of institutional pressures on the intentions to continue green information technology usage. https://doi.org/10.1186/s41180-018-0023-1

Li, K., Gharehgozli, A., & Lee, J. Y. (2023). Smart technologies and port operations: Optimal adoption strategy with network externality consideration. Computers & Industrial Engineering, 184(16), 109557. https://doi.org/10.1016/j.cie.2023.109557

Min, H. (2022). Developing a smart port architecture and essential elements in the era of Industry 4.0. Maritime Economics & Logistics, 24(2), 189. https://doi.org/10.1057/s41278-022-00211-3

Potter, A., Wang, Y., & Naim, M. (2025). Scaling-up 5G adoption in smart ports: barriers and enablers. Maritime Policy and Management, 52(4), 517–534. https://doi.org/10.1080/03088839.2024.2399524

Sooprayen, K., Van de Kaa, G., & Pruyn, J. F. J. (2024). Factors for innovation adoption by ports: a systematic literature review. Journal of Ocean Engineering and Marine Energy 2024 10:4, 10(4), 953–962. https://doi.org/10.1007/s40722-024-00339-9

Zhang, B., Zhao, S., Shao, D., Fan, X., & Wang, S. (2025). Institutional pressures and green supply chain integration intention: Evidence from Chinese manufacturing firms. PLoS ONE, 20(5 May). https://doi.org/10.1371/journal.pone.0322200

Fraightmind: AI-Powered Cargo Optimization Via LLM-Driven Decision Intelligence & Interactive 3D Visualization for Real-Time "What-If" Analysis

Yoshita Singh[2], Tripti Singh[3], Dhawal Thakkar[1], Balamurugan Palaniappan[1]

1: Indian Institute of Technology (IIT), Bombay, India; 2: Sardar Patel Institute of Technology (SPIT), Mumbai; 3: CV Raman Global University, Bhubaneshwar

Purpose of this Paper

Efficient cargo loading remains a cornerstone of global logistics, yet it persists as a critical operational bottleneck due to the inherent computational complexity of the Three-Dimensional Bin Packing Problem (3D-BPP). Operationally difficult loading decisions cascade into higher transportation costs, wasted container space, and delivery delays. Although recent advancements have produced promising strategies using deep reinforcement learning [6] and heuristic methods [5], these solutions frequently operate mostly as black boxes. They often lack the flexibility to accommodate dynamic, real-world constraints or the implicit knowledge held by on-ground personnel. Consequently, the industry often relies on manual planning, which is inherently unscalable and error-prone. The purpose of this paper is to introduce FraightMind, an end-to-end intelligent decision support system designed to bridge the gap between algorithmic precision and human expertise. By integrating a conversational Large Language Model(LLM) interface, users can either select standard truck and cargo types from a pre-defined database or simply describe custom dimensions and quantities in a natural, conversational manner. Unlike static solvers, it provides an interactive 3D environment that empowers users to intuitively perform real-time what-if analysis or modify the solutions provided by the algorithm to make them operationally better based on their on-ground knowledge. By capturing and storing these user-driven refinements, FraightMind aims to create a scalable, user-friendly architecture that transforms loading process into a collaborative, seamless process between artificial intelligence and human decision-makers.

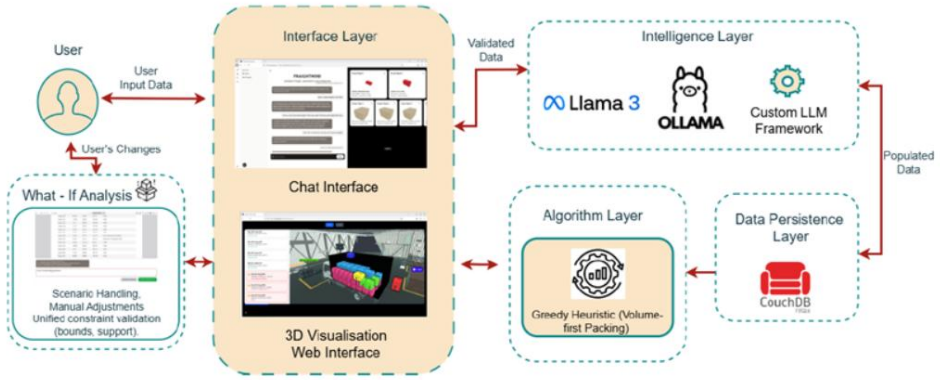


Figure 1: FraightMind System Architecture: End-to-end workflow from natural language input via LLM chatbot, through data persistence (CouchDB), 3D packing via heuristic optimization, to interactive visualization in Unity. Users perform real-time what-if analysis; adjusted layouts are persisted for audit and re-planning, with final reports routed back to the chatbot for seamless human-AI collaboration.

Design/methodology/approach

The FraightMind framework is architected as a modular, end-to-end decision support system that unifies Generative AI, a packing algorithm, and interactive 3D visualisation. As illustrated in Figure 1, the workflow begins at the Interface Layer, which is a conversational chatbot powered by Llama 3[3] and orchestrated via Lang Chain [2] serving as the primary entry point. Here, the user provides input through two distinct methods: selecting from a pre-populated database of

standard fleet and cargo types, or conversationally specifying unique dimensions and quantities. This input is processed by the Intelligence Layer, where an LLM-based parser (Llama 3) converts natural language into structured, schema-compliant JSON data.

Once validated, this data drives the Algorithm Layer, where a constraint-aware constructive heuristic generates a near-optimal 3D packing plan prioritizing volume utilization and stability as depicted in Figure 2. The process sorts cargo by volume and utilizes a layer-building strategy to place items, dynamically managing a heightmap to ensure structural integrity. A local search mechanism resolves placement failures or makes the placements better by reorienting subsets of boxes. The resulting load plan is rendered in the Unity engine [4], creating a physics-enabled environment where users can perform real-time what-if analysis. This interactive layer allows for drag-and-drop adjustments with immediate validation against physical constraints (e.g., overlaps, overhangs). The system closes the feedback loop by capturing these manual refinements in the database for future packing strategies. A demonstration video of the complete system workflow is available at [Link].

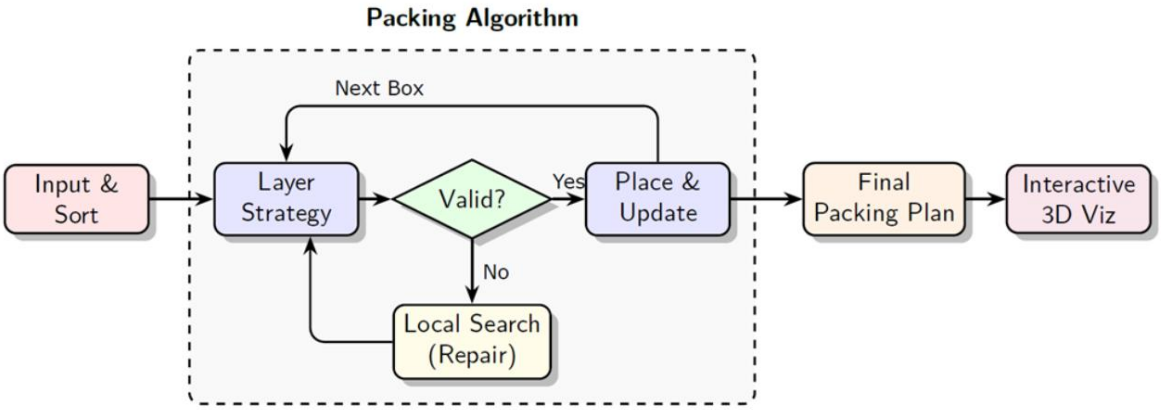


Figure 2: Logic flow of the FraightMind heuristic packing strategy.

Findings

The development and evaluation of FraightMind yielded critical findings regarding AI and human interaction in logistics. We observed that decoupling the LLM from the core algorithm, using it strictly as a semantic translator to extract structured JSON from natural language, effectively eliminated hallucinations, ensuring the heuristic solver received only valid constraints. Chatbot interface helps the user to interact in a conversational flow with the algorithm and the solutions. Performance analysis of the packing algorithm demonstrated that the layer-building strategy combined with local search backtracking achieves a nice balance of computational speed and packing arrangement required for real-time web interaction. The integration of interactive Unity-based visualization enabled what-if analysis capability allowing users to inject tacit operational knowledge, which pure algorithms often miss. We found that real-time constraint validation during manual drag-and-drop adjustments significantly reduced potential loading errors by immediately flagging physical violations like overhangs or instability. Our modular design enables that the packing algorithm can be replaced with future learning based algorithms to take advantage of the human based refined solutions. Ultimately, the results confirm that a collaborative human-AI architecture, where the algorithm handles combinatorial complexity while the human operator manages strategic exceptions, provides a more robust, transparent, and scalable solution than fully automated black box solvers.

Value

Our work presents a holistic framework merging Large Language Models with 3D packing algorithms and physics-based visualization. The novelty lies in FraightMind's architecture, which democratizes interaction with platform based solution for non-technical staff via natural language. The value extends to operations by transforming logistics processes into a collaborative dialogue. By supporting real-time what-if analysis through physics-aware 3D

interaction, the system empowers users to visually verify algorithmic solutions. Additionally, the architecture captures human feedback to create a dataset of practical loading patterns, offering immense value to industry practitioners seeking deployable tools and for researchers exploring human-AI collaboration.

Research limitations/implications

The current iteration of FraightMind relies on a constructive heuristic approach for packing. While this ensures computational speed suitable for real-time web interaction,it does not evolve with data especially the one that we are collecting from the human feedback. Future research implications involve integrating learning-based components capable of adapting placement strategies by leveraging the human feedback loop established in this work. Additionally, there is significant potential to expand the system's scope by integrating many other allied logistics operations, thereby creating a comprehensive end-to-end logistics solution.

Practical implications

FraightMind offers a pathway to modernize logistics by deploying AI as a collaborative assistant, significantly reducing planning time and loading errors while boosting container utilization. Additionally, the system facilitates better cross-functional communication between planning and warehouse teams through standardized, visual digital reporting.

REFERENCES

[1] Apache CouchDB. 2025. https://couchdb.apache.org/. Accessed: 09/02/2026.

[2] LangChain. 2025. https://www.langchain.com/. Accessed: 09/02/2026.

[3] Ollama Team. 2024. Ollama: Run LLMs Locally. https: //ollama.com. Accessed: 09/02/2026.

[4] Unity Technologies. 2023. Unity. Game development platform.

[5] Zhu, Q. et al. 2021. Learning to pack: A data-driven tree search algorithm for large-scale 3d bin packing problem. In Proc. CIKM, 4393–4402.

[6] Hu, H. et al. 2017. Solving a new 3d bin packing problem with deep reinforcement learning method. arXiv preprint arXiv:1708.05930.

The Role of Supplier Loyalty in Building Regenerative and Resilient Agri-Food Supply Chains

Abdulaziz Mardenli[1], Dirk Sackmann[2] Mohammad Alghababsheh[3]

1: University of Applied Sciences Merseburg, Germany; 2: University of Applied Sciences Merseburg, Germany; 3: School of Business, Mutah University, Jordan

Purpose of this paper

The agri-food sector is experiencing mounting pressure to transform conventional supply chains (SCs) into regenerative and resilient systems. This pressure is driven by escalating environmental degradation, including soil depletion and biodiversity loss, growing social challenges such as unequal power relations and declining farm viability, as well as increasing economic and geopolitical uncertainty (Islam and Zheng, 2025). Regenerative SC concepts go beyond conventional sustainability approaches by not only aiming to reduce negative impacts but by actively restoring ecological and social systems. Such concepts emphasise long-term collaboration, trust and shared value creation across SC actors, requiring deeper relational engagement and long-term exchange. However, implementing regenerative practices often involves higher upfront investments, longer time horizons and increased interdependence, which fundamentally alters the nature of buyer-supplier relationships. Despite the shift towards a more relational approach, there is still limited understanding of how particular relational dynamics can promote the development of regenerative and resilient agri-food supply chains (AFSCs) (Meyer *et al.,* 2025). In particular, supplier loyalty, defined as "*long-term supplier commitment"*, remains insufficiently understood. While existing SC research (e.g., Ahmed *et al.,* 2024) has extensively examined transactional efficiency, contractual governance and sustainability performance outcomes, relational foundations such as loyalty are often treated implicitly, reduced to trust or long-term orientation or overlooked as *"soft"* factors. As a result, little is known about how loyalty-based relationships shape stability, risk-sharing and collaborative learning processes that are critical for regenerative transformation. Therefore, the purpose of this study is to examine the role of supplier loyalty in building regenerative and resilient AFSCs. Specifically, the study seeks to uncover how loyalty-based supplier relationships enable the implementation of regenerative practices and resilience across different stages of the AFSC.

Design/methodology/approach

This study uses a qualitative research approach involving interviews with experts from three distinct groups in AFSCs: (a) organisations with indirect influence, such as consulting and advisory firms; (b) organisations with direct influence, including seed producers, farmers, manufacturers, wholesalers and retailers; and (c) organisations in special coordinating positions, particularly agricultural cooperatives. Such a differentiated selection reflects the heterogeneous roles, power structures and interdependencies that characterise contemporary AFSC networks. A total of 17 expert interviews were conducted between January and March 2023 in Germany. Based on their strategic position and decision-making responsibility, interviewees included department heads and managing directors with professional experience ranging from four to 35 years. With a duration ranging from 20 to 70 minutes, interviews were conducted using a mix of digital communication platforms, telephone interviews and in-person meetings, reflecting the post-pandemic transformation of professional interaction. An open-ended approach to interviewing was employed to allow respondents to articulate their perspectives freely while maintaining analytical comparability. To analyse the qualitative data, the GABEK® methodology was employed, supported by the WinRelan® software. GABEK® enables the systematic analysis of complex qualitative data by focusing on semantic meaning and contextual associations (Zelger, 2000).

Findings

The relationship between supplier loyalty and SC resilience emerged consistently across interviews and was described as particularly salient under conditions of heightened uncertainty. In this context, supplier loyalty was not merely portrayed as a relational outcome, but rather as

a critical cognitive and informational resource for regenerative supply chain intelligence. As experts emphasised, long-term relationships facilitate the accumulation of tacit knowledge regarding production conditions, risk factors and partner capabilities, which in turn enhances supply chain actors' ability to anticipate disruptions and align strategic decisions with regenerative objectives. According to experts, loyal suppliers are therefore more willing to adjust production volumes, delivery schedules and quality specifications in response to disruptions. These adaptive behaviours were most evident during periods of extreme uncertainty, such as climate-related production shocks, logistical bottlenecks and regulatory changes. In this context, supplier loyalty was found to mitigate the adverse effects of SC disruptions by facilitating cooperative risk-sharing and informal coordination mechanisms. Rather than relying solely on contractual enforcement, loyal partners were described as engaging in problem-solving behaviours based on mutual understanding and shared interests. The findings further indicate that supplier loyalty is linked to a shift from transactional to relational governance structures. Loyalty-based relationships were highlighted as reducing opportunistic behaviour and fostering a governance environment in which regenerative goals can be jointly pursued. This pattern is particularly relevant given the prevalence of power asymmetries and price pressures that undermine sustainability initiatives in AFSCs. Relatedly, the data reveal that supplier loyalty is associated with a reduced dependence on formal control mechanisms. According to the experts, loyal relationships allow for greater reliance on informal coordination, trust-based agreements and shared norms, which in turn lower coordination costs and enhance responsiveness.

Value

By offering empirical insight into the relational foundations of regenerative and resilient AFSCs, this study provides valuable contributions to both theoretical and practical domains. Moreover, the research transcends the conceptual discourse on regeneration, elucidating the operational dynamics of supplier loyalty as a pivotal facilitator of long-term resilience, ethical governance and adaptive capacity. Building upon extant SC management literature, the study offers an empirical linkage between supplier loyalty and regenerative outcomes, whilst also unveiling qualitative associations between loyalty, resilience and intelligence-driven decision-making. Furthermore, the results of the study demonstrate how loyalty-based relationships can reduce vulnerability to disruptions, support regenerative investments, and enhance collaborative problem-solving across supply networks.

References

Ahmed, A.A.A., Kumar, V.S., Jena, S.K., Nagpal, A., Shukla, P.K. and Balachandar, K., (2024), "Maximizing Profits and Efficiency: The Intersection of AI, Machine Learning, and Supply Chain Financial Management", *Utilization of AI Technology in Supply Chain Management,* pp. 225-239.

Meyer, C., Luiz, J.M., Grutter, A. and Parker, H., (2025), "Disintermediation and Reintermediation of Seafood Supply Chains for Social and Ecological Regeneration", *Journal of Supply Chain Management*, Vol. 0, pp. 1–17

Islam, M. Z. and Zheng, L., (2025), "Why is it necessary to integrate circular economy practices for agri-food sustainability from a global perspective?", *Sustainable Development*, Vol. 33 No. 1, pp. 600-620.

Zelger, J. (2000). Twelve steps of GABEK WinRelan. In: Buber, R., Zelger, J. (Eds.): GABEK II. Zur Qualitativen Forschung. *On Qualitative Research, Studienverlag*. Innsbruck, Wien, pp. 205-220.

Operationalizing Climate Resilience in Container Port Logistics: Evidence from European Ports

Meysam Shaverdi, Mohamed Benmerikhi

EDHEC Business School, Lille, France

Purpose of this paper

Ports and container terminals are critical nodes in global logistics systems, yet they are increasingly exposed to climate-related risks that threaten operational continuity, infrastructure reliability, and supply chain performance. Climate change has intensified hazards such as flooding, sea-level rise, heatwaves, extreme rainfall, and strong winds, particularly in coastal and estuarine environments. These risks directly affect terminal operations, asset lifecycles, safety conditions, and multimodal connectivity, while also generating cascading disruptions across wider logistics networks and ecosystems. Despite growing awareness of these challenges, climate resilience in port logistics is often addressed through reactive disruption management rather than integrated, data-driven operational strategies.

The purpose of this paper is to examine how climate resilience can be operationalised within container port logistics through the deployment of digital technologies, structured risk assessment, and real-time decision-support systems. The paper focuses on European ports implemented at the container terminals, which serves as a demonstrator for embedding climate risk management into day-to-day terminal operations. Specifically, the paper aims to (i) identify the main climate-related risks affecting container terminal infrastructure and operations in Ports, (ii) analyse how digital platforms, sensor networks, and operational data are integrated to support early warning, impact assessment, and adaptive response, and (iii) assess the implications of these measures for logistics resilience and supply chain continuity.

By addressing these aims, the paper responds to the need for empirical studies that move beyond conceptual discussions normative recommendations of resilience and provide practical insights into how ports can adapt to climate uncertainty. The pilot ports offer a timely and relevant case, combining ongoing terminal modernisation with climate-resilience deployment in a complex, urban, and multimodal logistics context.

Design/methodology/approach

This paper adopts a qualitative, case-based research design with a systems-oriented perspective to analyse the deployment of climate-resilience measures within the ports. The study is grounded in the SAFRAN risk assessment methodology, which provides an evidence-based approach for identifying climate hazards, assessing asset exposure and vulnerability, and analysing potential cascading failures across interconnected systems. This methodology is particularly appropriate for port logistics environments, where infrastructure, operations, and external conditions are tightly coupled.

The empirical material is drawn from the design and early-stage implementation of risks measures at the Yilport Liscont container terminal. Data sources include climate risk assessments, port infrastructure analyses, and technical descriptions of the digital architecture supporting the pilot. The analysis focuses on how different digital components are integrated, including the Capacity Calculation Module for operational forecasting, the NextPort digital platform for dashboards and decision support, and the APL and MARLO systems for governance and sensor management. These internal systems are connected to terminal operational data as well as external information sources such as weather forecasts, tidal data, traffic conditions, and AIS data.

The methodological approach emphasises the operational lifecycle of climate-related disruptions in port logistics. Use cases are structured around six sequential stages: event detection, early warning, risk and impact estimation, contingency planning, response and adaptation, and monitoring and feedback. This process-oriented perspective enables the study to capture how resilience measures support logistics decision-making before, during, and after disruptive

events. The theoretical scope of the paper lies at the intersection of logistics resilience, risk management, and digitalisation in port and terminal operations.

Findings

The analysis of European ports provides several key findings regarding the operationalization of climate resilience in container port logistics. First, climate-related risks at ports terminals are highly multidimensional. Flooding, storm surge, and intense rainfall threaten quay structures, drainage systems, and yard accessibility, while heatwaves and extreme temperatures affect crane performance, electrical equipment, and energy systems. Strong winds further disrupt navigation and cargo handling activities. These hazards do not operate in isolation but interact across infrastructure, operations, and multimodal transport connections, thus increasing the likelihood of cascading disruptions.

Second, the findings highlight the central role of digital integration in enhancing resilience. The combination of real-time sensors, terminal operational data, and external environmental information significantly improves situational awareness and early risk detection. The NextPort platform and Capacity Calculation Module enable dynamic assessment of terminal capacity under different climate scenarios, enabling operators to anticipate disruptions and adjust operational plans proactively. This represents a shift from static contingency planning to adaptive, data-driven decision-making in terminal logistics.

Third, the structured use-case framework adopted in the ports supports a systematic response to climate events. Linking early warning systems to predefined contingency and response actions reduces uncertainty and response time during disruptions. However, the findings also show that resilience outcomes depend not only on technology but on organisational coordination, data interoperability, and governance arrangements among terminal operators, port authorities, and technology providers. Without these ecosystem components, the potential benefits of digital tools remain constrained.

Value

This paper provides original value by offering empirical evidence on how climate resilience can be embedded into container terminal logistics through an integrated digital and operational framework. Unlike much of the existing literature, which remains largely conceptual or policy-oriented, the study demonstrates how resilience strategies are translated into concrete operational processes at the terminal level. The ports illustrates a scalable and transferable model for combining risk assessment, real-time monitoring, and decision support in port logistics. The value of the paper extends to multiple audiences. For logistics researchers, it advances understanding of resilience as an operational capability supported by digitalisation. For practitioners, it provides a practical reference for designing and implementing climate-resilient terminal operations. For policymakers and port authorities, the findings highlight the importance of coordinated, data-driven approaches to climate adaptation in critical logistics infrastructure.

Research limitations/implications

The study has several limitations. First, it focuses on the design and early deployment stages of the ports, meaning that long-term operational performance outcomes and quantitative resilience metrics are not yet fully observable. Second, as a single case study, the findings may not be directly generalisable to all port contexts, particularly those with different governance structures or climatic conditions. Future research should include longitudinal evaluations and comparative studies across multiple ports to assess scalability, transferability, and long-term effectiveness.

Practical implications

The findings suggest that climate resilience should be integrated into core terminal management and investment decisions rather than treated as a standalone environmental concern. Port authorities and terminal operators should prioritise interoperable digital platforms, sensor-driven monitoring, and structured response workflows to enhance preparedness and recovery. The ports shows that proactive climate risk management can strengthen operational reliability, reduce disruption impacts, and improve the resilience of logistics networks often dependent on container terminal performance.

Quantifying the Value of Age-Information in Pharmaceutical Supply Chain Network Design: A Deterministic Model with Shelf-Life Constraints

Yukun Zhang, Chandra Irawan, Fengfeng Xie

University of Nottingham Ningbo China, China

Purpose of this paper

The pharmaceutical industry is currently facing a "Triple Crisis": proliferating economic costs due to ineffective supply chains, social injustice in medicine acquisition, and environmental issues related to the improper pharmaceutical waste processing. Unlike ordinary products, medicines are characterised by strict perishability constraints and toxicity upon expiration. The World Health Organisation stated that a significant portion of medical waste was caused by mismatches between demand and supply and inefficient inventory management. In response, the Circular Economy (CE) has been proposed to transition the industry to a closed-loop system (Tirkolaee et al., 2022). However, a prerequisite for a viable Closed-Loop Supply Chain is a robust forward logistics network that can precisely manage inventory shelf-life.

The current literature in supply chain network design (e.g., Shah, 2004; Zahiri et al., 2017) usually sees inventories as homogeneous pools or implements simplified decay rates, ignoring the shelf-life (s) of inventory batches (Nahmias, 1982). This oversimplification leads to severe risk underestimations of wastage and stockouts in strategic planning. Hence, our research aims to bridge the gap between microscopic perishable inventory management and macroscopic strategic network design by designing a deterministic Mixed-Integer Linear Programming (MILP) model to determine the optimal network configuration while explicitly minimising end-of-life wastage. Also, we introduce a novel metric, the Value of Age-Information (VoAI), measuring economic losses from neglecting shelf-life conditions of medicines when designing supply chain networks.

Design/methodology/approach

Our study provides a multi-echelon, product-and-period MILP model with a network structure comprising Wholesalers (L), Stores/Hospitals (N), and Customers (C). Unlike traditional models that only track inventory quantity (y_t), our model introduces the age index (s) to track the physical trajectories of stocks. The logic of the age index is that the inventory of age s at time t physically transitions to age $s+1$ at time $t+1$ ($y_{l,p,s,t} \rightarrow y_{l,p,s+1,t+1}$), unless shipped or sold. A strict boundary condition is applied: when the age s reaches the maximum shelf-life θ_p, the inventory is mathematically forced out of the available pool and recorded as wastage (w).
To validate the model and illustrate the significance of the "Age Information", a comparison test between two model variations, the Age-Based Model (Model A) with full shelf-life constraints and the Traditional Model (Model B) without age constraints, treating inventory homogeneously with infinite shelf-life, is conducted. Solving Model B to fix the network design structure (service links and facility locations), these strategic decisions are then imported into Model A to compute the "realistic cost". Finally, this "realistic cost" is compared with the "optimal cost" calculated independently by Model A, with the difference constituting the VoAI. The model is implemented in Python through Pyomo and solved through the CPLEX solver.

Findings

Tested by the dataset, including $2L$, $3N$, $6C$, 4 product types (P) and 12 time-periods (T), the outputs of the model present three primary findings:

Inevitable Wastage: The optimal solution yielded a total cost of 631,119.11. Contrary to expectations of avoiding waste, the optimisation generated 661 units of waste. Observing locations of waste (e.g., Wholesaler l_2 generates waste for p_3 at early stages; n_3 experiences

expirations of p_3 at the third stage), they indicate wastages not randomly appearing but being induced by network constraints.

Physical Capacity vs Shelf-life: As shown, waste occurs when capacity constraints prevent the system from simultaneously storing "aged" inventory and receiving "fresh" inventory needed for future surges in demand. Hence, to prevent stockouts during future peak demand periods, the model removes older (but still valid) inventory to free up cargo capacity, a trade-off that traditional models fail to capture.

Significant VoAI: The positive VoAI calculated by the comparison test demonstrates that Model B underestimates total costs by ignoring potential spoilage. When implementing the strategic network design derived from Model B in the simulation under realistic shelf-life conditions, the actual cost was higher than that of Model A. Since the traditional mode is incapable of foreseeing expirations, it results in passive and urgent reactions and procurements, increasing costs. This confirms that integrating shelf-life constraints at the design phase significantly improves operational efficiency.

Value

Theoretically, this work bridges gaps between strategic network design and operational perishable inventory management. Unlike models using hypothetical decay rates, this framework evidently traces the shelf-life of inventory, enabling the identification of when, where, and quantities of expired products within the network. Defining VoAI, it also provides a novel methodological tool to quantify the importance of data granularity. Practically, the study offers supply chain managers a decision-support tool to visualise the hidden waste. It shifts the management focus from simple "safety stock" construction (with the risk of expiration) to "flow velocity" management, providing blueprints for the pharmaceutical industry's transition to CE.

Research limitations/implications

Even validating the "ageing engine" mechanism, this model simplifies the stochastic volatility of actual demands. Therefore, to address spoilage, the model should be extended into a Closed-Loop Supply Chain, adding reverse logistics and waste recycling. Besides, assuring robustness against uncertainty, stochastic programming or fuzzy-based approaches are necessary. Finally, as NP-hard problems, practical implementations require incorporating advanced mathematical methods, optimising the effectiveness and solubility of solvers (Goodarzian et al., 2021).

Practical implications

The result illustrates the relationship between capacity and economic losses. Limited capacity pushes companies to discard still-usable medicines for incoming stock, meaning that investments in storage and/or logistics may be more effective at reducing waste than simply optimising procurement. Also, the study warns that excessively reducing inventory to avoid expiration may increase stockout risks during demand spikes, highlighting the priority of patients' drug availability over waste-reduction goals.

References

Goodarzian, F., Taleizadeh, A.A., Ghasemi, P., Abraham, A., 2021. An integrated sustainable medical supply chain network during COVID-19. Eng. Appl. Artif. Intell. 100, 104188.

Nahmias, S., 1982. Perishable Inventory Theory: A Review. Operations Research 30, 680–708.

Shah, N., 2004. Pharmaceutical supply chains: key issues and strategies for optimisation. Comput. Chem. Eng. 28, 929–941. 、

Tirkolaee, E.B., Goli, A., Mirjalili, S., 2022. Circular economy application in designing sustainable medical waste management systems. Environ Sci Pollut Res Int 29, 79667–79668.

Zahiri, B., Zhuang, J., Mohammadi, M., 2017. Toward an integrated sustainable-resilient supply chain: A pharmaceutical case study. Transportation Research Part E: Logistics and Transportation Review 103, 109–142.

LOGISTICS CONNECTIVITY

Evaluating the Impact of Logistics Service Quality on "Silver" Economy's Customer Satisfaction: A Case Study on E-Commerce in Northern Region of Vietnam

Tran Bao Huy, Nguyen Lan Anh

VNU University of Economics and Business, Vietnam

Abstract

As Vietnam's e-commerce landscape matures in the post-pandemic era, a powerful yet often overlooked demographic is stepping into the digital spotlight: the "Silver" consumer. While the country's digital transformation is accelerating, the logistics infrastructure—the physical heartbeat of e-commerce—must now adapt to the unique needs of an ageing society. This study investigates how logistics service quality (LSQ) directly shapes the satisfaction and trust of older shoppers in this booming market.

Building on the classic framework by Mentzer et al. (1999), we analysed four critical pillars of the delivery experience: staff service quality, communication service quality, delivery service quality, and after-sales service quality. Through an empirical study of 466 Vietnamese "Silver" age consumers, we utilized factor analysis and multi-linear regression to map out these relationships.

Our findings reveal a powerful truth: for the Silver Economy, logistics is not just about speed—it is about service quality. We found a direct, positive correlation between high-standard logistics and customer satisfaction. By prioritizing age-inclusive logistics, businesses can unlock the massive potential of the Silver Economy and build lasting loyalty in one of the world's most dynamic emerging markets.

Keyword: Silver Economy, Customer Satisfaction, E-commerce Logistics service quality, Factor analysis.

Determinants of Rail Transport Development in Developing Landlocked Countries: The Case of North Macedonia

Jakub Donski-Lesiuk

University of Lodz, Poland

Purpose of this paper

The North Macedonia, classified as a developing country, is aspiring to EU membership (EU Strategic Agenda 2024-2029 of June 2024) and is supported by the World Bank in terms of infrastructure development. For the period 2024-2028, support in the amount of USD 437.8 million has been approved for the state, with an additional USD 30 million earmarked for "Regional Trade and Transport Facilitation". These funds are intended to ensure increased competitiveness and sustainable development, social inclusion and resilience, with an emphasis on competitiveness, human capital development and environmental sustainability.

The modernization of the Macedonian railway system began in 2015-2017 (work on Corridor VIII, the Kriva Palanka – the border with Bulgaria), but the consequences of the COVID-19 pandemic have slowed down the processes related to the revitalization and expansion of the existing network. Currently, there are signs of a lack of hope for the successful launch of a rail transport system that would serve economic and social needs. This may be linked to the long-term marginalization of this mode of transport and the parallel development of road transport.

The case of North Macedonia, which is, on the one hand, a country with uneven development of transport sectors (with a clear dominance of road transport)[1] and, on the other hand, a consequence of political changes, points to the particular importance of rail transport development for landlocked countries that rely on imports.

Design/methodology/approach

The study conducted in North Macedonia involved identifying the determinants of rail transport development with the aim of increasing the efficiency of the flow handling system, including international flows. These take place in an East – West (from Bulgaria through Macedonia/Serbia towards the Western Balkans) and North – South (from Greece towards Kosovo/Serbia), and in the absence of an effective logistics system, they will be directed to other (alternative) routes with a higher degree of readiness to provide transport and related services (customs, forwarding, etc.).

The study is based on the Delphi method and included:

1) collection of secondary data, expert interviews, and observations at logistics service points,
2) analysis and systematization of the collected materials,
3) consultation with transport/logistics experts on the correctness of the preliminary conclusions,
4) development of final conclusions and recommendations with particular emphasis on practical implications.

The analysis covered database resources and documents content, including logistics sector development plans, which made it possible to verify the data obtained in terms of the scope and subject matter of the projects declared by the interested parties, as well as to collect data from the participatory observations "on the ground", and interviews with experts. The use of this approach made possible to raise the level of the final conclusions[2], while the comparison of the results of the Delphi study with experts ensured that the results obtained are grounded in reality and, therefore, reliable.

Findings

While the assessment of the current state of railway infrastructure is based on objective indicators such as the capacity of railway sections, availability of rolling stock, punctuality of traffic, and transport safety, the experts pointed to a number of phenomena which, in a broader sense , have had and continue to have an impact on the scope of plans for the development of the railway sector in North Macedonia and their implementation. It should be emphasized that the experts' findings often deviated from a strictly transport-related assessment, leading to broader conclusions. These include the generally low level of competence of public authorities (including sectoral authorities responsible for transport policy-making), their insufficient involvement in solving economic problems, and their low capacity for action.

Participatory observations allowed for the identification of many organizational problems that constantly occur on the railway network, including: unrealistic train schedules, insufficient rolling stock that is unable to handle the accepted connection system (including freight connections for which there are not enough locomotives to drive trains to/from ports), low-quality infrastructure causing delays, including—particularly troublesome—cascading delays (better known as the domino effect).

While the conclusions do not seem to give reason for a positive assessment of the current performance of the railway sector, some experts remain convinced that the situation has a chance to improve in the future.

Value

The value of the study lies in the fact that it was conducted in a country which, on the one hand, is landlocked and has a relatively underdeveloped railway network (the total length of operational railway lines is 699 km), and on the other hand is a developing country aspiring to membership in the European Union, with close economic relations with the EU countries (those accounted for 78.6% of total exports and 49.1% of imports)[3]. In addition, the United Kingdom accounts for 11.1% of imports to Macedonia[4]. Meanwhile, the only EU country with which rail connectivity is provided is Greece (apart from Kosovo and Serbia). At the same time, the main seaport handling international trade to/from Macedonia is Thessaloniki.

The study also points to the existence of significant potential for development in the country's railway sector, which, struggling with the consequences of the relatively recent past, unlike other countries (e.g., neighboring Serbia), has not yet managed to implement a coherent sustainable transport policy.

Research limitations/implications

Although a relatively small group of experts (9) took part in the study, there is still a chance that their number will increase by the time the results are published. This is due to the niche nature of the railway industry in a country where rail transport is not very popular and where, due to local circumstances, people are very cautious about commenting on issues that require an assessment of political actions.

References

[1] Jovanović, B., Zlatanović, A., Kluge, S., Zec, A., Ibrahimi, M., Brašanac, M., Vasić, J., Šelmić, R., Mima, R., Tomić, V., Ćulafić, B., Lalović, O., Manova Stavreska, A., Nikolova, S., Rajič, A., & Alihodžić, B. (2024). *Transforming the Western Balkans through Near-shoring and Decarbonisation*. The Vienna Institute for International Economic Studies and Western Balkans 6 Chamber Investment Forum.

[2] Gephart, R. (2004). *Qualitative Research and the Academy of Management Journal*. Academy of Management Journal, Vol. 47, №4, pp. 454–462.

[3] Kovachevska Stefanova, S., Ma, M., Popescu, A., & Sulejmani, F. (2025). *Impact of international shocks on North Macedonia and the Western Balkans*. International Monetary Fund Selected Issues Paper (SIP/2025/065).

[4] *European Union, Trade with North Macedonia*. Directorate General Trade and Economic Security, 08-05-2025, available at https://webgate.ec.europa.eu/isdb_results/factsheets/country/details_north-macedonia_en.pdf, Accessed: 23.02.2026.

MATRA: A National Agent-Based Model for Freight System Resilience and Sustainability

Dhanan Sarwo Utomo, Philip Greening

Heriot Watt University, United Kingdom

Purpose of this paper

The purpose of this paper is to contribute to the TransiT research programme (https://transit.ac.uk/), which seeks to support the development of a sustainable and resilient future transport system in the United Kingdom. A central objective of TransiT is the creation of a national-scale digital twin of the UK transport and logistics system, built upon large-scale agent-based models (ABMs). These ABMs are designed to run thousands of scenarios, generating extensive simulation-derived data pools from which optimal and robust system configurations can be identified. By exploring alternative infrastructural, operational, and behavioural arrangements, the programme aims to inform long-term strategies for decarbonisation and resilience.

A key innovation of TransiT is the planned integration of real-world sensor data into the digital twin. Signals indicating disruption in the physical system will trigger machine-learning models that interrogate the data pools to recommend effective mitigation or response actions, creating a dynamic decision-support capability.

This paper presents the development of the Multi-Agent Transport Resilience and Adaptation (MATRA) Model, one of TransiT's core ABMs. MATRA is a national-scale model designed to identify least-cost pathways towards a resilient and sustainable freight system. The current version focuses on the road freight sector and builds on earlier last-mile (Utomo et al., 2021) and long-haul delivery ABMs (Greening et al., 2024). Designed to be generalisable and to function with minimal input data, MATRA is implemented in Python and can operate in platforms such as Google Colab or, as demonstrated in this study, a High-Performance Computing environment.

Methodology

The development of MATRA began with constructing a mathematical representation of the decision-making processes of each agent. Two core agent types (transport managers and charge point operators (CPOs)) have been fully implemented. Transport managers determine how payloads should be moved between company facilities (such as ports, airports, depots, stores, or delivery offices) and customers (warehouses, retail outlets, or households) while minimising overall cost. Their decisions include the number of vehicles required, daily routes or trips, whether customers are served by single or multiple vehicles, optimal sequencing of collections and deliveries, and, for electric vehicles, the timing and location of charging. These requirements led to a modular mathematical structure capable of handling both routing logic and energy constraints.

To reflect transitions toward more sustainable fleets, the CPO agent models decisions on how many charging bays to operate, which charger power levels to deploy, and what prices to set. After defining individual agent logic, interactions between agents were formulated. Vehicles interact through queuing dynamics at charging bays and connect with the wider energy system via charging infrastructure, allowing emergent system-level behaviour to arise from localised decisions.

The model is currently parameterised using journey data from logistics operators curated since 2019, though such data are difficult to obtain due to commercial sensitivity. However, because MATRA is designed to operate with minimal inputs, future calibration can also be conducted through expert interviews where detailed operational data are unavailable.

Findings

The initial implementation of MATRA demonstrates its ability to evaluate a broad range of scenarios relevant to the future evolution of freight transport systems. The model supports systematic experimentation across multiple factors. First, vehicle choice can be varied to compare fleets composed of internal combustion engine (ICE) vehicles, fully electric vehicles (EVs), or mixed fleets, with future extensions allowing heterogeneous characteristics such as differing payload capacities. Second, depot charging availability can be tested either through manual configuration or optimisation routines that retain only highly utilised assets. Equivalent flexibility applies to public charging stations, whose locations may also be manually defined or optimised.

Third, MATRA incorporates electric road system (ERS) scenarios, drawing on established light, medium, and heavy infrastructure configurations (de Saxe et al., 2023). Fourth, the model allows exploration of charging station design parameters, including the number of charging bays, charger power, and opening hours, which may vary across sites or be optimised. Fifth, MATRA can simulate electricity disruptions of differing magnitudes, durations, and spatial impacts, affecting depots, public chargers, ERS infrastructure, or combinations thereof.

Across these scenarios, MATRA generates a wide set of economic, environmental, and social metrics, including logistics costs, operational efficiency (distance, time, and queuing delays), EV adoption levels, congestion proxies, and delivery delays. Initial sensitivity analyses and theoretical validation indicate that agents respond adaptively to different incentive structures and that logistics operators adjust their optimal EV uptake according to the broader system conditions.

Value

This paper contributes value by introducing one of the first national-scale agent-based models designed to analyse the resilience and sustainability of future freight transport in the United Kingdom. MATRA integrates flexible agent-level decision-making with system-wide interactions, enabling assessment of operational, economic, environmental, and social outcomes under both normal and disrupted conditions. Its ability to examine alternative vehicle technologies, infrastructure strategies, and disruption scenarios offers a novel framework for understanding pathways towards low-carbon logistics. The model’s generalisable design and minimal data requirements further enhance its utility, allowing policymakers, researchers, and industry stakeholders to explore strategic planning questions even where detailed operational datasets are limited.

Research limitations

MATRA currently models only road freight and two agent types, limiting representation of broader system actors such as energy networks or multimodal operators. Simplified assumptions on charging behaviour, operating hours, and disruption timing reduce real-world fidelity. Even so, the model provides a solid basis for future extensions, including multimodal modelling, richer infrastructure optimisation, and analysis of large-scale behavioural and resilience dynamics.

References

de Saxe, C., Ainalis, D., Miles, J., Greening, P., Gripton, A., Thorne, C., & Cebon, D. (2023). An electric road system or big batteries: Implications for UK road freight. Transportation Engineering, 14, 100210. https://doi.org/10.1016/j.treng.2023.100210

Greening, P., Utomo, D. S., O'Connor, Z., Logan, A., Elombo, A., Bartholomew, M., Andrews, J., & Smith, A. (2024). Towards Zero Emission HGV Infrastructure in Scotland.

Utomo, D. S., Gripton, A., & Greening, P. (2021). Analysing charging strategies for electric LGV in grocery delivery operation using agent-based modelling: An initial case study in the United Kingdom. Transportation Research Part E: Logistics and Transportation Review, 148, 102269. https://doi.org/10.1016/j.tre.2021.102269

Last-Mile Pharmaceutical Distribution and Spatial Demand Alignment: A Network-Based Accessibility Analysis of Elderly Populations in Taipei City

Hsien-Mei Wang[1], Hui-Chieh Li[2]

1: Department of Transportation Management, Tamkang University, Taiwan; 2: Department of Business Administration, National Taipei University of Business, Taiwan

Purpose of this Paper

Urban healthcare provision can be examined through the lens of service supply chain management. In this perspective, healthcare facilities represent distribution nodes embedded within transportation networks that connect supply to geographically dispersed demand. Community pharmacies, although commonly viewed as retail health outlets, also function as decentralized last-mile distribution points for pharmaceutical products and consultation services. Their spatial placement influences not only market coverage but also equity in access to essential medication.

In aging societies, elderly populations represent a key demand segment with frequent prescription needs, chronic disease management, and limited mobility. As their proportion grows, last-mile pharmaceutical distribution efficiency becomes a critical operational issue beyond public health. Aggregate distribution structures may seem adequate but yield uneven coverage when factoring in mobility constraints and street-network conditions. From a supply chain perspective, this highlights misalignment between facility locations and spatial demand patterns.

Spatial accessibility has been widely studied in health geography and regional planning (Guagliardo, 2004). However, traditional measures often rely on Euclidean distance or simple provider-to-population ratios, which may overstate effective service reach. More recent research emphasizes network-based measurement and the interaction between supply nodes and demand points (Luo & Qi, 2009; Stacherl et al., 2023; Mao & Nekorchuk, 2013). Parallel developments in healthcare logistics research examine network resilience and distribution efficiency under demographic change(Paul & Chowdhury, 2022; Azadeh et al., 2021). Despite this progress, limited attention has been given to community pharmacies as components of decentralized healthcare distribution systems within high-density Asian cities.

This study examines last-mile pharmaceutical distribution in Taipei City, assessing whether community pharmacies' spatial reach aligns with elderly resident distribution. Pharmacies are conceptualized as decentralized distribution nodes within the urban road network, rather than mere retail outlets. The central question is whether existing structures provide adequate network-based coverage to high-elderly villages under walking-distance constraints.

Accessibility is measured as a village-level coverage ratio: the proportion of sampled road network points within 300 meters of any pharmacy. This infrastructure metric gauges effective distribution reach per village, then compared against elderly population density to evaluate spatial alignment between service and demand.

By decoupling network coverage from demographic assessment, the framework identifies misalignment areas, advancing discussions on decentralized distribution, spatial allocation, and last-mile performance in aging cities.

Design/Methodology/Approach

The analytical framework defines pharmacies as supply nodes and the urban road network as the distribution infrastructure through which service reach is realized. Accessibility is measured at the village level as the proportion of sampled road network points that fall within a 300-meter walking distance of any pharmacy relative to the total sampled network points within that village. This coverage-based indicator reflects the spatial extent of last-mile service reach within each village-level administrative boundary

The study area is Taipei City, a dense metropolitan region characterized by heterogeneous urban morphology and a rapidly increasing proportion of residents aged 65 and above. Pharmacy location data and elderly population statistics are compiled from official government sources. The road network dataset includes pedestrian-accessible streets to reflect realistic travel conditions.

A GIS-based network service area model is constructed to estimate last-mile coverage. Service areas are generated using walking-distance thresholds that represent plausible mobility conditions for older adults. Multiple threshold scenarios are applied in order to examine sensitivity to mobility assumptions. This approach avoids reliance on straight-line buffers and instead measures coverage along actual street connections, thereby representing travel constraints more accurately (Guagliardo, 2004).

The resulting coverage ratios are compared across villages to assess spatial variation in last-mile service reach. Spatial overlap among pharmacy service areas is examined to identify areas with concentrated supply coverage. Villages characterized by high elderly population density but low network coverage ratios are identified as potential service gaps, indicating a spatial misalignment between infrastructure reach and demographic demand.

Model validation includes verification of network topology, inspection of disconnected segments, and sensitivity testing of impedance parameters. These procedures are conducted to assess the stability of accessibility results under reasonable variations in modeling assumptions. The overall analytical strategy aligns with recent methodological developments that emphasize scenario testing and network-constrained evaluation in healthcare accessibility research(Chen et al., 2021; Yu et al., 2022; Stacherl et al., 2023).

This study's contribution lies in redefining network-based coverage as a measure of last-mile distribution performance within a decentralized service network. By conceptualizing service areas as representations of effective network reach, rather than as geometric proximity zones, the analysis integrates spatial accessibility modeling with distribution performance assessment.

Findings (Expected Outcomes)

The analysis is also expected to demonstrate that facility counts alone do not provide an accurate representation of distribution performance. Although Taipei City may have a relatively high number of pharmacies per capita, network-based evaluation may reveal localized mismatches between supply nodes and elderly demand clusters. Such mismatches may arise from historical site selection patterns driven by commercial considerations rather than demographic alignment.

Sensitivity analysis is expected to show that reductions in walking thresholds lead to a measurable decline in effective coverage. This outcome would reflect the impact of mobility constraints on service reach and reinforce findings from recent accessibility research. In practical terms, elderly residents located near steep terrain or disconnected street segments may experience lower effective access despite short straight-line distances.

Overall, the results are expected to indicate that evaluation of pharmaceutical distribution systems in aging cities requires explicit consideration of network structure, demand concentration, and realistic mobility assumptions. The findings may suggest that certain districts exhibit supply concentration beyond what is required to achieve adequate coverage, while others face relative undersupply. From a supply chain perspective, this pattern represents inefficiency in spatial allocation rather than an absolute shortage of facilities.

Value

This study contributes to transportation and logistics research by examining community pharmacies as components of a decentralized last-mile distribution system. Rather than introducing a new accessibility metric, it interprets network-based coverage intensity—measured as the proportion of reachable road network points within village boundaries—as an indicator of distribution reach. By separating infrastructure coverage measurement from demographic comparison, the analysis provides a structured approach to evaluating spatial alignment between service reach and elderly population density. The case of Taipei City offers empirical evidence from a high-density metropolitan environment undergoing rapid demographic aging.

Research Limitations and Implications

This study evaluates last-mile pharmaceutical distribution using a network-based coverage ratio derived from sampled road network points. The analysis focuses on spatial reach and does not incorporate operational characteristics such as prescription volume, pharmacy capacity, inventory levels, or service hours. As a result, the findings reflect infrastructure-based distribution reach rather than full operational performance.

Future research could extend this framework by integrating demand-weighted accessibility measures, pharmacy capacity constraints, or facility location optimization models to evaluate potential reallocation or expansion strategies. Incorporating time-dependent travel impedance or multimodal transport options may also improve the assessment of distribution performance under varying conditions. Such extensions would allow for a more comprehensive evaluation of pharmaceutical distribution efficiency in aging urban environments.

Practical Implications

From a transportation and logistics perspective, the findings indicate that evaluation of pharmaceutical distribution systems should consider network-based service reach rather than relying solely on aggregate facility counts. Coverage intensity measured at the village level provides a structured method for identifying spatial differences in last-mile infrastructure reach.

By comparing coverage ratios with elderly population density, planners can detect areas where infrastructure coverage is relatively low despite high demographic demand. This approach supports more targeted decisions regarding pharmacy placement, complementary service provision, or alternative delivery mechanisms.

In aging metropolitan settings, aligning distribution infrastructure with demand concentration may enhance service equity and efficiency. This study's network-based coverage framework provides a replicable diagnostic tool for decentralized service systems where mobility constraints limit access.

Reference

Azadeh, A., Farahani, R. Z., Asadzadeh, S. M., & Zarrin, M. (2021). A sustainable-resilient healthcare network for handling COVID-19 outbreak. Annals of Operations Research. https://doi.org/10.1007/s10479-021-04238-2

Chen, Y., Wang, J., & Jin, F. (2021). Network constrained and classified spatial pattern analysis of healthcare accessibility in Beijing, China. International Journal of Environmental Research and Public Health, 18(5), 2593.

Guagliardo, M. F. (2004). Spatial accessibility of primary care: Concepts, methods and challenges. *International Journal of Health Geographics, 3*(1), 3.

Luo, W., & Qi, Y. (2009). An enhanced two-step floating catchment area (E2SFCA) method for measuring spatial accessibility to primary care physicians. *Health & Place, 15*(4), 1100–1107.

Mao, L., & Nekorchuk, D. (2013). Measuring spatial accessibility to healthcare for populations with multiple transportation modes. *Health & Place, 24*, 115–122.

Paul, S. K., & Chowdhury, P. (2022). Improving resilience of the healthcare supply chain in a pandemic: Evidence from the COVID-19 outbreak in India. Journal of Business Research, 139, 425–438.

Stacherl, B., Kühling, J., & Wübker, A. (2023). Gravity models for potential spatial healthcare access measurement: A systematic methodological review. BMC Health Services Research, 23, 1324.

Yu, J., Zhang, X., & Gong, H. (2022). Older adults' access to and satisfaction with primary hospitals in urban China: A case study of Hefei City. Frontiers in Public Health, 10, 866234.

Characteristics of Integrated Seaport–Dry Port Systems in Hinterland Logistics: A TCCM-Based Literature Review

My Tran, Lam Nguyen, Son Nguyen

RMIT University, Vietnam

Purpose of this paper

Terminal congestion and decarbonization pressures are prompting many ports to rely on inland terminals and dry ports to manage cargo growth and extend their hinterlands (Notteboom et al. 2026). The integration of seaports and dry ports has become an increasingly prominent topic as ports deepen their connections with inland logistics networks, yet there is still a limited consensus of how this integration is studied in the academic literature. The study systematically review sea – dry port literature to addresses three objective: (1) to clarify how existing studies conceptualize and operationalize the characteristics of dry port integration, (2) to synthesize research trends in the study of seaport–dry port relationships over time, and across regions and port system configurations, and (3) to structure an agenda for future research on seaport–dry port integration and port–hinterland logistics In doing so, the paper responds to a fragmented body of work in which seaport–dry port integration. The overarching purpose of this research is to build a conceptual framework that links drivers of seaport–dry port integration to the operational, environmental, and regional development outcome, thereby reframing this knowledge in a way that supports more coherent theoretical development and more informed empirical and policy work on port–hinterland integration.

Design/methodology/approach

The study is designed to capture the evolution of seaport and dry port research. It adopts a systematic literature review following the PRISMA 2020 guideline (Page et al. 2021), ensuring transparent and replicable screening and selection of studies as well as reporting process Peer-reviewed journal articles in the period of 2003 until 2025, using search term structed of "seaport" AND "dry port" with expansion among their synonym strings, are retrieved from Scopus and Web of Science. Selection criteria focusing on conceptual, empirical, and modelling work that explicitly addresses the relationship between seaport and dry port in regional or national contexts. The Theory–Context–Characteristics–Methodology (TCCM) framework will be used to structure the review (Paul and Criado 2020). The analysis section will include (1) theoretical lenses applied (e.g. supply chain management, network design, environmental economics), (2) contextual settings (e.g. regions, port systems), (3) characteristics of seaport- dry port integration (e.g. roles, drivers, governance form), and (4) methodological approaches (e.g. qualitative, quantitative or mixed-method). This structured coding enables comparative analysis across studies and supports the development of a conceptual framework that links integration characteristics to outcomes and identifies under-explored theoretical, contextual, and methodological combinations, thereby revealing patterns and gaps that might remain hidden in a narrative review.

Findings

First, the study is expected to identify different theoretical lenses used to frame seaport–dry port integration. At the same time, it is to show which theoretical applications remain fragmented. Understanding the existing theoretical landscape is a prerequisite for building more coherent explanations of integration phenomena and for avoiding duplication of efforts in future studies. Second, the study will reveal how seaport–dry port relationships are studied across regions and diverse port–hinterland systems, allowing the analysis of researched contexts. The study will delineate existing forms of integration, the degree to which knowledge is generalized beyond specific cases and areas with limited empirical evidence.

Third, the study will derive a conceptual framework of "seaport- dry port integration". This central construct comprises several interrelated dimensions that collectively determine the contribution of integration to the port-hinterland logistics system.

Finally, the review will document methodological approach that dominante the seaport–dry port literature, explore why particular methodological choices have been favored, and how this constrains or enables cumulative knowledge development. This finding can point to underused methods and study designs that may be needed to address identified gaps, such as limited longitudinal, multi-actor, or cross-regional analyses of seaport–dry port integration.

Value

The research's value lies in offering a systematic synthesis of seaport–dry port integration research. It consolidates fragmented and case-based evidence into a coherent framework that clarifies the main dimensions and configurations of seaport - dry port integration in port–hinterland logistics systems. For academics, the review provides a structured basis for future theory development and empirical testing. The study maps theories used to investigate different aspects of integration, identifies under-explored theoretical perspectives, and show how particular port system contexts and integration configurations have been privileged or neglected. It also highlights opportunities to extend research methodology to better capture the dynamic and multi-level nature of port–hinterland integration processes.

Research limitations/implications

The review will be limited by its reliance on published academic literature in English and selected databases, which may under-represent practice-oriented reports and non-English studies. The TCCM may also privilege certain theoretical perspectives while giving less attention to others. Future research includes comparative studies across regions and governance models, quantitative impact evaluations, and theory-building work that combines organizational theories to better capture the complexity of port–hinterland integration processes.

Practical implications

For seaport authorities and dry port operators, the expected framework can support more informed decisions on whether to integrate dry ports into regional logistics strategies. Empirical evidence suggests that well-designed seaport–dry port integration can help meet policy goals on emissions and external cost reduction. For policymakers, the study is expected to highlight how integration can influence accessibility, investment attraction, and exposure to different types of risk, providing a basis for aligning port and transport with regional logistics systems.

References

Notteboom T, Pallis A and Rodrigue J-P (2026) Port Economics, Management and Policy, Second edn, doi:doi.org/10.4324/9781003585367, New York: Routledge.
Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, Shamseer L, Tetzlaff JM, Akl EA, Brennan SE, Chou R, Glanville J, Grimshaw JM, Hróbjartsson A, Lalu MM, Li T, Loder EW, Mayo-Wilson E, McDonald S, McGuinness LA, Stewart LA, Thomas J, Tricco AC, Welch VA, Whiting P and Moher D (2021) 'The PRISMA 2020 statement: an updated guideline for reporting systematic reviews', BMJ, 372:n71, doi:10.1136/bmj.n71. https://www.bmj.com/content/bmj/372/bmj.n71.full.pdf
Paul J and Criado AR (2020) 'The art of writing literature review: What do we know and what do we need to know?', International Business Review, 29(4):101717, doi:https://doi.org/10.1016/j.ibusrev.2020.101717. https://www.sciencedirect.com/science/article/pii/S0969593120300585

Forecasting Airport Parking Demand under Fixed Tariffs: A Multi-Node, Must-Serve Approach to Lunar-Holiday Capacity Preparation

Jingyu Choi, Suhyung Lee, Sein Ko, Chulung Lee

School of Industrial and Management Engineering, Korea University, Korea

Purpose of this paper

Existing parking research addresses a structural constraint that parking supply cannot expand short-term by regulating demand through pricing (Arnott & Rowse, 1999; Shoup, 2005; Inci, 2015). Public airports differ: as national infrastructure they must serve lunar-holiday demand such as Seollal and Chuseok, yet state-regulated tariffs remove price as a demand-shaping lever, so they prioritize short-term supply such as temporary parking. These peaks are also more explosive than price-managed ones. Forecasting thus becomes the operational lever: preparation depends on anticipating, not shaping, demand. Airport parking demand has been forecast before (Lin et al., 2015), but this price-fixed, must-serve framing is largely unaddressed. This is tractable because airport parking is derived demand with observable air-travel signals and stock-and-flow occupancy dynamics. Two difficulties define it. First, a calendar mismatch: classical and fixed-period deep models assume Gregorian periodicity, but lunar holidays drift roughly eleven days annually, making same-day-of-year features unreliable at peaks. Second, multi-node networks have heterogeneous demand drivers such as service mix, holiday polarity, data depth, and demand structure, so no architecture fits all. The study asks how to formulate this as capacity preparation, address the mismatch, identify fit-governing node characteristics, and operationalize the result.

Design / Methodology / Approach

Hourly and daily 2014–2026 parking data from four airports, split into five nodes by separating the largest hub's domestic and international demand, are integrated with the operator's OpenAPI streams (flight schedules, passenger volumes) and engineered features: Temporal Window Encoding of holiday effects, lunar same-day prior-year demand, periodic sine/cosine encoding of day-of-week and month, hourly time-table flags, and forward-hour flight look-ahead variables. The COVID-19 period (2020–2022) is excluded to prevent structural-break contamination. Demand censored once lots fill is reconstructed by truncated simulation, limiting peak under-counting. Five deep learning architectures, TimesNet, iTransformer, TFT, N-HiTS, and DLinear, are trained per node with 5-seed multi-run evaluation (seeds 0/7/42/99/123), reporting mean ± standard deviation. Optuna tuning uses 30 trials, 40 epochs, median pruning, and leakage-free train/validation/test splits. A leakage-free stacking ensemble (Ridge, LightGBM, bias-corrected averaging, per-day weighting) is calibrated on a separate validation window. Performance is evaluated over three holiday windows, Seollal 2025, Chuseok 2025, and the record-peak Seollal 2026, using sMAPE, MAPE, MAE, and Total Volume Error (TVE), the last tying forecast error to supply sizing. The pipeline is packaged as a command-line tool with OpenAPI auto-update, parking-lot-level model selection, and a ±1–15% practitioner adjustment interface.

Findings

Across five nodes and three holiday windows, no single architecture dominates; fit depends on traffic mix, holiday polarity, data depth, and demand heterogeneity against a 5% holiday sMAPE proxy. (i) Nodes with a balanced mix of domestic and international traffic are the most forecastable, well captured by a periodicity-modeling approach, at roughly 3–5% holiday sMAPE. (ii) Small nodes with shallow operating history are best handled by transfer learning: weights from a similar larger hub, fine-tuned on the target, beat direct training and reach sub-4% sMAPE. (iii) Nodes with many short-haul domestic and few long-haul routes show reverse-holiday demand, with outflow-induced drops during Lunar New Year, and need channel-token modeling, near 6–7% sMAPE. (iv) International long-haul nodes with weak holiday correlation show large seed-to-seed variance that only multi-seed evaluation exposes; single-run results overstate stability, risking capacity shortfall from under-forecast. (v) Island tourist-resident nodes are the hardest and least generalizable, with high variance only partly reduced by attention-based

fusion. For the record-peak Seollal 2026 out-of-distribution test, where demand exceeds the training range, single models degrade sharply, while a leakage-free stacking ensemble combining diverse architectures stays markedly more robust, supporting model diversity as a safeguard under demand shocks.

Value

This study contributes to supply chain analytics and transport-hub operations in three ways. First, it reframes parking forecasting for price-fixed public infrastructure: where prior work treats peaks as price-shapeable (Arnott & Rowse, 1999; Shoup, 2005), it formalizes the must-serve case where forecasting is the primary lever, linking parking research to service-operations capacity-preparation work. Second, it offers a node-characteristic model-selection taxonomy for multi-airport networks: heterogeneous nodes need differentiated architectures, not one universal model. Third, it delivers a deployable research-to-operation pipeline for capacity rather than pricing decisions. Its significance lies in specifying what demand forecasting must capture when price cannot absorb peaks.

Research Limitations / Implications

Its training-data range (2014–2026, COVID gap excluded) limits extrapolation to record-breaking events. Accuracy is reported as point-estimate sMAPE; probabilistic upper-bound coverage (quantile regression, conformal prediction) is left to future work. Validation is confined to Korean airports, and island-hub nodes generalize poorly; cross-cultural validation is needed.

Practical Implications

The integrated command-line decision support system is deployable at the operator, refreshing data automatically through the public API, producing 10–14-day-ahead forecasts with node-specific best-fit models for temporary-capacity and staffing preparation, and exposing a ±1–15% practitioner adjustment with audit trail acting as a human-in-the-loop safety buffer for out-of-distribution holiday peaks, including activating idle land as overflow capacity.

References

Arnott, R., & Rowse, J. (1999). Modeling parking. Journal of Urban Economics, 45(1), 97–124.

Challu, C., Olivares, K. G., Oreshkin, B. N., et al. (2023). N-HiTS: Neural hierarchical interpolation for time series forecasting. AAAI 2023.

Inci, E. (2015). A review of the economics of parking. Economics of Transportation, 4(1), 50–63.

Lim, B., Arık, S. Ö., Loeff, N., & Pfister, T. (2021). Temporal fusion transformers for interpretable multi-horizon time series forecasting. International Journal of Forecasting, 37(4), 1748–1764.

Lin, C., Li, W., Huang, Y., & Yang, G. (2015). Parking demand forecasting in airport ground transportation system: case study in Hongqiao Airport. In 2015 International Symposium on Computers & Informatics (pp. 2242–2250). Atlantis Press.

Liu, Y., Hu, T., Zhang, H., et al. (2024). iTransformer: Inverted transformers are effective for time series forecasting. ICLR 2024.

Shoup, D. C. (2005). The High Cost of Free Parking. Planners Press.

Wu, H., Hu, T., Liu, Y., et al. (2023). TimesNet: Temporal 2D-variation modeling for general time series analysis. ICLR 2023.

Zeng, A., Chen, M., Zhang, L., & Xu, Q. (2023). Are transformers effective for time series forecasting? AAAI 2023.

SMART/DIGITAL SUPPLY CHAINS

Digital Technologies Enabling Efficient Re-commerce Logistics in secondhand Fashion Supply Chains

Kanchana Dissanayake, Rudrajeet Pal

Swedish School of Textiles, University of Borås, Sweden.

Purpose of this paper

The purpose of this paper is to investigate how digital technologies enable more efficient and scalable logistics operations within secondhand fashion re-commerce supply chains. Secondhand fashion has gained increasing attention as a key pathway toward circularity in the textile and fashion industry (Hultberg, 2024), driven by regulatory pressure, sustainability commitments, and shifting consumer preferences (Koay et al., 2022). Despite this growing importance, logistics operations in the secondhand fashion sector remain highly complex, labour-intensive, and challenging to scale due to extreme product heterogeneity, uncertain quality, and manual processing requirements (Valtere et al., 2025). These logistics challenges pose significant barriers to operational efficiency and scalability, limiting the ability of re-commerce actors to expand their operations beyond niche markets.

While existing literature has explored circular business models and consumer acceptance of secondhand fashion, limited attention has been paid to the operational and logistics-level mechanisms that enable re-commerce to scale effectively. In particular, the role of digital technologies in addressing logistics constraints remains underexplored. This paper addresses this gap by focusing on how re-commerce firms deploy digital technologies to manage logistics challenges and improve efficiency and scalability. By examining technology adoption in re-commerce logistics, this paper contributes to a deeper understanding of how digitalisation supports circular supply chains.

Methodology

This study adopts a qualitative research design based on semi-structured interviews to explore logistics challenges in fashion re-commerce and to analyse the role of digital technologies in mitigating these challenges. A qualitative approach is appropriate given that re-commerce logistics practices are emergent, context-specific, and insufficiently conceptualised in existing research. The empirical material comprises 15 semi-structured interviews with secondhand fashion retailers engaged in re-commerce business models and technology providers delivering digital solutions for re-commerce operations. The interviewed firms differ in size, operating mode, and level of vertical integration, including organisations managing their own re-commerce platforms as well as those collaborating with external platforms and logistics partners.

The Technology–Organisation–Environment (TOE) framework to structure and analyse the digitalisation in re-commerce logistics (Tornatzky et al., 1990). The *technology* context refers to the digital tools currently implemented and emerging solutions relevant to re-commerce operations; the *organisational* context reflects firms' internal resources, capabilities, and structural arrangements, including interactions among supply chain actors; and the *environmental* context captures external influences such as regulatory developments, market dynamics, and platform ecosystems that shape firms' technological choices. Applying the TOE framework, this study examined how the interplay of technological opportunities, organisational capabilities, and environmental pressures drives the adoption of digital technologies in secondhand fashion supply chains.

Findings

The findings indicate that re-commerce logistics in secondhand fashion are characterised by a set of highly granular and labour-intensive operational challenges. Unlike conventional fashion supply chains, re-commerce requires firms to handle each product as a unique item rather than as part of a standardised batch. Core challenges include photographing individual garments, writing detailed product descriptions, listing each item separately on digital platforms, managing

webshop content, and synchronising inventory data with online storefronts. These activities demand significant manual effort and coordination across logistics and digital systems, while inbound volumes and product characteristics remain unpredictable. The TOE framework was used to explain how firms overcome these challenges by reconfiguring re-commerce logistics through the combined effects of technological opportunities, organisational readiness, and environmental pressures, as detailed below.

Technology: To address logistics challenges, firms increasingly adopt digital technologies that restructure key logistics processes. Advanced batch photography and image processing systems are used to accelerate photography, reducing manual effort while maintaining standardisation. AI-powered Image recognition and text extraction technologies are used to automate attribute generation and visual content creation, mitigating errors and inefficiencies caused by manual data entry. Additionally, NFC and RFID tags are integrated into the products to create a digital product identity, enabling rapid identification, data retrieval, and tracking of individual items. These tags function as digital passports, enhancing information availability across logistics processes and supporting more efficient sorting, inventory management, and coordination within reverse logistics networks. Furthermore, advanced machine-learning algorithms and data-driven pricing tools are created to support digital pricing by integrating data on product condition, brand value, historical sales, and demand patterns. Overall, digital technologies function not only as efficiency-enhancing tools but also as mechanisms to cope with the product heterogeneity and informational complexity inherent in re-commerce logistics.

Organisation: The adoption and integration of these technologies are shaped by organisational factors such as firm size, resource availability, digital capabilities, and operating models. Larger and vertically integrated firms tend to implement more comprehensive digital systems, whereas smaller firms rely on modular or partially automated solutions due to limited resources and technical capabilities. Collaboration with technology providers and logistics partners also influences the depth and scope of digitalisation. Operating modes also shape technology use: firms managing their own platforms exhibit greater control over digital infrastructure, whereas those dependent on third-party platforms face constraints in data access and system integration. These differences reflect broader disparities in logistics capabilities and resource configurations, influencing firms' ability to scale re-commerce operations.

Environment: The environmental context plays a crucial role in shaping the digital adoption of re-commerce among secondhand fashion companies. Increasing competition in the secondhand market, driven by the entry of large digital platforms and traditional fashion retailers, pressures other secondhand retailers to enhance their digital capabilities. At the same time, shifting consumer expectations toward online shopping of secondhand fashion, motivated by convenience, accessibility, and broader product availability, further accelerate the need for digital transformation. Both the market competition and consumer expectations create a dynamic external environment that pushes secondhand fashion companies toward the adoption of digital re-commerce technologies.

Value

This study provides a novel, empirical examination of how digital technologies enable efficient logistics in fashion re-commerce, an area that remains underexplored in academic literature. It contributes to re-commerce and circular supply chain research by shifting the analytical focus from business models and consumers to logistics processes and operational practices. The TOE framework offers a novel, structured analysis linking technological adoption to operational challenges, organisational capabilities, and environmental pressures.

Research limitations

The empirical material is based on a limited number of interviews, primarily conducted in a European context, which may affect the generalizability of the findings. The study relies on qualitative data, which may not fully capture actual performance improvements resulting from technology adoption. Quantitative studies measuring efficiency, cost, or lead-time impacts could complement these findings.

Practical implications

The findings offer several practical implications for re-commerce firms and logistics practitioners. First, investments in digital technologies can significantly reduce manual labour and processing time, thereby improving operational efficiency and scalability. Second, collaboration with technology providers and platform partners is critical, particularly for smaller firms that lack internal digital capabilities. Third, the study highlights the importance of aligning technology adoption with operating modes and growth strategies.

References

Hultberg, E., 2024. Scaling circular business models: strategic paths of second-hand fashion retail. J. Fash. Mark. Manag. https://doi.org/10.1108/JFMM-10-2023-0260

Koay, K.Y., Cheah, C.W., Lom, H.S., 2022. An integrated model of consumers' intention to buy second-hand clothing. Int. J. Retail Distrib. Manag. 50, 1358–1377. https://doi.org/10.1108/IJRDM-10-2021-0470

Tornatzky, L.G., F., M., Chakrabarti, A.K., 1990. The processes of technological innovation. Lexington Books.

Valtere, M., Bezrucko, T., Lauka, D., Blumberga, A., Blumberga, D., 2025. What Drives the Circular Economy? Textile Sorting or Consumption Reduction. Circ. Econ. Sustain. 5, 2725–2749. https://doi.org/10.1007/s43615-025-00584-6

From Low-Budget Pilots to Scalable AI in Operations and Supply Chain Management: a Roadmap Built on the "Blueprints" of Implementation

Maria Ciano[1], Nicolò Saporiti[2], Rossella Pozzi[2], Mirco Peron[3]

1: University of Nottingham, United Kingdom; 2: Carlo Cattaneo University, Italy; 3: NEOMA Business School, France

Purpose of the paper

The prevailing discourse on artificial intelligence (AI) in operations and supply chain management (OSCM) overemphasises large-scale, capital-intensive digital transformations (Choi et al., 2018; Belhadi et al., 2024). However, most organisations, both small- and medium-sized enterprises (SMEs) and large enterprises (LEs), begin their AI journeys with deliberately modest, low-budget pilots that allow them to learn, test feasibility, and preserve option value before committing to larger investments (Moeuf et al., 2018; Wu and Pagell, 2011). The purpose of this paper is to explore why some of these frugal pilots successfully scale into reliable, production-grade systems while others stall. We argue that scaling success depends on systematically upgrading the operational foundations, termed the "blueprints" of implementation (data infrastructure, hardware, integration, and governance), rather than relying solely on algorithmic sophistication (Sculley et al., 2015).

Design/methodology/approach

Drawing on a portfolio of 15 industrial AI projects as illustrative field evidence, we analyse implementations spanning image recognition, data mining, and agentic AI. The projects were conducted across both SMEs (7 projects) and LEs (8 projects). All 15 projects began as low-budget pilots and achieved technical feasibility, but their ultimate scaling outcomes varied. By examining these divergent paths, we identify recurring bottlenecks and patterns, distil them into four distinct implementation archetypes, and map them to a proposed five-stage implementation roadmap.

Findings

Out of the 15 projects, 10 (67%) successfully scaled to production. Four key patterns emerged that support the logic of our roadmap. First, data readiness is the single strongest predictor of scaling success: projects starting with structured data scaled 100% of the time, while those with messy or partial data scaled in only 25% of cases. Second, operational complexity is the true barrier, not algorithmic complexity. Counterintuitively, high-complexity projects reached production more frequently (83%) than low-complexity ones (33%), because complex algorithms required deliberate investment in operational blueprints, whereas simple algorithms often led to complacency. Third, there is a scaling divergence by enterprise size: LEs scaled at a higher rate (75%) than SMEs (57%), which is tied to prior maturity in IT infrastructure and governance rather than just budget differences (Moeuf et al., 2018; Tortorella and Fettermann, 2018). Finally, bottlenecks consistently concentrate in the blueprints (integration and data governance accounted for the majority of scaling hurdles), and never in the AI model itself.

These findings are categorised into four "blueprints" archetypes:

- Archetype A: Data Foundation.

  Developing models (e.g., clustering for lead times) stalls for firms with incomplete records, whereas firms with high-quality, structured data successfully integrate the same algorithm into operations (Wamba et al., 2015).

- Archetype B: Hardware and Performance.

  Consumer-grade pilots (e.g., Raspberry Pi object detection) prove valuable but require targeted upgrades to industrial hardware to meet real-time production constraints (Dubey et al., 2020).

- Archetype C: Integration and Workflow.

  Cloud-based NLP models can easily handle discrete tasks, but scaling requires extensive orchestration layers to handle heterogeneous document pipelines and privacy constraints (Holmström and Partanen al., 2014; Sculley et al., 2015).

- Archetype D: Governance and AI Guardrails.

  Agentic AI carries hallucination risks (Baryannis et al., 2019), meaning scaling requires strict validation mechanisms before outputs enter enterprise systems (Davis et al., 2024).

Value/Originality

This paper challenges the "glamour" narrative of AI in OSCM by providing a pragmatic, operations-centric framework. It introduces a novel five-stage stage-gate roadmap: (1) Data Foundation and Governance, (2) Feasibility Pilot, (3) Value-Validated Pilot, (4) Industrialization and Scaling Preparation, and (5) Production Deployment and Replication. It establishes that while early stages (1–3) suit low-budget approaches to validate value with minimal capital exposure (Ferreira et al., 2016), the critical transition occurs at Stage 4, where upgrading the operational blueprints (hardware, IT/OT integration, data pipelines, and MLOps) is mandatory (Ivanov et al., 2019). The paper shifts the focus from pure algorithmic innovation toward the operational conditions that enable real-world implementation.

Research limitations/implications

The portfolio approach serves as illustrative field evidence rather than formal hypothesis testing. The findings open a research agenda for OSCM scholars. Future research should formalize the economics of low-budget pilots as real options versus full-scale deployment (Wu and Pagell, 2011). Scholars should also investigate differences in organisational absorptive capacity between SMEs and LEs, develop agile governance frameworks for agentic AI that ensure reliability without compromising agility (Davis et al., 2024), and study data readiness as a managed operational resource subject to accumulation and degradation.

Practical implications

The five-stage roadmap and four archetypes function as a diagnostic instrument for practising managers, helping them locate a project on its implementation trajectory and identify exactly what is required to move it forward. Key practical rules include: do not attempt Stage 2 modelling without a credible Stage 1 data foundation; treat Stage 4 industrialization investments as real options to be exercised only after value is validated in Stages 2–3; map the workflow integration surface early, regardless of enterprise size; and, for agentic AI, establish human-in-the-loop fallback mechanisms and guardrails during Stage 4 before granting autonomous power.

References

Baryannis, G., Validi, S., Dani, S. and Antoniou, G., 2019. Supply chain risk management and artificial intelligence: state of the art and future research directions. *International journal of production research*, *57*(7), pp.2179-2202.

Belhadi, A., Mani, V., Kamble, S.S., Khan, S.A.R. and Verma, S., 2024. Artificial intelligence-driven innovation for enhancing supply chain resilience and performance under the effect of supply chain dynamism: an empirical investigation. *Annals of operations research*, *333*(2), pp.627-652.

Choi, T.M., Wallace, S.W. and Wang, Y., 2018. Big data analytics in operations management. *Production and operations management*, *27*(10), pp.1868-1883.

Davis, A.M., Mankad, S., Corbett, C.J. and Katok, E., 2024. OM Forum—The best of both worlds: Machine learning and behavioral science in operations management. *Manufacturing & Service Operations Management*, *26*(5), pp.1605-1621.

Dubey, R., Gunasekaran, A., Childe, S.J., Bryde, D.J., Giannakis, M., Foropon, C., Roubaud, D. and Hazen, B.T., 2020. Big data analytics and artificial intelligence pathway to operational performance under the effects of entrepreneurial orientation and environmental dynamism: A

study of manufacturing organisations. *International journal of production economics*, *226*, p.107599.

Ferreira, K.J., Lee, B.H.A. and Simchi-Levi, D., 2016. Analytics for an online retailer: Demand forecasting and price optimization. *Manufacturing & service operations management*, *18*(1), pp.69-88.

Holmström, J. and Partanen, J., 2014. Digital manufacturing-driven transformations of service supply chains for complex products. *Supply Chain Management: An International Journal*, *19*(4), pp.421-430.

Ivanov, D., Dolgui, A. and Sokolov, B., 2019. The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. *International journal of production research*, *57*(3), pp.829-846.

Moeuf, A., Pellerin, R., Lamouri, S., Tamayo-Giraldo, S. and Barbaray, R., 2018. The industrial management of SMEs in the era of Industry 4.0. *International journal of production research*, *56*(3), pp.1118-1136.

Sculley, D., Holt, G., Golovin, D., Davydov, E., Phillips, T., Ebner, D., Chaudhary, V., Young, M., Crespo, J.F. and Dennison, D., 2015. Hidden technical debt in machine learning systems. *Advances in neural information processing systems*, *28*.

Tortorella, G.L. and Fettermann, D., 2018. Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies. *International journal of production research*, *56*(8), pp.2975-2987.

Wamba, S.F., Akter, S., Edwards, A., Chopin, G. and Gnanzou, D., 2015. How 'big data'can make big impact: Findings from a systematic review and a longitudinal case study. *International journal of production economics*, *165*, pp.234-246.

Wu, Z. and Pagell, M., 2011. Balancing priorities: Decision-making in sustainable supply chain management. *Journal of operations management*, *29*(6), pp.577-590.

Competency Framework for Smart Warehousing Managers: Expectations in the Industry 4.0 Era

Ashwini Kulkarni[1], Senthilkumar Thiyagarajan[2], Prakash Jeganathanperumal[3], Nachiappan Subramanian[4]

1: UNDOCKED, INC, United States of America; 2: Medline Industries LP, United States of America; 3: Genuine Parts Company, United States of America; 4: University of Sussex, United Kingdom

Purpose of this paper

The competency requirements of operations managers in distribution centers (DCs) are rapidly evolving as smart warehousing practices driven by Industry 4.0 technologies become mainstream. However, it remains unclear what specific knowledge and skill sets are essential for managers operating in these complex, hybrid human–automation environments. Therefore, this study aims to develop a theoretically grounded and practice-oriented competency framework that clarifies the capabilities needed to meet the expectations of smart warehouses. The framework identifies how managers must adapt and upskill to effectively oversee technologically advanced DC operations, where behavioral agility, digital literacy, and specialized domain expertise are increasingly critical. Guided by Roberts' sensing-and-aligning competency framework and the APICS Supply Chain Manager Competency Model, the study reveals the key competencies required for DC operations managers in the industry 4.0 era.

Design/Methodology/Approach

This study employs a qualitative exploratory research design, leveraging semi-structured interviews to gather rich, in-depth data. Primary data was collected from 10 DC operations managers and senior supply chain leaders from various organizations. Participants represented a cross-section of industries including retail, e-commerce, manufacturing, and third-party logistics providers. The selected organizations span various levels of warehouse automation maturity, ranging between foundational automated systems to highly integrated smart warehousing solutions. The interview protocol was designed to elicit nuanced perceptions regarding the impact of smart warehousing technologies, the escalating complexity of decision-making processes, and the perceived inadequacy of existing managerial competencies within Industry 4.0 contexts.

Data analysis followed a three-level thematic coding process. In the first cycle (open coding), participants' core ideas about competency were captured using vivo and descriptive codes to reflect their lived interpretations. In the second cycle (axial coding), conceptually similar codes were grouped into higher-order categories to identify patterns across interviews. In the third cycle (theoretical coding), these categories were synthesized into overarching themes and systematically mapped onto Roberts' personality, cognitive, and behavioral constructs and the APICS competency framework, resulting in an integrated competency model grounded in both empirical data and established theory (APICS, 2020; Roberts, 1997).

Findings

The findings reveal that managerial effectiveness in Industry 4.0-enabled distribution centers (DCs) extends beyond traditional operational expertise. Thematic analysis of interviews with DC operations managers and senior supply chain leaders identified a multidimensional competency configuration best represented as a Star-shaped profile. Unlike the conventional "T-shaped" model, where managers demonstrate deep expertise in one functional domain supported by broader general knowledge (Oskam, 2009; Career minds, 2020), the findings indicate that smart warehouse managers should simultaneously demonstrate strength across multiple, interdependent competency domains (Coverdale, 2019; SHRM, 2021).

Five core competency themes emerged from the analysis. First, Occupation-Specific Competencies form the operational backbone, encompassing deep knowledge of warehouse processes and fluency in enabling technologies such as WMS, WES, AGVs, robotics, and IoT systems. Participants emphasized that technological sophistication has redefined operational control, requiring managers to interpret system-generated signals and intervene in complex, automated workflows. Second, Data and Analytics Competencies were consistently highlighted as central to managerial effectiveness. In data-rich environments, managers must translate dashboards, exception reports, and predictive outputs into actionable decisions. Data fluency was not viewed as a specialist skill, but as a core managerial capability underpinning responsiveness and performance optimization.

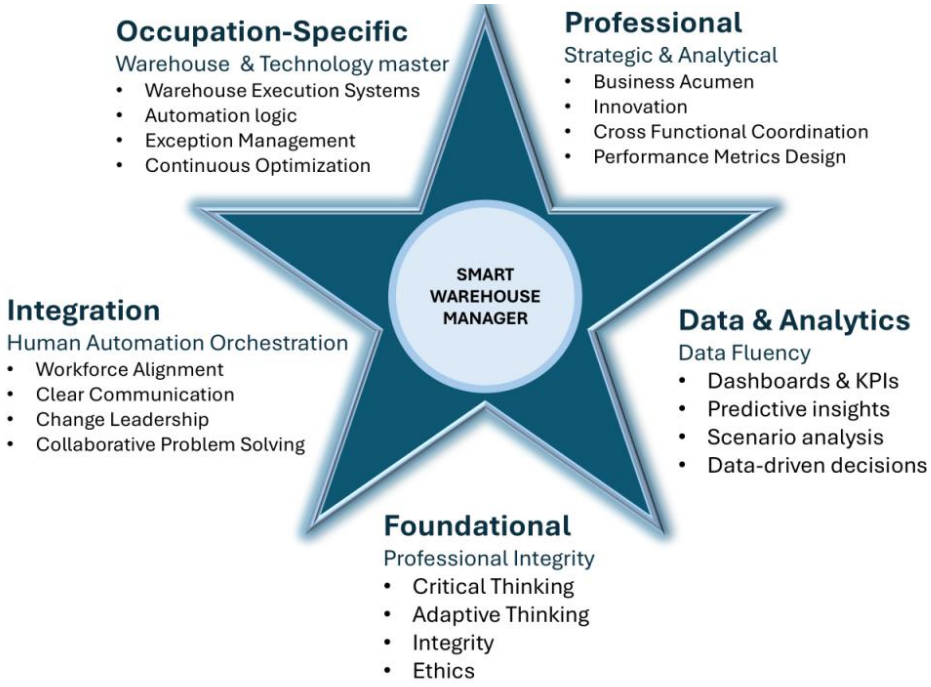


Figure 1: STAR shaped Skill Profile

Third, Professional Competencies, including strategic thinking, business acumen, and cross-functional collaboration, enable managers to connect operational decisions to enterprise-level objectives. Participants noted that automation investments demand justification through measurable value creation, requiring managers to align operational metrics with financial and strategic outcomes. Fourth, Human-Technology Integration Competencies reflect the hybrid nature of smart warehouses. Managers are required to orchestrate collaboration between human associates and automated systems, lead digital transformation initiatives, and manage resistance to technological change. This competency theme underscores the socio-technical complexity of Industry 4.0 environments. Finally, Foundational Competencies, such as critical thinking, ethical judgment, and adaptive agility, were identified as cross-cutting enablers. These competencies support sense-making under uncertainty and sustain performance amid technological disruption.

Mapping these themes onto Roberts' (1997) Sensing and Aligning framework and the APICS Supply Chain Manager Competency Model demonstrates that managerial effectiveness arises from the dynamic interplay between sensing (interpreting environmental and operational signals) and aligning (translating insights into coordinated action). The resulting integrated framework conceptualizes competencies as an integrated skill profile rather than a static inventory of skills. By articulating this Star-shaped profile and adapting Robert's competency model, the study contributes a structured blueprint for leadership development in automated DCs and advances competency theory within smart warehousing contexts.

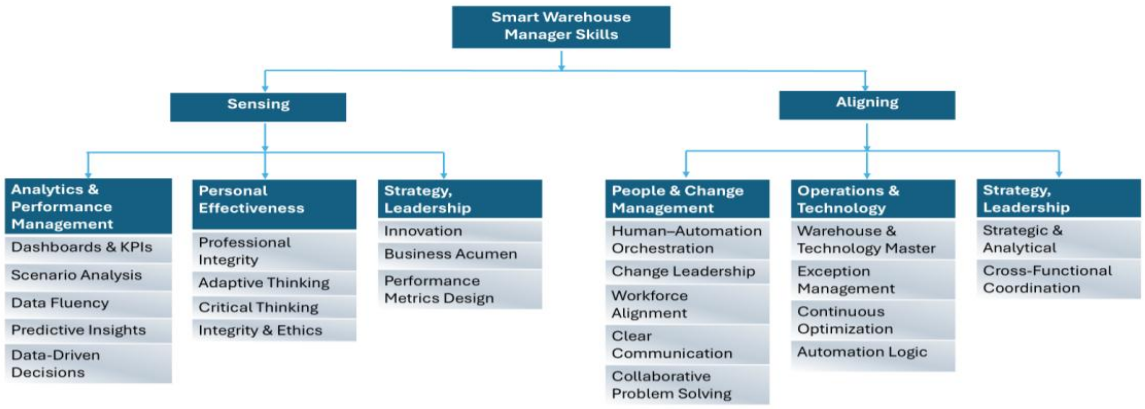


Figure 2: Integrated Competency Model for Managers in Smart Warehousing Environment

Value and Originality

This study advances competency research by theoretically and empirically extending Roberts' (1997) sensing and aligning framework into the underexplored domain of smart warehousing and Industry 4.0-enabled distribution centers. While prior competency models have largely focused on traditional supply chain roles, this research reconceptualizes managerial effectiveness within highly automated, data-intensive warehouse environments. By integrating Roberts' behavioral and cognitive constructs with the APICS Supply Chain Manager Competency Model, the study develops a unified, Star-shaped framework that captures the socio-technical complexity of modern DC operations.

Unlike existing models that list discrete skills, the proposed framework explicates the dynamic linkage between digital sensing capabilities (e.g., data analytics, real-time visibility) and operational alignment mechanisms (e.g., cross-functional coordination, human-technology orchestration), thereby connecting competencies directly to resilience and performance outcomes. Empirically grounded in practitioner insights, this research offers one of the first context-specific competency models tailored to DC operations managers in automated environments, addressing a critical gap in both supply chain theory and workforce development.

Research limitations

This study's qualitative approach offers rich, in-depth insights into managerial competencies for smart warehousing but limits the ability to generalize findings to all warehouse settings. The results are drawn from a purposive sample of 10 DC operations managers and supply chain leaders, which may reflect specific industry contexts and varying levels of automation maturity, potentially introducing biases. For future research, we propose operationalizing the identified sensing and aligning competencies into quantifiable measures to enable broader validation. Large-scale quantitative surveys across diverse industries and automation stages could validate the framework's applicability in a broader context. Additionally, longitudinal studies would be valuable to monitor how these competencies evolve amid rapid technological advancements, providing a more dynamic understanding of skill requirements in Industry 4.0 environments.

Practical implications

The findings provide a structured blueprint for organizations transitioning toward smart warehouse technologies. First, firms should embed the proposed competency framework into DC

leadership development strategies by aligning recruitment, assessment, and succession planning with automation maturity levels. Selection criteria should extend beyond traditional operational expertise to include demonstrated capability in digital systems (e.g., WMS, WES, AGVs), data-driven decision-making, and human-technology integration.

Second, organizations should implement targeted upskilling initiatives, such as advanced analytics training, digital change leadership programs, and cross-functional simulation exercises, to strengthen sensing and aligning capabilities. These interventions can reduce implementation risks, enhance adoption of automation technologies, and improve system-wide performance. Third, professional bodies such as APICS may consider revising certification standards to incorporate behavioral, digital, and integrative competencies identified in this study, thereby promoting industry-wide alignment between technological advancement and managerial capability development. Collectively, these implications support creating more adaptive, technology-enabled leadership practices, enabling organizations to enhance operational efficiency, mitigate change resistance, and sustain competitive advantage in increasingly automated supply chain environments.

Keywords: Warehouse 4.0, Smart Warehouse Manager, Competency Model, Industry 4.0 Skills

References

1. Roberts, M. J. (2018). *Sensing and Aligning: A Framework for Managerial Competencies in Dynamic Environments*. Harvard Business Review Press.
2. APICS. (2020). *Supply Chain Manager Competency Model: Foundation, Competencies, and Performance Indicators*. APICS Foundation for Supply Chain Research.https://www.apics.org/apics-for-business/products-and-services/apics-scc-professional-designation/apics-competency-model
3. Ivanov, D., Dolgui, A., & Sokolov, B. (2022). *Supply Chain Resilience and Industry 4.0: A Conceptual Framework*. International Journal of Production Research, 60(5), 1450-1468.
4. Winkelhaus, S., & Grosse, E. H. (2021). *Logistics 4.0: A Systematic Review Towards a New Logistics System*. International Journal of Production Research, 58(1), 18-43.
5. Hofmann, E., & Rüsch, M. (2017). *Industry 4.0 and the Current Status as Well as Future Prospects on Logistics*. Computers in Industry, 89, 23-34.
6. Oskam, I. (2009). T-shaped engineers for interdisciplinary innovation: An attractive perspective for young people as well as a must for innovative organizations. In 37th Annual Conference–Attracting students in Engineering (pp. 1-10). Rotterdam, The Netherlands.
7. Coverdale, K. (2019, April 18). Beyond the T-shaped person: Becoming star-shaped. https://medium.com/@kris.coverdale/beyond-the-t-shaped-person-becoming-star-shaped-4ec80ab94543
8. Career minds. (2020, October 7). How to use the STAR method to assess leadership skills. https://careerminds.com/blog/how-to-use-the-star-method-to-assess-leadership-skills
9. Society for Human Resource Management (SHRM). (2021, March 12). Viewpoint: How using a STAR profile led to HR success story. https://www.shrm.org/topics-tools/news/employee-relations/viewpoint-how-using-star-profile-led-to-hr-success-story

Additive Manufacturing vs. Conventional Manufacturing: A Multi-Criteria Decision Analysis Using the Analytic Hierarchy

Christos Braziotis[1], Kulwant Pawar[1], Nachiappan Subramanian[2], Ajeseun Jimo[3]

1: Nottingham University Business School, University of Nottingham, UK; 2: University of Sussex Business School, UK; 3: Henley Business School, University of Reading, UK

Purpose of this paper

Additive Manufacturing (AM) is expected to have a transformative impact on operations and strategy (Eyers et al., 2022), with implications for the performance of individual operations and the Supply Chain (SC). However, its evolving technology makes its adoption over Conventional Manufacturing (CM) a complex decision (Sgarbossa et al., 2021), The literature reports on several cases of either standalone AM adoption over CM, or as a hybrid approach in which AM and CM are used interchangeably or in sequence. Occasionally, the two manufacturing technologies overlap, and in many use cases, they can both produce functional parts. While the literature acknowledges the success of AM in high-variety, low-volume applications, adoption of AM also poses challenges, which are associated with switching to a less mature and less proven technology with significant competitive implications for the production system, the overall investment cost, and skilled labour. The simple choice of the technology based on the output geometry, part material and overall economic benefits has become less obvious, and additional performance objectives need to be considered

Our research, which is work in progress, aims to shed light on how managers rate AM-related Relative Advantage (RA) factors (including competitive priorities and performance criteria) when considering the new manufacturing technology adoption for low-volume production and the aftermarket domain in the context of High Value Manufacturing (HVM). The Research Question guiding our research is: "What's the difference between Additive Manufacturing and Conventional Manufacturing in terms of importance for a product with low-volume production and spares aftermarket?"

Design/methodology/approach

Our paper extends the work published by Jimo et al. (2025). We focus on how AM compares to CM for making metal components for assembly or as aftermarket parts (spares). Since we're working with low-volume production and a small aftermarket in HVM domain, we look at different operations and SC factors that would be important for both scenarios, depending on the product and the manufacturing process. We developed a multi-criteria decision analysis using the Analytic Hierarchy Process (AHP) (Saaty, 1977), with the aim to identify the operational and supply chain strategic aspects, and their potential effects on sustainability. Our research approaches AM not as a mere machine replacement of CM-dedicated equipment, but as a capability-building system: identifying cases for application, adopting the relative technology, and reconfiguring the manufacturing process and business case for competitive advantage. Through pairwise comparisons of RA factors and measures for operations and SCs, our survey identifies the key decision factors influencing the adoption of AM over CM, determining their relative importance. Our research was grounded on, and contributes to two underpinning theories, namely the Resource-Based View and Dynamic Capabilities.

Findings

We present the theoretical grounding, research approach, and data collection approach with for the pairwise comparisons of RA factors and measures for operations and SCs. Our contribution, which is work in progress, presents Relative Advantage domains of industrial operations when deciding the manufacturing technology and the factors/measures to be considered with implications for operations and SCs. We elaborate on the bundles of factors that are visible and measurable, and constitute the RA sources.

Value

Our research aims to add clarity and prioritisation on the decision-making influencing factors and measures, and their relative significance, when deciding on the adoption of AM and CM in terms of importance for a product with low-volume production and a small spares aftermarket. The outcomes of the advanced production processes in the focal industrial context of HVM are of high economic and strategic value, making HVM a relevant ground for the transition to AM in producing metal components. However, it remains a sector not sufficiently explored in terms of the systematic comparison of benefits when considering Additive over the Conventional Manufacturing technology, and past research has mainly been qualitative or case-based, not ascertaining the hierarchy of the relevant decision-making process.

Practical implications

Our research aims to assist practitioners in their decision-making process in terms of the choice of adoption of AM by elaborating on the relative importance of RA factors, including competitive priorities and performance criteria.

References

Eyers, D.R., Potter, A.T., Gosling, J. and Naim, M.M. (2022), "The impact of Additive Manufacturing on the product-process matrix", *Production Planning & Control*, Vol. 33 No. 15, pp. 1432–1448, doi: 10.1080/09537287.2021.1876940.

Jimo, A., Braziotis, C. and Pawar, K. (2025) 'Beyond Prototyping: Mapping the Relative Advantages of Adopting Additive Manufacturing for Industrial Production'. *International Journal of Production Research*: 1–30. https://doi.org/10.1080/00207543.2025.2504165.

Saaty, T.L. (1977), "A scaling method for priorities in hierarchical structures", *Journal of Mathematical Psychology*, Vol. 15 No. 3, pp. 234–2

Sgarbossa, F., Peron, M., Lolli, F. and Balugani, E. (2021), "Conventional or additive manufacturing for spare parts management: An extensive comparison for Poisson demand", *International Journal of Production Economics*, Vol. 233, p. 107993, doi: 10.1016/j.ijpe.2020.107993.81, doi: 10.1016/0022-2496(77)90033-5.

Infrastructure and Participation in Cargo-Bike Crowdshipping: A Discrete Choice Experiment

Sun-Ho Bang[1], Jia-Rong Chen[2], Kwang-Sup Shin[1], Mark Goh[3], Woojung Kim[1]

1: Incheon National University, Korea, Republic of South Korea; 2: Kyungpook National University, Korea, Republic of South Korea; 3: National University of Singapore, Singapore

Purpose of this paper

The rapid growth of e-commerce has intensified the demand for last-mile delivery in urban areas, exacerbating traffic congestion, greenhouse gas emissions, and competition for limited kerb space. In response, crowdsourced delivery has emerged as a flexible complement to traditional logistics systems with the view to improving sustainability in urban freight operations. Crowdshipping research has primarily focused on the socio-demographic and attitudinal predictors of delivery participation (Cebeci et al., 2023; Fessler et al., 2022), while systematic reviews highlight ongoing operational challenges that may constrain large-scale implementation (Mohri et al., 2023). However, the role of urban infrastructure in shaping operational participation decisions remains insufficiently understood. This gap is particularly critical for cargo-bike-based delivery, which is increasingly promoted as a low-emission logistics alternative but whose feasibility depends heavily on infrastructural readiness, including cycling safety, route continuity, and traffic conditions. Participation in this context reflects a behavioral response to working conditions rather than a purely attitudinal intention. Therefore, this underscores the importance of examining operational factors that affect delivery workforce availability.

Addressing this gap, our study investigates how infrastructural conditions and operational job attributes jointly influence the willingness of individuals to accept cargo-bike delivery tasks. By identifying the conditions under which such individuals are more likely to engage in delivery work, we hope to advance a behaviorally grounded understanding of crowdshipping labor supply and support the development of scalable and environmentally sustainable last-mile logistics systems.

Design/methodology/approach

This study employs a stated preference discrete choice experiment to model how participants evaluate and accept cargo-bike delivery tasks under varying operational conditions. The study respondents are presented with hypothetical delivery scenarios in which the transportation mode is fixed to cargo bikes, while key job attributes vary systematically. The attributes include compensation, safety provisions, workload, equipment requirements, delivery window flexibility, and the quality of supporting urban infrastructure, particularly cycling safety and route continuity.

The study focuses on the task acceptance behaviour, enabling the analysis to capture how individuals respond to realistic delivery constraints commonly encountered in crowdshipping environments. By examining participation as an operational decision, the study provides a structured approach to understanding labor supply mechanisms within emerging logistics systems.

The data obtained from the experiment are analyzed using multinomial and conditional logit models to estimate the task acceptance probabilities and quantify the willingness to accept compensation under adverse operating conditions. These choice models facilitate the identification of marginal effects associated with infrastructural improvements and job design attributes, drawing on established discrete choice modelling approaches (Sarrias & Daziano, 2017). This methodological framework supports a systematic evaluation of how operational conditions influence participation decisions and provides an empirical basis for assessing workforce availability in cargo-bike-based delivery systems.

Findings

This study examines how infrastructural readiness and operational job attributes jointly influence individuals' willingness to accept cargo-bike delivery tasks. By estimating task acceptance probabilities and willingness-to-accept compensation under varying working conditions, the analysis provides empirical evidence on the behavioral mechanisms shaping the crowdshipping labor supply.

The findings contribute to identifying the value of infrastructural support and job design attributes in participation decisions, enabling a clearer understanding of how operational constraints affect the availability of delivery workers in urban logistics contexts. In particular, the study clarifies how variations in working conditions are associated with differences in task acceptance, offering a structured basis for evaluating participation behavior in cargo-bike-based delivery systems.

The analysis captures variation in participation preferences across individuals and gender, providing insights into how labor supply responses may differ under heterogeneous operational environments. Understanding these variations is important for assessing the extent to which crowdshipping platforms can rely on flexible delivery labor under various urban conditions.

The results provide an empirical foundation for evaluating how infrastructure and delivery job design interact to influence participation decisions. By quantifying behavioral responses to operational attributes, the study supports informed assessments of workforce availability and contributes to evidence-based discussions on the design of scalable and sustainable last-mile logistics systems.

Value

This study contributes to the urban logistics literature by shifting the analytical focus from attitudinal intention toward operationally grounded participation behavior. While research has largely examined who is willing to participate in crowdshipping, this study advances the understanding by identifying the operational conditions under which individuals are willing to accept delivery tasks.

By integrating behavioral choice modelling with infrastructural attributes, the study provides an early empirical examination into how cycling environments influence labor supply in cargo-bike-based logistics systems. The findings generate actionable insights for policymakers, platform operators, and urban planners seeking to scale low-emission delivery solutions without compromising workforce stability.

Moreover, conceptualizing participation as a task acceptance decision establishes a replicable analytical framework for examining labor supply in emerging logistics models, supporting pertinent research on sustainable and resilient last-mile delivery systems.

References

Cebeci, M. S., Tapia, R. J., Kroesen, M., de Bok, M. A., & Tavasszy, L. (2023). The effect of trust on the choice for crowdshipping services: Evidence from a stated choice experiment. Transportation Research Part A: Policy and Practice, 170, 103622.

Fessler, A., Thorhauge, M., Mabit, S. L., & Haustein, S. (2022). A public transport-based crowdshipping concept as a sustainable last-mile solution: Assessing user preferences with a stated choice experiment. Transportation Research Part A: Policy and Practice, 158, 210–223.

Mohri, S. S., Ghaderi, H., Nassir, N., & Thompson, R. G. (2023). Crowdshipping for sustainable urban logistics: A systematic review. Transportation Research Part E: Logistics and Transportation Review, 176, 103145.

Sarrias, M., & Daziano, R. (2017). Multinomial logit models with continuous levels of alternatives. Transportation Research Part B: Methodological, 103, 42–59.

Model for Shaping Innovative Logistics Services for Supply Chains by Logistics Service Providers (LSPs, 3PLs, 4PLs)

Iwona Wasielewska-Marszałkowska

Nicolaus Copernicus University in Torun, Poland

Purpose of this paper

Changing political and economic conditions and growing customer demands are forcing logistics service providers to adapt to changes in the logistics services offered by modern supply chains. As indicated in the literature, research on innovation, innovation in logistics services for supply chains, and the role of the most developed models for providing these services (3PL operators and 4PL logistics integrators) has been ongoing for several decades and is becoming increasingly popular among many researchers, but this area has not been fully explored. This aspect has also been highlighted by other researchers, such as Flint, Larsson et al. (2005).

The dynamics of globalization, including new trends in the economy, require continuous research and focus on this issue. Regardless of positions and views, it seems reasonable to conclude that research on innovation should be further developed and deepened, both in theoretical considerations and empirical research.

Therefore, for Logistics Service Providers, activities related to the implementation of innovation, especially in the face of turbulent changes and advancing digitalization, play an important role in supply chain logistics services.

This article presents selected research results that have made it possible to propose a model for shaping the innovativeness of logistics services in supply chains by LSPs.

Design/methodology/approach

A multi-stage research approach was used, including a systematic literature review in line with the concept of Tranfield, Denyer, and Smart (2003) and the use of the PRISMA approach (Page et al., 2020). The results of the literature review showed a lack of empirical research on this topic. The next step was to conduct empirical research using several research methods (quantitative research method, Delphi method, and case study). The case study method was based on the approach proposed by R.K. Yin (2015), both in terms of methodology and the definition of a research case. Individual case studies were conducted. The Delphi study was conducted among experts, bearing in mind that it involves the structuring of a group communication process that enables a group of independent experts to jointly solve a complex problem (Linstone, Turoff, 1975), while the knowledge and experience of the people (experts) participating in the study determine the reliability of the Delphi study results (Hasson, Keeney, 2011) (Wasielewska-Marszałkowska 2023). The Delphi study involved 11 experts from Poland, 12 experts from Slovakia, and 12 experts from Bulgaria, while the case study included the 11 largest LSPs (3PLs, 4PLs) in Poland and Slovakia and the 5 largest LSPs (3PLs, 4PLs) in Bulgaria.

Findings

The analysis of the research results, as well as the conclusions and findings from the research, allowed to propose a model for shaping innovative logistics services for modern supply chains by logistics operators and integrators. The developed model consists of key components, namely:

- participants in the process of shaping innovative logistics services,
- internal factors, both stimulating and blocking the creation of innovation and innovative forms (services and solutions) in the logistics services of supply chains,
- external factors, both motivating and preventing the implementation of any innovations or innovative forms in the logistics of supply chains,
- the process of shaping innovation in the logistics of supply chains, broken down into eight stages,

- innovative solutions in supply chain logistics developed within four types of supply innovations,
- the efficiency of supply chain logistics, treated as the result of the process of shaping innovation in supply chain logistics.

The component of participants in the process of shaping innovative logistics services, as determined by empirical research, should be interpreted as entities that are involved in creating the process of innovative logistics services. Therefore, based on the conclusions of the research, the following entities were identified:

- 3PL operators and 4PL logistics integrators and their employees, as well as dedicated departments established to conduct research and cooperate with other entities in the field of innovative activities, identified as internal stimulating factors,
- competitors (competition), who were identified as an external stimulating factor,
- customers, who are, on the one hand, a causative factor and, on the other hand, recipients of developed and implemented innovative solutions (innovations),
- scientific centers, research institutes, open not only to conducting research in the field of innovation and innovative solutions, but also interested in cooperation with enterprises and the implementation of research results in economic practice,
- start-ups, i.e., companies focused on testing, developing, and implementing new innovative solutions, open to cooperation with operators and logistics integrators in this area,
- government (public authorities of individual countries), closely linked to legal and political regulations, which have been identified as external factors that stimulate but also limit innovation.

It should also be emphasized that the entities indicated in the model are in line with the approach proposed by H.W. Chesbrough, referred to as open innovation. This approach focuses on drawing ideas from both inside and outside the company, i.e., ideas generated by various entities, often the direct recipients (users) of the developed innovations.

The adopted components and the constructed model can serve as a basis for further in-depth research and analysis in this area. In the author's opinion, they should focus, among other things, on finding ways to overcome barriers, i.e., factors limiting the possibility of creating a process and implementing innovations and innovative solutions in logistics services by Logistics Service Providers. (Due to the abstract limit, the graphic form of the developed model has not been presented.).

Research limitations/implications

The results obtained should be interpreted with due regard to significant limitations. The main limitation is the fact that the empirical research was conducted on a sample of logistics service providers from selected Central and Eastern European countries (Poland, Slovakia, Bulgaria), which may limit the possibility of generalizing the conclusions to other regions with different institutional, economic, and technological conditions.

Practical implications

The proposed model for shaping innovative logistics services for supply chains by logistics operators and integrators can and should provide logistics service providers with suggestions and valuable guidance on how to shape innovation in logistics services, adapt model components to the current market situation, and thus build and maintain a competitive advantage.

References

Chesbrough H.W., (2003). Open Innovation. The New Imperative for Creating and Profiting from Technology, Harvard Business School Press, Boston.

Flint, D. J., Larsson, E., Gammelgaard, B., & Mentzer, J. T. (2005). Logistics innovation: A customer value-oriented social process. Journal of Business Logistics, 26 (1), pp. 113-147, https://doi.org/10.1002/j.2158-1592.2005.tb00196.x.

Hasson F., Keeney S. (2011). Enhancing rigour in the Delphi technique research, Technological Forecasting and Social ChangeVol. 78, No. 9, pp. 1695-1704, https://doi.org/10.1016/j.techfore.2011.04.005

Linstone H.A., Turoff M. (1975). The Delphi method: Techniques and applications, Addison-Wesley, London.

Page M.J., Moher D., Bossuyt P.M., Boutron I., Hoffmann T.C., Mulrow C. D. et al. (2021). PRISMA 2020 explanation and elaboration: updated guidance and exemplars for reporting systematic reviews BMJ, 372, 160. https://doi.org/10.1136/bmj.n71.

Tranfield D., Denyer D., Smart P., (2003). Towards a methodology for developing evidence-informed management knowledge by means of systematic review, British Journal of Management, Vol. 14, Issue 3, pp. 207–222. https://doi.org/10.1111/1467-8551.00375 .

Business-to-Business Sharing Platforms in Chinese Electronics Supply Chains: Drivers, Value Capture and Environmental Sustainability

Zhang Jiayi

University of Sussex, United Kingdom

Purpose of this paper

This paper explains how business-to-business (B2B) sharing-economy practices contribute to environmental sustainability in Chinese electronics manufacturing, and under which institutional and organisational conditions such contributions materialise. It responds to ongoing debates about whether the sharing economy can deliver environmental benefits beyond cost reduction, and to the scarcity of empirical evidence from high-impact manufacturing sectors and emerging economies. Focusing on B2B sharing platforms through which electronics firms access externally controlled production capacity, logistics infrastructure and service resources, the study examines the influence of four drivers—actor pressure, market uncertainty, servitization and innovation diffusion—on value capture from B2B sharing practices. It then investigates how value capture from B2B sharing relates to environmental sustainability performance and whether it mediates the effects of these drivers. By concentrating on Chinese electronics supply chains, where environmental regulation, global buyer requirements and technological turbulence are particularly salient, the paper provides a theoretically grounded and empirically robust assessment of when and how B2B sharing can be aligned with environmental sustainability objectives.

Design/methodology/approach

The paper develops an integrated framework that combines institutional theory, resource dependence theory and the practice-based view. Actor pressure is conceptualised as coercive, normative and mimetic influences from regulators, industry associations, key customers and competitors. Market uncertainty, servitization and innovation diffusion are theorised as resource-dependence and capability-based conditions that heighten firms' need and ability to access external resources via B2B sharing arrangements. Drawing on the practice-based view, B2B sharing is treated as a bundle of organisational practices for accessing externally owned capacity and services, and value capture from B2B sharing as the economic and strategic benefits realised through these practices. Environmental sustainability performance is defined as improvements in resource and energy efficiency, reductions in waste and hazardous materials, and enhanced environmental image. The framework is tested using survey data from 300 managers in Chinese electronics manufacturing firms. Confirmatory factor analysis is used to assess the reliability and validity of the constructs, and structural equation modelling with mediation analysis (PROCESS) is used to estimate the proposed relationships.

Findings

The measurement model exhibits satisfactory reliability and validity for all constructs. Structural equation modelling shows that actor pressure, market uncertainty, servitization and innovation diffusion each have a significant positive effect on value capture from B2B sharing practices. Firms that are more strongly exposed to institutional pressures, operate in more turbulent markets, pursue more advanced service strategies and possess stronger innovation diffusion capabilities realise higher levels of economic and strategic benefits from B2B sharing. Crucially, value capture from B2B sharing is strongly and positively associated with environmental sustainability performance: firms that capture more value from sharing arrangements also report better performance in reducing resource and energy use, waste and hazardous materials, and in improving their environmental image. Mediation analysis demonstrates that value capture from B2B sharing mediates the relationships between the four drivers and environmental sustainability performance. This indicates that the environmental implications of institutional and resource-dependence conditions are realised primarily through the way firms configure and

monetise B2B sharing practices. An additional analysis shows that trust in B2B platform providers has a positive main effect on environmental performance but modestly attenuates the marginal environmental benefit of additional value capture, suggesting a nuanced interplay between relational conditions and value-capture strategies.

Value

The paper extends sharing-economy research into a B2B industrial context, providing rare large-sample evidence from Chinese electronics manufacturing and empirically aligns value capture from B2B sharing with environmental sustainability performance in electronics manufacturing firms. It demonstrates, using large-sample data, that in the Chinese electronics context economic and strategic value capture from B2B sharing is not in tension with environmental performance but is positively associated with it, and acts as the main mechanism through which institutional, market and organisational drivers translate into environmental outcomes. This advances sharing-economy and sustainable business model research by moving beyond generic claims about "potential" environmental benefits and specifying when and how value-capture practices support environmental improvement. In addition, it advances a theoretically integrated explanation of B2B SE by combining institutional, resource-dependence and practice-based perspectives and demonstrating empirically that value capture from B2B SE is the primary mechanism linking external pressures and internal capabilities to environmental sustainability outcomes. Managerially, the findings indicate when and how B2B sharing arrangements are most likely to generate both economic and environmental benefits, highlighting the importance of investing in servitized offerings, internal innovation capabilities and collaborative relationships with platform providers.

Practical implications

For managers in electronics manufacturing, the results emphasise that B2B sharing should be regarded as a strategic component of business model and sustainability innovation rather than a peripheral experiment. Firms facing strong actor pressure, high market uncertainty, advanced servitization and strong innovation diffusion capabilities are particularly well positioned to benefit. Managers should design B2B sharing arrangements that prioritise high utilisation of existing assets, integration with service offerings and transparent collaboration with platform providers. Policymakers and industry associations can use these insights to design regulations, incentives and support programmes that promote substantive, value-generating B2B sharing practices aligned with environmental objectives.

Research limitations/implications

The cross-sectional survey design limits causal inference and cannot capture the dynamic evolution of B2B sharing practices and performance. The focus on Chinese electronics manufacturing constrains generalisability to other sectors and institutional contexts, and reliance on self-reported data introduces potential common-method bias. Future research could employ longitudinal and mixed-method designs, incorporate objective environmental indicators and extend the framework to other industries and countries. Further studies might also disaggregate value capture into cost, revenue and risk components and explore interactions between B2B sharing and other circular-economy strategies.

References

Baines, T.S., Lightfoot, H.W., Benedettini, O. and Kay, J.M. (2009) 'The servitization of manufacturing: A review of literature and reflection on future challenges', Journal of Manufacturing Technology Management, 20(5), pp. 547–567.

Bocken, N.M.P., Short, S.W., Rana, P. and Evans, S. (2014) 'A literature and practice review to develop sustainable business model archetypes', Journal of Cleaner Production, 65, pp. 42–56.

Delmas, M.A. and Toffel, M.W. (2008) 'Organizational responses to environmental demands: Opening the black box', Strategic Management Journal, 29(10), pp. 1027–1055.

Frenken, K. and Schor, J. (2017) 'Putting the sharing economy into perspective', Environmental Innovation and Societal Transitions, 23, pp. 3–10.

Teece, D.J. (2010) 'Business models, business strategy and innovation', Long Range Planning, 43(2–3), pp. 172–194.

Zhu, Q. and Sarkis, J. (2007) 'The moderating effects of institutional pressures on emergent green supply chain practices and performance', International Journal of Production Research, 45(18–19), pp. 4333–4355.

Trust-Based Blockchain Architectures for Regenerative Food Supply Chains: A Proof-of-Trust Approach Using a Tomato Supply Chain Case

Alexandra Fiedler, Robert Schönfeld, Sven Karol, Dirk Sackmann, Richard Reinick, Merle Wilk

University of Applied Sciences Merseburg, Germany

Purpose of this paper

Food supply chains (FSCs) face persistent challenges related to transparency, trust asymmetries, and limited coordination capacity, which hampers both sustainability and circularity. In this paper, we focus on regenerative supply chains - systems that not only reduce environmental harm but restore ecological and social value by enabling circular flows such as donation, composting, or bioenergy recovery. FSCs are particularly prone to information asymmetries and fragmented governance, making trust a central requirement for coordination and fair decision-making (Vasileiou et al. 2025).

In perishable supply chains, asymmetric data access, cold-chain breaks, and limited automation contribute to food loss, inefficiency and lack of accountability. Although permissioned blockchain architectures have been proposed to enhance traceability and data integrity (Rajput et al. 2025), practical adoption remains limited. A major barrier is that many blockchain systems rely on high-computing-power consensus mechanisms (e.g., Proof-of-Work (PoW), which do not align with the governance structures and trust relationships found in real supply chains. Emerging research shows blockchain can support circular practices by strengthening traceability and trust (Olech and Anyebe 2024; Shiraishi et al. 2025).

To address these challenges, this study proposes a trust-based blockchain architecture tailored to regenerative FSCs. Building on reputation-based consensus research (Sarfaraz et al. 2023), we introduce a Proof-of-Trust (PoT) consensus mechanism that prioritises stakeholder credibility, roles, and behavioural history rather than computational effort or token ownership. A supporting prototype and use cases illustrate how trust-aware digital infrastructures can strengthen regenerative outcomes.

The research aims to:

(1) conceptualise PoT as a consensus mechanism for regenerative supply chains,
(2) validate its applicability through supply chain scenarios, and
(3) demonstrate how trust-based infrastructures can support regenerative supply-chain intelligence beyond traditional sustainability metrics.

Design/methodology/approach

We apply a design-science research methodology combining conceptual modelling, artefact development, and scenario-based evaluation. A detailed analysis of a food supply chain identifies decision points where trust and data integrity strongly influence outcomes (e.g., quality deviations, cold-chain disruptions, contractual breaches, and routing of surplus products into circular recovery pathways).

We develop a stakeholder and role model that maps supply-chain actors (producers, logistics providers, wholesalers, retailers, recyclers, and regulators) to blockchain permissions (transaction initiators, validators, observers) and obligations. This model is essential because PoT weights actions based on roles rather than anonymous authority.

Trust is formalised as a multi-dimensional construct, combining: institutional credibility, economic incentives and role-relevant responsibilities, historical compliance behaviour, data reliability and interaction quality. These dimensions form the trust score used for PoT-based validation.

To operationalise PoT, we built a containerised blockchain runtime, deployable on simple hardware using open-source components. Its architecture supports modular consensus logic, meaning trust-weighting methods can be adapted without infrastructure replacement. Scenario-based testing simulates temperature deviations, delays, and circular recovery triggers, evaluating system behaviour, trust-based validation, and governance alignment.

Findings

The evaluations show that PoT supports faster and more context-sensitive validation compared to high-computing-power mechanisms (e.g., PoW), and significantly reduces computational and energy requirements. Automated contracts combined with trust-differentiated roles improve responsiveness to deviations and support efficient, auditable rerouting of products into circular recovery options.

The containerised blockchain environment supports modular consensus logic and effective integration of trust-based validation rules. Observations suggest that trust is highly context-dependent, varying across roles, historical behaviour, and data quality - confirming the need for differentiated rather than uniform consensus privileges. While still being refined, the prototype demonstrates PoT's feasibility and highlights its potential to align digital infrastructure with real governance structures in regenerative FSCs.

Value

The paper contributes original value by introducing and operationalising a Proof-of-Trust consensus within a functioning prototype for regenerative supply chains. Unlike many existing blockchain approaches centred on traceability or token-based incentives, PoT embeds trust, role-based governance, and circular decision logic as primary design features. It offers practitioners and researchers a blueprint for trust-aware, permissioned blockchain systems, with the FSC use case demonstrating broader applicability to other perishable and circular supply chains.

Research limitations/implications

The findings are based on a prototype and simulation rather than industrial deployment. Long-term behavioural effects, performance scalability, and cross-tier interoperability require further study. Future research should formalise trust metrics, evaluate governance consequences of trust-weighted validation rights, and test PoT in multi-tier networks.

Practical implications

For practitioners, trust-aware blockchain designs provide a pathway to move beyond generic consensus mechanisms toward governance-aligned, low-energy, high-responsiveness infrastructures. By aligning validation privileges with verifiable trust dimensions, PoT can reduce overhead, increase transparency, and strengthen circular outcomes in regenerative FSCs.

References

Olech, Igor; Anyebe, Daniel (2024): From Trust to Circular Economy: Evolution of Blockchain's Impact on Agri-Food Supply Chains. In: JARD 73 (3). DOI: 10.17306/j.jard.2024.01839.

Rajput, Devraj V.; More, Pavankumar R.; Adhikari, Preeti A.; Arya, Shalini S. (2025): Blockchain technology in the food supply chain: a way towards circular economy and sustainability. In: Sustainable Food Technology 3 (4), S. 930–946. DOI: 10.1039/D5FB00065C.

Sarfaraz, Aaliya; Chakrabortty, Ripon K.; Essam, Daryl L. (2023): Reputation based proof of cooperation: an efficient and scalable consensus algorithm for supply chain applications. In: J Ambient Intell Human Comput 14 (6), S. 7795–7811. DOI: 10.1007/s12652-023-04592-y.

Shiraishi, Carlos S. H.; Roriz, Custódio Lobo; Carocho, Márcio; Prieto, Miguel A.; Abreu, Rui M. V.; Barros, Lillian; Heleno, Sandrina A. (2025): Blockchain revolution in food supply chains: A

positive impact on global food loss and waste. In: Food Chemistry 467, S. 142331. DOI: 10.1016/j.foodchem.2024.142331.

Vasileiou, Marios; Kyrgiakos, Leonidas Sotirios; Kleisiari, Christina; Lappas, Pantelis Z.; Tsinopoulos, Christos; Kleftodimos, Georgios et al. (2025): Digital Transformation of Food Supply Chain Management Using Blockchain: A Systematic Literature Review Towards Food Safety and Traceability. In: Bus Inf Syst Eng. DOI: 10.1007/s12599-025-00948-0.

Blockchain Adoption Maturity for an Integrated and Regenerative Agricultural Supply Chain: A Dynamic Capability Perspective

Minh Luu, Hung Nguyen, Irfan Ul Haq

The Business School, RMIT University, Vietnam

Purpose of this paper

The traditional agricultural supply chain (SC) often faces critical challenges related to traceability, transparency, integration, and sustainable farming practices, all essential to advancing regenerative agriculture (Vasileiou et al., 2025; Vern et al., 2025). These challenges can hinder the ability of agricultural stakeholders to meet increasing consumer and regulator demands for safe, high-quality and ethically produced products, creating a pressing need for innovative solutions (Pal et al., 2025; Vu et al., 2023). Blockchain (BC) technology is recognized for its transformative potential to address these challenges (Queiroz et al., 2021; Shaharudin et al., 2022; Sharma et al., 2023); however, BC adoption within the agricultural SC remains underdeveloped and inconsistent across contexts (Sternberg et al., 2021). This discrepancy raises concerns about the practical feasibility and actual outcomes of BC implementation.

Furthermore, the literature reveals a significant research gap, as studies examining end-to-end BC lifecycle adoption remain scarce. Most existing research focuses on conceptual frameworks or remains at the pre-adoption stage, lacking empirical evidence on actual implementation and post-adoption outcomes (Mishra et al., 2025; Rogerson & Parry, 2020). This gap stems from the tendency to view BC adoption as a static implementation decision, rather than an evolutionary, multi-stage process (Fosso Wamba & Queiroz, 2022), which limits our understanding of how firms develop capabilities and allocate resources to adopt, integrate, and leverage BC over time. To address these critical gaps, our study employs Dynamic Capability Theory (Teece et al., 1997) to conceptualize BC adoption as a strategic capability-building process with three stages: sensing, seizing, and transforming. To examine the end-to-end adoption process of BC in the agricultural SC, this study aims to answer the following three research questions:

1) How do agricultural stakeholders perceive BC adoption motivations and challenges (sensing)?

2) How do agricultural stakeholders make BC adoption decisions (seizing)?

3) How do BC adoption decisions influence SC integration and regenerative SC performance (transforming)?

Design/Method/Approach

This study employs the Dynamic Capabilities Theory (DCT) as the theoretical framework because DCT explains how organizations adapt to emerging digital technologies in the turbulent business environment through capability development and strategic reconfiguration (Teece et al., 1997), making it particularly suitable for investigating BC-enabled agricultural SC transformation.

A qualitative multiple-case study is employed to explore in-depth, contextual understandings and the emerging patterns of BC adoption (Yin, 2018). Vietnam serves as the empirical setting due to its strong agricultural export performance (Ministry of Agriculture and Environment, 2025), but underdeveloped digitalization and technology application (Yap et al., 2023), making it a compelling research context.

With a theoretical sampling approach, eight cases (agricultural organizations) were purposively selected to ensure diversity across product categories, SC roles, organizational size, and BC adoption maturity. Each case represents a focal SC actor within respective SC networks, with the SC serving as the unit of analysis.

Data collection involved semi-structured interviews, field visits and analysis of company documents (triangulation). A total of 21 interviews were conducted with senior managers, operational staff, and external experts. We visited 6 companies. The analyzed company

documents included annual reports, operational manuals, and internal memos. Interview transcripts were analyzed in NVivo using iterative thematic coding (Braun & Clarke, 2021) and cross-case analysis (Kittipanya-ngam & and Tan, 2020).

Findings

Sensing (antecedents): Our findings indicate that all firms view BC adoption as an opportunity to meet institutional and market demands for product traceability, transparency, and sustainability. However, adoption is constrained by limited resources and infrastructure, insufficient technical expertise, low partner readiness, and resistance to change. Notably, some firms adopt BC as a strategic move to strengthen their reputations as technological innovators, whereas others resist BC because they fear that greater transparency would expose their non-compliant business practices (e.g., tax irregularities).

Seizing (decisions): The results show that adoption decisions vary across cases, depending on resource availability (limited or abundant) and the strategic intent (symbolic adoption, compliance-driven adoption, or strategic SC transformation). Cross-case analysis identifies two key dimensions of adoption maturity: scope, referring to the number of SC processes using BC (single or multiple) and depth, indicating the degree of BC integration across SC partners (internal or inter-organizational). Based on these dimensions, four adoption maturity configurations emerge. The Minimalist (4 cases) adopts BC for a single SC process with no external integration. The Technology Initiative (1 case) expands BC usage to multiple SC processes internally. The Integration Initiative configuration (1 case) emphasizes external partner integration with a single process. Lastly, the Proactive (2 cases) demonstrates the highest level of BC adoption maturity, with various processes and extensive partner integration. Overall, these maturity configurations reveal that BC adoption follows multiple strategic pathways rather than a linear process, which explains the diversity in adoption outcomes.

Transforming (outcomes): While all firms confirmed that BC adoption consistently enhances SC traceability and transparency, the broader SC performance outcomes vary across maturity configurations. Firms with higher partner integration demonstrate better SC integration in terms of information sharing, trust, and collaboration, whereas firms with more diverse SC processes show better SC operational efficiency thanks to automated smart contracts. Remarkably, our findings challenge the common assumption that BC can directly generate regenerative SC performance. Instead, firms only consider BC as a verification mechanism to validate regenerative practices and prevent greenwashing. Furthermore, because BC guarantees data immutability rather than accuracy, firms suggest complementary technologies, such as IoT, to monitor and automate data-capturing processes.

In short, the adoption process of BC is not a uniform pathway for all firms but a case-specific, evolutionary, capability-building process, depending on resource allocation, capability reconfiguration, and strategic priorities.

Value

This study contributes to BC and SC literature in several ways. First, through the lens of Dynamic Capabilities Theory, our study enhances the understanding of digital transformation by explaining how firms progress through sensing, seizing, and transforming, thereby emphasizing that BC adoption is a progressive, capacity-reconfiguring process. Second, it advances BC adoption research by providing empirical evidence on the end-to-end adoption process within the context of an emerging economy. Third, this study introduces a novel typology of BC adoption maturity to explain heterogeneous adoption pathways and performance outcomes. Lastly, the study refines prevailing assumptions about BC-enabled sustainability by showing that BC primarily functions as a verification tool rather than a direct driver of regenerative agriculture performance. Practically, the study offers valuable insights for practitioners seeking to strategically implement BC in their agricultural SC.

Research Limitations

While the study encompasses eight cases within Vietnam’s agricultural sector, it may not fully capture the diversity of BC adoption practices across other institutional/cultural contexts, limiting

its generalizability. Future research could extend to different geographies or industries, conduct longitudinal studies to examine how BC adoption maturity evolves over time, or use quantitative methods to validate the proposed maturity typology with larger datasets.

Practical Implications

Agricultural managers should approach BC adoption as a multi-staged process rather than a one-time investment. Firms with limited resources can start with pilot BC projects, while firms pursuing SC transformation should extend BC adoption to both processes and partner integration. Complementary technologies, such as IoT or AI, are crucial for ensuring accurate and reliable data in BC systems.

References

Braun, V., & Clarke, V. (2021). *Thematic Analysis*. SAGE Publications. https://uk.sagepub.com/en-gb/eur/thematic-analysis/book248481

Fosso Wamba, S., & Queiroz, M. M. (2022). Industry 4.0 and the supply chain digitalisation: A blockchain diffusion perspective. *Production Planning & Control*, *33*(2–3), 193–210. https://doi.org/10.1080/09537287.2020.1810756

Kittipanya-ngam, P., & and Tan, K. H. (2020). A framework for food supply chain digitalization: Lessons from Thailand. *Production Planning & Control*, *31*(2–3), 158–172. https://doi.org/10.1080/09537287.2019.1631462

Ministry of Agriculture and Environment. (2025). Promising growth in agricultural exports. *Nhan Dan Online*. https://en.nhandan.vn/promising-growth-in-agricultural-exports-post143036.html

Mishra, N. K., Raj, A., Mukherjee, I., & Chakraborty, A. (2025). Blockchain adoption in the supply chain management based on technology–organization–environment framework: Evidence from developing and developed economies. *Journal of Business & Industrial Marketing*, *40*(3), 815–832. https://doi.org/10.1108/JBIM-04-2024-0253

Pal, T., Bommisetti, V., Suvarnakanti, P., Dudala, S. S., Asha, S., & Jaiswal, V. (2025). The Revolutionary Role of Blockchain Technology in the Agri-Food Sector Focusing on the Food Supply Chain. *Food Reviews International*, *41*(3), 770–801. https://doi.org/10.1080/87559129.2024.2418464

Queiroz, M. M., Fosso Wamba, S., De Bourmont, M., & Telles, R. (2021). Blockchain adoption in operations and supply chain management: Empirical evidence from an emerging economy. *International Journal of Production Research*, *59*(20), 6087–6103. https://doi.org/10.1080/00207543.2020.1803511

Rogerson, M., & Parry, G. C. (2020). Blockchain: Case studies in food supply chain visibility. *Supply Chain Management: An International Journal*, *25*(5), 601–614. https://doi.org/10.1108/SCM-08-2019-0300

Shaharudin, M. S., Fernando, Y., Ganesan, Y., & Shahudin, F. (2022). Development of Blockchain Agriculture Supply Chain Framework Using Social Network Theory: An Empirical Evidence Based on Malaysian Agriculture Firms. In *The Digital Agricultural Revolution* (pp. 411–445). https://doi.org/10.1002/9781119823469.ch19

Sharma, Anandika, Sharma, Anupam, Singh, R. K., & Bhatia, T. (2023). Blockchain adoption in agri-food supply chain management: An empirical study of the main drivers using extended UTAUT. *Business Process Management Journal*, *29*(3), 737–756. https://doi.org/10.1108/BPMJ-10-2022-0543

Sternberg, H. S., Hofmann, E., & Roeck, D. (2021). The Struggle is Real: Insights from a Supply Chain Blockchain Case. *Journal of Business Logistics*, *42*(1), 71–87. https://doi.org/10.1111/jbl.12240

Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. *Strategic Management Journal*, *18*(7), 509–533. https://doi.org/10.1002/(SICI)1097-0266(199708)18:7%253C509::AID-SMJ882%253E3.0.CO;2-Z

Vasileiou, M., Kyrgiakos, L. S., Kleisiari, C., Lappas, P. Z., Tsinopoulos, C., Kleftodimos, G., Ntemou, A., Kateris, D., Moulogianni, C., & Vlontzos, G. (2025). Digital Transformation of Food Supply Chain Management Using Blockchain: A Systematic Literature Review Towards Food Safety and Traceability. *Business & Information Systems Engineering*. https://doi.org/10.1007/s12599-025-00948-0

Vern, P., Panghal, A., Mor, R. S., Kumar, V., & Sarwar, D. (2025). Unlocking the potential: Leveraging blockchain technology for agri-food supply chain performance and sustainability. *The International Journal of Logistics Management*, *36*(2), 474–500. https://doi.org/10.1108/IJLM-09-2023-0364

Vu, N., Ghadge, A., & Bourlakis, M. (2023). Blockchain adoption in food supply chains: A review and implementation framework. *Production Planning & Control*, *34*(6), 506–523. https://doi.org/10.1080/09537287.2021.1939902

Yap, T. L., Nayak, R., Vu, N. T. H., Bui, D. T., Pham, T. T. T., & Allen, D. W. E. (2023). Adopting blockchain-based traceability in the fruit supply chain in a developing economy: Facilitators and barriers. *Information Technology & People*. https://doi.org/10.1108/ITP-02-2023-0168

Yin, R. (2018). *Case Study Research and Applications* (6th ed.). SAGE Publications, Inc. https://uk.sagepub.com/en-gb/eur/case-study-research-and-applications/book250150

Decarbonising Fast-Fashion Logistics: Digital Twin Evidence to Support Sustainable UK–Sri Lanka Textile Trade

Reem Hadeed[1], Md Hanif Seddiqui[1], Rivini Mataraarachchi[2], Muhammad Azmat[1], Nandhini Mahesh[1]

1: Aston University, United Kingdom; 2: University of Moratuwa, Sri Lanka

Purpose of this paper

The purpose of this paper is to generate policy-relevant and industry-grounded evidence on how freight transport decarbonisation can be achieved in fast-fashion supply chains without undermining export competitiveness in Global South production hubs. International freight transport remains a significant and growing contributor to global greenhouse gas emissions, with apparel supply chains particularly exposed due to long distances, tight lead times, and frequent dependence on carbon-intensive air freight (UNCTAD, 2023). Despite increasing regulatory attention in importing countries such as the UK, decarbonisation strategies often focus on downstream markets and logistics providers, with limited empirical consideration of upstream production realities in exporting countries (BEIS, 2021).

This research focuses on apparel trade between Sri Lanka and the United Kingdom, a strategically important corridor linking a major Global South textile producer with a high-consumption, policy-active market. Sri Lanka's apparel sector is central to national export earnings and employment, yet faces structural logistics challenges, including volatility in demand, exposure to air freight cost shocks, and increasing sustainability compliance pressures from international buyers (Marwah, R., & Ramanayake, S. S, 2024). These pressures are particularly pronounced in fast-fashion segments, where speed-to-market incentives frequently conflict with emissions reduction objectives.

The paper aims to demonstrate how a Digital Twin of real-world apparel logistics can be used to reconcile these competing pressures by enabling evidence-based evaluation of alternative freight strategies and policy interventions. Focusing on three product categories (activewear, intimates, and denim) the study examines how differences in lead-time sensitivity, production complexity, and demand volatility shape decarbonisation potential. By embedding producer-side operational data into a Digital Twin modelling framework, the research seeks to identify pathways that reduce emissions, stabilise production planning, and enhance export resilience, while generating actionable insights for UK sustainable freight and trade policy (BEIS, 2021).

Design/methodology/approach

This research employs a mixed-methods, case-based approach centred on developing and applying a bespoke Digital Twin of a Sri Lankan apparel manufacturer's supply chain for three product categories: activewear, intimates, and denim. The design involves in-person, collaborative engagement with the partner company in Sri Lanka to map logistics processes, collect operational data (e.g., transport modes, lead times, costs, carbon factors), and co-define key performance indicators. The Digital Twin, a dynamic computational model, serves as the primary analytical tool to simulate the end-to-end logistics from Sri Lankan factory to UK distribution. The methodology involves creating a baseline scenario and then running comparative simulations to evaluate the impact of alternative logistics practices (e.g., modal shift from air to sea, production planning adjustments, inventory optimisation) and policy interventions (e.g., carbon pricing, green corridor incentives). The approach is interdisciplinary, integrating supply chain management, sustainability science, and digital modelling to provide a holistic analysis of economic and environmental trade-offs.

Findings

Simulation results from the Digital Twin are expected to indicate that significant emissions reductions can be achieved in UK–Sri Lanka apparel logistics without proportionate increases in

total supply-chain costs, provided that decarbonisation interventions are tailored to product-specific characteristics. Across the three product categories, the model is expected to demonstrate whether air freight is a disproportionate contributor to emissions intensity, particularly for activewear and intimates, where short lead times and volatile demand frequently trigger last-minute shipments.

For activewear, the Digital Twin is expected to show that improved production planning and earlier order finalisation could substantially reduce reliance on air freight, enabling a shift towards lower-carbon sea transport with limited impacts on service levels. In the case of intimates, where product complexity and smaller batch sizes increase logistics variability, hybrid strategies combining sea freight with targeted inventory buffers are expected to have the potential to stabilise lead times while reducing emissions. Denim, characterised by longer production cycles and lower fashion volatility, is expected to exhibit the greatest decarbonisation potential, with simulations indicating that near-complete elimination of air freight may be feasible under existing commercial conditions.

At a system level, the expected findings are likely to highlight significant trade-offs between emissions reduction, cost efficiency, and operational resilience, while also identifying multiple "win–win" scenarios in which emissions and logistics costs decline simultaneously. Policy-aligned interventions, for example incentives for slower steaming, improvements in port efficiency, and regulatory signals discouraging routine use of air freight are expected to amplify these benefits. Importantly, the analysis is expected to demonstrate that decarbonisation strategies developed without producer-side input risk shifting costs and operational volatility upstream, whereas co-designed solutions are more likely to enhance export competitiveness and resilience for Sri Lankan manufacturers.

Value

This paper offers original value by applying a Digital Twin methodology to a real, global South to UK fast-fashion supply chain, moving beyond conceptual discussions of sustainable logistics to provide operationally grounded, policy-testable evidence. Unlike most freight decarbonisation studies, which focus on downstream markets or single transport modes, this research integrates product-level dynamics, producer-side constraints, and international policy considerations within a unified modelling framework.

The study is valuable to multiple audiences. For policymakers, it provides concrete evidence on how UK sustainable freight objectives interact with upstream production realities, supporting more inclusive and effective regulation. For industry stakeholders, particularly apparel exporters and buyers, it demonstrates how digital supply-chain tools can identify cost-effective decarbonisation pathways while improving operational stability. For researchers, the paper advances methodological approaches to Digital Twins in global supply chains and highlights the importance of equitable international collaboration in sustainability research.

Practical implications

The findings will have direct implications for supply chain managers and policymakers. For apparel manufacturers and logistics providers, the study will provide a replicable model for using digital twins to assess and implement low-carbon logistics strategies tailored to product characteristics. It will recommend practices like product category-specific transport planning and enhanced production scheduling to facilitate modal shift. For policymakers, particularly in the UK, the evidence will support the creation of targeted interventions, such as developing 'Green Textile Corridors' with Sri Lanka, which provide reliable, low-emission shipping options. The research would suggest that supporting supplier-side capacity and stability is essential for the viability of broader retail sector net-zero commitments. For Sri Lankan exporters, the research will highlight pathways to enhance competitiveness through stability and predictability rather than cost-cutting alone.

Research limitations/implications

This study is based on in-depth collaboration with a single major Sri Lankan apparel exporter, which may limit the generalisability of findings across the entire sector. While the selected firm

is representative of large-scale export operations, future research should extend the Digital Twin framework to multiple firms, different sourcing regions, and alternative destination markets. Data availability and confidentiality constraints also limit the resolution of certain operational parameters, particularly buyer-side decision rules. Future work could integrate real-time demand data and multi-tier supplier modelling to enhance predictive capability.

References

BEIS (2021). *Decarbonising Transport: A Better, Greener Britain*. UK Department for Business, Energy & Industrial Strategy. Decarbonising Transport – A Better, Greener Britain

Marwah, R., & Ramanayake, S. S. (2024). Pandemic-led trade shocks & supply chain disruption: case studies of the readymade garments (RMG) sector in Sri Lanka and Bangladesh. *International Journal of Innovation and Sustainable Development*, *18*(1-2), 45-70.

UNCTAD (2023). *Review of Maritime Transport 2023*. United Nations Conference on Trade and Development.
https://unctad.org/publication/review-maritime-transport-2023

CSR Relational Governance Mechanisms in Vietnamese Textile Supply Chains

Minh Pham[1,2], Thuy Nguyen[1], Aswini Yadlapalli[1], Paul Childerhouse[1]

1: Royal Melbourne Institute of Technology/RMIT University, Australia; 2: Foreign Trade University, Vietnam

Purpose of this paper

Corporate Social Responsibility (CSR) practices in global supply chains have traditionally relied on compliance-oriented mechanisms such as audits, codes of conduct, and monitoring systems. However, these mechanisms alone have delivered limited improvements in social conditions, particularly in labour-intensive and emerging-economy contexts (Huq et al., 2014; Yadlapalli et al., 2018). In parallel, digital transparency tools are increasingly promoted as mechanisms to enhance visibility and accountability, yet their effectiveness remains inconsistent and context dependent (Garcia-Torres et al., 2022; Schäfer et al., 2023).

This study aims to explore how CSR is understood, enacted, and negotiated by firms within Vietnam's textile supply chains. The study examines the role of relational governance mechanisms, particularly trust, collaboration, relational norms, and information sharing, in shaping firms' engagement with socially oriented CSR practices. Drawing on the relational view (Dyer & Singh, 1998) and social capital theory (Nahapiet & Ghoshal, 1998), the study addresses a gap in supply chain governance literature by shifting attention away from isolated examinations of formal compliance or technological solutions and towards the relational foundations of CSR. By focusing on textile firms operating in a major global sourcing hub characterised by weak institutional enforcement and strong relational norms, the research provides context sensitive insights into how CSR is negotiated in developing market supply chains.

Methodology approach

An interpretivist qualitative research design is adopted to capture how CSR practices are experienced and interpreted by firms within Vietnam's textile supply chains. Data is generated through semi-structured interviews with managers and key informants from textile firms, complemented by analysis of internal CSR-related documents and accounts of transparency and reporting practices currently in use.

An exploratory and abductive analytical approach is employed, allowing iterative movement between empirical material and theory (Chen et al., 2020). The analysis draws primarily on relational governance literature to examine how trust, collaboration, relational norms, and information sharing shape CSR practices at the firm level (Nyaga et al., 2010; Mwita et al., 2023). Digital transparency is examined not as a fully implemented technological solution, but as a set of expectations, practices, and challenges articulated by firms in their interactions with other supply chain actors. Thematic and process coding techniques are used to identify key relational mechanisms and to explore how these mechanisms influence firms' engagement with CSR and transparency related practices.

Expected findings

The analysis is expected to suggest that trust plays a central role in shaping how firms interpret and respond to CSR requirements. Where trust and collaborative relational norms are present, firms should appear more willing to share socially relevant information and to engage constructively with CSR expectations, including corrective action and capability building initiatives (Nyaga et al., 2010; Jha et al., 2024).

The findings are also expected to indicate that digital transparency is interpreted and evaluated by firms primarily through a relational lens rather than as a purely technical instrument. Transparency practices perceived as collaborative, fair, and supportive should be more likely to be associated with trust-building and stronger relational governance (Garcia-Torres et al., 2022; Nyaga et al., 2010). In contrast, transparency practices perceived as one-sided and coercive monitoring may be associated with reduced trust and more defensive behaviours, including

strategic information withholding (Schäfer et al., 2023; Yadlapalli et al., 2018). Overall, the analysis is expected to highlight the importance of relational governance in shaping how transparency and CSR practices are enacted in supply chain relationships.

Value

This study will provide insights into how CSR and transparency are shaped by relationships in emerging economy supply chains. By focusing on how firms engage with CSR through trust, collaboration, and relational norms, the study moves beyond compliance and technology focused explanations. Practically, the findings are expected to highlight the importance of understanding relationship dynamics when developing or applying transparency initiatives in socially sensitive supply chain contexts.

References

Chen, Q., Seuring, S., & Wagner, C. (2020). Reviewing interfirm relationship quality in supply chains: A systematic literature review. *Management Review Quarterly, 70*(1), 1-29.

Dyer, J. H., & Singh, H. (1998). The relational view: Cooperative strategy and sources of interorganizational competitive advantage. *Academy of Management Review, 23*(4), 660-679.

Garcia-Torres, S., Rey-Garcia, M., & Sáenz, J. (2022). Traceability and transparency for sustainable fashion-apparel supply chains. *Journal of Fashion Marketing and Management, 26*(3), 344-364.

Huq, F. A., Stevenson, M., & Zorzini, M. (2014). Social sustainability in developing country suppliers: An exploratory study in the ready-made garments industry of Bangladesh. *International Journal of Operations & Production Management, 34*(5), 610-638.

Jha, P., et al. (2024). Relational embeddedness and CSR capability diffusion in supply chains. *Journal of Supply Chain Management*.

Nahapiet, J., & Ghoshal, S. (1998). Social capital, intellectual capital, and the organizational advantage. *Academy of Management Review, 23*(2), 242-266.

Nyaga, G. N., Whipple, J. M., & Lynch, D. F. (2010). Examining supply chain relationships: Do buyer and supplier perspectives on collaborative relationships differ? *Journal of Operations Management, 28*(2), 101-114.

Schäfer, N., Blome, C., Foerstl, K., & Henke, M. (2023). Making transparency transparent: A systematic literature review to define and frame supply chain transparency in the context of sustainability. *Management Review Quarterly, 73*(4), 979-1010.

Yadlapalli, A., Rahman, S., & Gunasekaran, A. (2018). Socially responsible governance mechanisms for manufacturing firms in apparel supply chains. *International Journal of Production Economics, 196*, 25-40.

BUILDING RESILIENCE FOR SUPPLY CHAINS

Feeding the Future: Vertical Integration and the Changing Face of European Food Retail

Kathrin Auer[1], Helen Rogers[2], Björn Sven Ivens[3]

1: Technische Hochschule Deggendorf, Germany; 2: Technische Hochschule Georg Simon Ohm, Germany; 3: Otto-Friedrich-Universität Bamberg, Germany

Purpose of this paper

Vertical integration is one means to create centrally controlled, more resilient (food) supply chains. It is the aim of this paper to investigate the current state of verticalization within the food supply chain in Europe led by retailers, especially when it comes to own production facilities. The paper examines trends in food supply chain verticalization, reasons for or against verticalization, patterns in verticalization, and to depict product groups particularly affected by this trend.

Design/methodology/approach

The study analyses 64 major European food retail companies using primarily company-reported data such as annual reports and company communication (sustainability reports, homepages) regarding own production practices, complemented by industry sources. A mixed methods-approach was applied, using qualitative and quantitative content analysis.

Findings

There is a trend towards vertical integration amongst certain bigger European food retail companies. While assortment planning, private label development, sourcing and supply chain management/ logistics are seen as core business and applied by all companies, own production facilities are a rising topic in the industry. Baked goods and meat and sausage products are frequently produced by the company itself. Non-alcoholic and alcoholic beverages, fish, dairy products, own agriculture, trade/processing of fruit and vegetables, and ready meals are also common. Other product groups such as sweets and snacks, ice cream, pasta, printed items, grain and rice processing, spices, fruit spreads, and honey are produced sporadically by the companies themselves. Some companies produce their own energy (photovoltaics, hydrogen) and in some cases even act as waste disposal/ recycling companies. There is also a noticeable trend toward vertical farming in northern Europe. Main reasons for vertical integration are control over the supply chain, resilience (security of supply), quality assurance and independence, responsiveness to customer requests, flexibility with regard to product range changes, pricing issues, cost efficiency and higher margins, regionality and marketing goals, brand management, differentiation from the competition, sustainability goals, economies of scale, traceability, and often more regional, shorter supply chains.

Originality/ Value

This study provides the first systematic overview over verticalization efforts in the European food retail. All major companies and their production facilities are covered. Areas of high vertical integration were identified as well as reasons for verticalization.

Research limitations/ implications

The focus on European firms and their self-reported data limit the generalizability of findings. Future research could aim at primary sources and focus on different regions and continents to add to the knowledge gained for Europe. Also, future research should investigate how strong verticalization disrupts markets and how it contributes to market power and how unilateral power and the resulting effects can be prevented.

Practical implications

This paper offers an overview and benchmarks for companies in the food industry that intend to understand the current state of verticalization and potential drivers to verticalize their own food

supply chain. It also creates insights for policymakers for better assessment whether regulation might be relevant within the market.

Social implications

This paper describes current developments in food retailing from the retailer's perspective. It does not assess whether the trend toward verticalization is positive or negative. However, greater vertical integration in food retailing can have an impact on access to food, labour markets, concentration of power and social dependency, food culture and consumer behaviour, sustainability and environmental effects, data power and algorithmic control, and social relationships and communities, among other things.

Keywords: Food Supply Chain, Vertical Integration, Food Retail, Resilient Food Supply Chains, Supermarkets, Europe

From Crisis to Competitive Advantage: A Dynamic Capabilities Approach to Opportunity Exploitation in Maritime Supply Chain

Hang Thi Minh Hoang, Lam Canh Nguyen, Vinh Van Thai, Shahrooz Shahparvari

RMIT University, Australia

Purpose of this paper

Maritime service providers face increasingly frequent disruptions from pandemics, geopolitical conflicts, regulatory changes, and climate events (Li *et al.*, 2024). These disruptions generate paradoxical outcomes within the maritime sector: whilst many organisations experience severe operational and financial distress, others achieve exceptional growth. During COVID-19, numerous shipping companies recorded unprecedented profitability (Notteboom *et al.*, 2021). This phenomenon appears particularly pronounced in developing countries such as Vietnam, where smaller and flexible organisations rapidly exploited opportunities from global supply chain reconfigurations. Despite this reality, understanding how maritime organisations identify and exploit disruption-induced opportunities remains limited. Whilst substantial research exists on maritime supply chain disruption management, previous studies have predominantly focused on defensive resilience strategies such as how organisations mitigate threats, recover from disruptions, and build robustness (Nguyen *et al.*, 2022). This research addresses this gap by investigating opportunity identification and exploitation mechanisms in maritime logistics providers through three specific aims. First, the study identifies opportunity types that disruptions create. Second, it uncovers sensing mechanisms through which organisations detect these opportunities. Third, it determines seizing capabilities deployed to capitalise on them.

Design/Methodology/Approach

This study employed a inductive qualitative research design grounded in critical realism and dynamic capabilities theory (Teece, 2007). Semi-structured in-depth interviews were selected as the primary data collection method for their capacity to capture rich, contextualised insights within maritime contexts.

Data saturation (Hennink and Kaiser, 2022) was achieved with 15 participants from diverse maritime logistics organisations, including shipping lines and maritime logistics providers in Vietnam. Purposive expert sampling was employed to involve information-rich participants in senior management positions with minimum five years of experience, complemented by snowball sampling to reach out to industry experts.

The interview protocol comprised three thematic sections. The first explored types of opportunities emerging from past disruptions. The second examined how organisations identify early signals of opportunity arising from disruptions. The third investigated the capabilities deployed to capitalise on identified opportunities. These questions specifically probed participants' experiences navigating COVID-19, geopolitical conflicts, regulatory changes, and market volatility. Interviews lasted 45-90 minutes, were audio-recorded, transcribed verbatim, and rigorously translated from Vietnamese using forward-backward translation (Koller et al., 2012).

Data analysis was conducted, using the Gioia methodology (Gioia et al., 2013), progressing through first-order concepts, second-order themes, and aggregate theoretical dimensions. This systematic process revealed eight distinct opportunity and capability themes. Trustworthiness and rigour were ensured following established qualitative criteria: credibility, dependability, confirmability, transferability, and authenticity (Connelly, 2016) guaranteeing that findings were robust and reflective of participants' experiences.

Findings

The research reveals that maritime disruptions create three primary opportunity dimensions. First, strategic rethinking evolution manifests through enhanced inter-organisational collaboration, resilience-oriented perspectives, and sustainability integration into core strategies. Disruptions forced organisations to abandon traditional paradigms and adopt adaptive frameworks prioritising proactive foresight, with sustainability evolving from regulatory compliance to competitive differentiation. Second, accelerated innovation emerges as disruptions catalyse technology adoption, fleet modernisation, and creative problem-solving typically resisted under stable conditions. Regulatory pressures and operational constraints drove innovative solutions generating new revenue streams. Third, market dynamics encompass competitive filtering that eliminates weaker firms whilst rewarding resilient ones, operational boundary expansion into integrated logistics ecosystems, and supply-demand imbalances creating exceptional profitability through freight rate escalations.

The research identifies sophisticated sensing capabilities including analogical sensing leveraging experiential learning and cultural foresight, and consensus-based sensing utilising relational intelligence networks. Systematic opportunity sensing appeared predominantly in larger, internationally connected organisations, whilst smaller entities relied on senior staff experience with minimal formalisation.

Regarding exploitation, organisations deployed fast and frugal decision-making adapted to time pressures, including satisficing approaches and familiarity-based triggers. Coordinated response mechanisms encompassed cross-functional collaboration and stakeholder engagement. Exploitation capability depended heavily on organisational size, with larger firms maintaining slack resources whilst smaller organisations often lacked capitalisation capacity. Ultimately, competitive advantage emerges only where sensing and exploitation mechanisms operate as an integrated, mutually reinforcing architecture.

Value

This research makes original contributions by reconceptualising disruptions as opportunity-rich environments rather than merely threats, challenging conventional resilience theory assumptions. It delivers scientific utility to scholars by systematically unpacking sensing-seizing mechanisms as micro-foundations of adaptive resilience, improving conceptual rigor for operationalising dynamic capabilities in crisis contexts. The study provides maritime executives with actionable frameworks for building opportunity-oriented cultures and capability development. It guides policymakers in designing targeted industry support mechanisms, whilst offering new entrant's strategic insights for navigating disruption dynamics in emerging markets.

Research Limitations/Implications

This qualitative study provides rich insights into mechanisms but limits statistical generalisability. The findings derive primarily from successful organisations, potentially introducing survivorship bias. Future research could employ quantitative methods to test relationships between capabilities and growth outcomes across larger samples. Comparative studies examining both successful and unsuccessful attempts would illuminate contingency factors, whilst longitudinal investigations tracking organisations through disruption cycles would reveal temporal dynamics.

Practical Implications

Maritime logistics providers should implement formal opportunity sensing frameworks rather than relying solely on senior staff experience. Managers should enhance relational intelligence networks through disciplined relationship maintenance and establish coordination mechanisms before disruptions materialise. Organisations should document lessons learned from previous disruptions to build institutional knowledge of opportunity patterns. Strategic financial management should maintain slack resources, enabling opportunity capitalisation when competitors lack resources. Industry associations and policymakers should facilitate information-sharing platforms enhancing collective sensing capabilities across the maritime ecosystem.

References

Connelly, L.M. (2016), "Trustworthiness in Qualitative Research", Medsurg Nursing: Official Journal of the Academy of Medical-Surgical Nurses, Vol. 25 No. 6, pp. 435–436.

Gioia, D.A., Corley, K.G. and Hamilton, A.L. (2013), "Seeking Qualitative Rigor in Inductive Research: Notes on the Gioia Methodology", Organizational Research Methods, SAGE Publications Inc, Vol. 16 No. 1, pp. 15–31, doi: 10.1177/1094428112452151.

Hennink, M. and Kaiser, B.N. (2022), "Sample sizes for saturation in qualitative research: A systematic review of empirical tests", Social Science & Medicine, Vol. 292, p. 114523, doi: 10.1016/j.socscimed.2021.114523.

Koller, M., Kantzer, V., Mear, I., Zarzar, K., Martin, M., Greimel, E., Bottomley, A., et al. (2012), "The process of reconciliation: Evaluation of guidelines for translating quality-of-life questionnaires", Expert Review of Pharmacoeconomics & Outcomes Research, Vol. 12, pp. 189–97, doi: 10.1586/erp.11.102.

Li, X., Chua, J.Y. and Yuen, K.F. (2024), "A review on maritime disruption management: Categories, impacts, and strategies", Transport Policy, Vol. 154, pp. 40–47, doi: 10.1016/j.tranpol.2024.05.013.

Nguyen, T.-T., My Tran, D.T., Duc, T.T.H. and Thai, V.V. (2022), "Managing disruptions in the maritime industry – a systematic literature review", Maritime Business Review, Emerald Publishing Limited, Vol. 8 No. 2, pp. 170–190, doi: 10.1108/MABR-09-2021-0072.

Notteboom, T., Pallis, T. and Rodrigue, J.-P. (2021), "Disruptions and resilience in global container shipping and ports: the COVID-19 pandemic versus the 2008–2009 financial crisis", Maritime Economics & Logistics, Vol. 23 No. 2, pp. 179–210, doi: 10.1057/s41278-020-00180-5.

Teece, D.J. (2007), "Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance", Strategic Management Journal, Vol. 28 No. 13, pp. 1319–1350, doi: 10.1002/smj.640.

Beyond Resilience: Transilience as a means to Drive Supply Chain Transformation and Regeneration

Booi Kam, Kamrul Ahsan, Muhammad Abdulrahman

RMIT Australia, Australia

Purpose of this paper

The changing dynamics of global disruptions—deadly COVID pandemics, extreme climate events, growing geopolitical conflicts, and unpredictable trade wars—in recent years calls into question the adequacy of the traditional stability-and-recovery supply chain risk management and resilience frameworks (Linnenluecke 2015; Mithani 2020). These frameworks have, unquestionably, generated valuable insights that help firms absorb shocks, adapt to changes, and restore operational performance. However, their preoccupation with returning to a stable equilibrium by building capabilities to prepare for, respond to, and recover from disruptions while maintaining operations continuity is becoming increasingly problematic (Guntuka et al. 2024). Such an emphasis assumes that the social and economic orders as well as the international institutional mechanisms that underpin the global business landscape would not change. This assumption ignores the disruption-induced fractures in the global trade systems upon which extant supply chain configurations, production and sourcing systems, and logistics infrastructures have been built.

Compounding the increasing vulnerability of the global trade structure to evolving forms of unprecedented disruptions is the emergence of regenerative supply chains (Gualandris et al. 2023). Sustainability scholarship, of late, has moved beyond the goal of minimizing negative environmental impacts toward the benefits of restoring and enhancing natural and social systems through supply chain activities (Bag et al. 2025a; Howard et al. 2018). This paradigm shift further highlights the limitations of the resilience framework as a theoretical lens for supply chain risk management. Resilience focuses on maintaining system functionality (Potts and Le Hunte 2024). Regenerative approaches warrant supply chain activities to contribute to ecological regeneration, community resilience, and long-term system vitality (Basile 2026; Hsu et al. 2025). This regeneration emphasis begs a "net positive" outcome, demanding transformation of production systems, sourcing strategies, and supply network governance, among others (Bag et al. 2025b; Onomakpo 2025).

This study argues that transilience offers a more appropriate theoretical lens for examining how supply chains respond to disruption while simultaneously advance sustainability and regenerative development. Craighead et al. (2020) explain that transilience amalgamates resiliency and transformability, defining it as "the ability to simultaneously restore some processes and change—often radically—others" (p. 840). Having been employed to explore how innovation shapes established production and marketing systems (Abernathy and Clark 1985), transilience offers a theoretical lens to capture the capacity of systems to both restore and transform besides maintaining systems functionalities when responding to disruption. Within supply chain management, transilience emphasizes the ability of supply networks to maintain critical operations while simultaneously experimenting with new configurations, technologies, and governance structures that enhance long-term adaptability.

By synthesizing the emerging literature on transilience (or transiliency), this paper presents the foundational principles of transilience, contrasting them with those of resilience. It proposes a generic model of supply chain transilience management and suggests an agenda for further investigations.

Methodology

This study synthesizes the conceptual underpinnings and empirical findings from 34 papers that either apply or discuss the transilience concept in management and supply chains. These papers were identified from a search in Scopus using the search string "transilient*" AND ("management" OR "supply chain"), which appears in "all fields." The initial search uncovered 65 papers. After removing papers not written in English and limiting them to only journal

publications, 44 documents remained. Further excluding papers not published in the knowledge domains of management and supply chain based on the source title of the publications resulted in 34 papers.

To establish the foundational principles of transilience (or transiliency), we employed an inductive analytical approach to identify core themes based directly on insights from the 34 papers. We followed the Grodal et al. (2021) data categorisation framework to systematically group key themes into conceptual clusters. This approach led to the development of a conceptual framework that illustrates the core dimensions of transilience and its pathways to engendering transformative change in supply chain structure.

Findings

Our preliminary findings suggest that transilience differs from resilience in five major aspects: overarching goal, system orientation, key attributes, response to disruption, and disruption management focus (see Table 1).

Table 1: Conceptual Differences between Resilience and Transilience

	Resilience	**Transilience**
Overarching Goal	Recover from disruption	Transform through disruption
System Orientation	Adaptation, stability and recovery	Adaptation, transformation and regeneration
Key Attributes	Redundancy, buffers, flexibility, and learning	Innovation, network redesign, and digitalization
Response to Disruption	Bounce back	Bounce forward
Disruption Management Focus	Operational continuity	Innovation and structural redesign

Integrating insights from resilience, sustainability transitions, and a host of management theories (e.g., resource orchestration theory, resource dependence theory, institutional theory, structural inertia, and real options theory), transilience reframes disruption more as an opportunity for systemic improvement and less as a threat. Embracing a transilience mindset appears to help drive supply chain beyond recovery toward innovation, sustainability transitions, and regenerative transformation.

Value

In contrast to resilience, transilience provides a broader and more forward-looking perspective, which is particularly relevant when supply chains are viewed as complex adaptive systems. Adopting transilience as a theoretical lens enables the dynamic processes through which supply chains manage disruptions while simultaneously build regenerative configurations to be captured.

Research Implications

Focusing on understanding how organizations are pressured to reconsider existing practices and explore alternative operations models during disruption, transilience provides a conceptual lens for studying how disruptions can catalyze innovations and resource restructure to build regenerative supply chains.

Research Limitations

Based exclusively on literature review, the proposed conceptual framework needs empirical validation.

Practical Implications

Understanding how transformations occur during periods of disruption offers pragmatic approaches for managerial practices to treat disruption as opportunities for change: process renewal, systems reset, and configuration redesign.

References

Abernathy, W. J. and Clark, K. B. (1985) Innovation: Mapping the winds of creative destruction. Research policy 14 (1), 3-22.

Bag, S., Chiarini, A. and Srivastava, G. (2025a) Building Regenerative Supply Chains: A Qualitative Study of SMEs in the Agro-Food Chains. Business Strategy and the Environment 34 (8), 10803-10823.

Bag, S., Rahman, M. S., Routray, S. and Khurana, R. (2025b) Regenerative supply chain orientation and coopetition in supply chain networks for ESG initiatives: A parallel mediation study. Journal of Business Research 201.

Basile, V. (2026) Resilient, Restorative, and Regenerative Business Model (3R-BM). Resilient Business Models: Innovating Through Global Challenges to Creating Sustainable Futures. Springer. 153-181.

Craighead, C. W., Ketchen Jr, D. J. and Darby, J. L. (2020) Pandemics and supply chain management research: toward a theoretical toolbox. Decision Sciences 51 (4), 838-866.

Grodal, S., Anteby, M. and Holm, A. L. (2021) Achieving rigor in qualitative analysis: The role of active categorization in theory building. Academy of Management Review 46 (3), 591-612.

Gualandris, J., Branzei, O., Wilhelm, M., Lazzarini, S., Linnenluecke, M., Hamann, R., Dooley, K. J., Barnett, M. L. and Chen, C. M. (2023) Unchaining supply chains: Transformative leaps toward regenerating social–ecological systems. Journal of Supply Chain Management 60 (1), 53-67.

Guntuka, L., Carnovale, S. and Falcone, E. (2024) Supply Chain Plasticity: A Responsive Network Capability to Ensure Resilience. Journal of Business Logistics 45 (4).

Howard, M., Hopkinson, P. and Miemczyk, J. (2018) The regenerative supply chain: a framework for developing circular economy indicators. International Journal of Production Research 57 (23), 7300-7318.

Hsu, K., Shevchenko, A. and Yang-Sun, Yang S. (2025) Regeneration and Supply Chain Complexity: Insights From the Forest Sector. Journal of Supply Chain Management.

Linnenluecke, M. K. (2015) Resilience in Business and Management Research: A Review of Influential Publications and a Research Agenda. International Journal of Management Reviews 19 (1), 4-30.

Mithani, M. A. (2020) Adaptation in the Face of the New Normal. Academy of Management Perspectives 34 (4), 508-530.

Onomakpo, H. O. (2025) AI-Enabled Regenerative Supply Chains: A RSSCM Framework. Scientific Research Journal of Business, Management and Accounting 3 (1), 1-31.

Potts, M. and Le Hunte, B. (2024) Reframing resilience as a systemic issue: Meta-competencies that transform individuals and learning ecologies. Systems Research and Behavioral Science 41 (5), 750-760.

Future-Proofing Sustainable Columbian Coffee Supply Chain: A Stakeholder Resource-Based View

Timothy Ramjaun[1], Madeleine Pullman[2], Maneesh Kumar[3], Vasco Sanchez Rodrigues[3]

1: Royal Holloway, University of London, United Kingdom; 2: Portland State University, Oregon; 3: Cardiff University, United Kingdom

Purpose of this paper

The purpose of this study is to investigate the long-term resilience of the Columbian coffee supply chain, with a particular focus on the producers (farmers), operating as a unified cooperative to enhance sustainable practices and improve living standards. Incorporating environmental and social initiatives into the coffee production processes can attract a price premium though accredited sustainability certification (e.g. Fairtrade) and marketing to conscientious consumers (Levy et al., 2015). However, sustainability initiatives need a stable operating environment as farm-level investments may take years to come to fruition (e.g. water infrastructure, tree-replanting). Projects aim to empower farmers as long-term value creators, rather than being reduced to simply delivering targets (Candelo et al., 2018). Creating these conditions can be challenging as producer activities occur in economies with less developed institutions (Bille et al., 2025). Coffee SCs are subject to various threats such as climate change, production costs and fluctuating consumer demand, all of which can erode stability. To counter these risks and disruptions, coffee SCs require dynamic capabilities and increasing levels of integration (Ramos et al., 2023). Our study outlines the major threats to the Columbian coffee SC and the complex, intertwined nature of sustainability initiatives that must meet the social, environmental and economic requirements of different actors from bean to cup.

Design/methodology/approach

We apply a qualitative case study approach to investigate the role of different actors along the supply chain. It is important to adopt a holistic approach to resilience because issues and disruptions can arise from point of origin through to consumer demand. To achieve this goal, we interviewed Columbian coffee Cooperatives, a national coffee exporter and a German buyer that sources directly and retails in Europe. Data was collected through semi-structured interviews and thematically coded to elicit issues that impact resilience, along with strategic responses by different supply chain members. Interviews were conducted in Spanish and transcribed into English. Three researchers independently coded the transcripts before the fourth researcher reviewed and consolidated the codes. Two researchers then categorised the codes and developed the major themes. The data was coded in-line with the interview questions (e.g., collaboration, stakeholder needs, sustainability certification) but also allowed to capture inductively derived concepts that effect supply chain resilience (e.g., climate change). Although sustainable coffee farming is incumbent on stable operations, this ideal situation is not always possible due to powerful stakeholders on the retail-side that may act in self-interest. Our focus is on the producer-side as a relevant stakeholder and the effect of instability on their living standards and environmental concerns (Rosca et al., 2025).

Findings

Our work shows that coffee SCs need to be tightly aligned to coordinate relevant and impactful sustainability activities. These projects should be jointly created with input from all SC members to ensure that value is evenly distributed and avoid isolated decision-making. This type of integrated and coordinated behaviour supports consumer preferences being conveyed upstream to producers so that investment and change are understood and implemented. The long-term resilience of the coffee industry is highly dependent on successful sustainability initiatives that include: social enhancement (e.g., women empowerment), environmental consideration (e.g., reduced water consumption), economic benefits (e.g., price premium for differentiated coffee). The reason that sustainability (in the context of the triple bottom line) and resilience (long-term continuity) are interlinked is through the price premium offered to producers that focus on social

and environmental issues, especially from sustainability certification (e.g., Fairtrade). In the absence of 'sustainable' coffee, supply and demand price negotiation dominates and leads to an erosion of resilience through different mechanisms, for example:

"Labour is becoming more scarce in Colombian fields. Producers are becoming elderly and young people move to the city… [it is] important to have social projects to empower these young people from the fields so that they won't abandon it... improve the fields income and better manage farms." (Cooperative_R).

Value

We offer two distinct contributions, first, the coffee SC needs to operate as an integrated unit, linking supply with demand in terms of product differentiation to enable resilience through sustainable practices. Second, enhancing resilience through sustainable practice introduces complexity as economic, social and environmental needs are balanced at the producer-level but need to be recognised and endorsed by all supply chain members. Downstream decision-making impacts sustainable practices and there can be a significant lag-time for producer response due to the nature of agri-food products (e.g., seasonal production). Our findings are relevant to exporters and Cooperative leaders that act as bridging agents between the producers and buyers.

Research limitations/implications

Future research could include a longitudinal study on resilience in the face of existing issues or additional proscriptive disruptions (e.g. US foreign policy changes). In terms of limitations, this research is contextualised within the Columbian coffee industry and is nuanced in accordance with local institutions, politics and legal frameworks, as well as customs, culture and geography.

Practical implications

Exporters and Cooperatives need to align and influence upstream/downstream supply chain members and reconcile conflicting requirements for different parties. Specifically, buyers should be informed of the impact of their decisions at the producer-level and the subsequent effects on long-term resilience.

References

Bille, A., Bjørndal Thomsen, K., Beske-Janssen, P., & Wieland, A. (2025). Understanding the political nature of supply chain management: a case study of the coffee supply chain. Supply Chain Management: An International Journal, 30(2), 195-212.

Candelo, E., Casalegno, C., Civera, C., & Mosca, F. (2018). Turning farmers into business partners through value co-creation projects. Insights from the coffee supply chain. Sustainability, 10(4), 1018.

Levy, D., Reinecke, J., & Manning, S. (2016). The political dynamics of sustainable coffee: Contested value regimes and the transformation of sustainability. Journal of management studies, 53(3), 364-401.

Ramos, E., Patrucco, A. S., & Chavez, M. (2023). Dynamic capabilities in the "new normal": a study of organizational flexibility, integration and agility in the Peruvian coffee supply chain. Supply Chain Management: An International Journal, 28(1), 55-73.

Rosca, E., Pullman, M., & Pagell, M. (2025). Brokering for the Benefit of Others: How Purpose-Driven Organizations Create Sustainable Supply Chains. Journal of Supply Chain Management.

From Platform to Ecosystem: Orchestrating Value Co-creation in the Digital Logistics Landscape of China

Li Qing

Shanghai Business School, China

Purpose of this paper

The digital transformation of theglobal economy is fundamentally reshaping traditional industry boundaries and competitive dynamics (Nambisan et al., 2019; Autio, 2021). In this new paradigm, platform-based business models have emerged as a dominant force, creating value by facilitating interactions between diverse user groups. However, a more profound organizational shift is now underway, as leading platforms evolve into complex, multi-layered ecosystems—a phenomenon described as the platform-based ecosystem (PBE) (Gawer, 2014; Jacobides et al., 2018).

The Chinese context provides a particularly compelling setting to investigate this phenomenon. Driven by national strategies like the "One Belt One Road Initiative" and "Guiding Opinions on Standardizing and Healthy Development about Promoting Platform Economy," China has witnessed an explosion of digital platforms across sectors, with logistics being a prime example. Companies like Full Truck Alliance (FTA) have rapidly scaled from simple freight-matching platforms into complex ecosystems, offering a wide array of services from financing and insurance to energy and vehicle sales. However, there is less understanding of the transitional process itself—the "how" and "why" behind the emergence of a PBE from its platform origins (Autio, 2021; Helfat and Raubitschek, 2018). This gap is especially pronounced in the context of emerging economies, where the interplay between corporate strategy, digital technology, and institutional forces creates unique pathways for ecosystem development.

The strategic choices and underlying mechanisms that facilitate this orchestration during the transition are not well understood. How do platform owners in an emerging economy like China persuade autonomous actors to contribute their resources and capabilities? How is value co-created and captured as the system's complexity increases? Through a multiple-case study of four distinct logistics platforms, we seek to uncover the structure and underlying mechanisms of PBE emergence. Our research is guided by the following questions:

RQ1. How do platform owners orchestrate the transition from a platform to a platform-based ecosystem in an emerging economy context?

RQ2. What are the key mechanisms for value co-creation among ecosystem participants during this transitional process?

Design/methodology/approach

According to Yin (2014), multiple case studies were selected for this research to comprehensively reflect the current developments of platform-based ecosystem in the logistics industry. We applied a theoretical sampling approach and four case firms are identified by purposefully following these criteria such as platform types, logistics service types, history, award, PBE structure. We selected four appropriate cases to represent typical logistics platforms that focus on specific logistics services. For instance, for Case B as one of the largest logistics park platform firm, we decided to select Case B which specializes in logistics park services. We found other logistics platform firms focusing on other specific logistics services, like logistics cloud service (Case C) and e-commerce logistics service (Case D). They have gained sustainable success and reputation that have established over 15 years on average, with fruitful experience of creating PBE. The study adopted multiple data collection methods including semi-structured interviews, workshop observation and document archives. The semi-structured interviews were conducted during 2018–2023 to ensure three-stage data collection stage for comprehensive data.

Findings

Our cross-case analysis reveals that the transition from a logistics platform to a full-fledged Platform-Based Ecosystem (PBE) is not a singular event but a managed process of architectural and strategic layering. We identify four constitutive layers—Actor, Service, Resource, and Platform—that interact dynamically to enable value co-creation.

Finally, we observed that successful PBEs are not monolithic but are composed of multiple, interconnected platforms. This multi-platform architecture provides the technical and strategic flexibility needed for scaling and adaptation, allowing the ecosystem to explore new opportunities without destabilizing its core operations. This represents a shift from a single, monolithic platform to a modular platform portfolio,

each module designed for specific functions or user segments while sharing common underlying resources and data. The transition from platform to PBE is not the result of any single layer but emerges from the dynamic interactions between them. The Resource Layer provides the foundational assets. The Service Layer, through digital servitization, transforms these assets into valuable customer offerings. The Actor Layer, through orchestration, mobilizes the human and organizational capital necessary for this transformation. Finally, the multi-faceted Platform Layer provides the technical architecture and governance that enables these interactions to scale and evolve. It is the recursive nature of these interactions—where services generate data that improves resource synergy, which in turn attracts more actors, leading to new service ideas—that creates the momentum for ecosystem growth.

Value

This research makes several key contributions to management theory, particularly in the context of emerging economies. First, it extends the literature on business ecosystems and digital platforms by offering a process-oriented, multi-layer framework for a critical but under-explored phase: the transition itself. We provide a granular view of how orchestration, servitization, synergy, and architectural design are not isolated activities but are deeply interconnected managerial levers. Second, the paper introduces and empirically validates the critical role of digital servitization as a core ecosystem driver and outcome. We demonstrate that service diversification is not merely a growth tactic but a fundamental mechanism for strengthening network effects, enhancing user loyalty, and transforming a transactional platform into an indispensable service ecosystem. Third, by grounding our study in the Chinese context, we provide much-needed empirical insight into ecosystem development in an emerging economy.

Research limitations/implications

If research is reported on in the paper this section must be completed and should include suggestions for future research and any identified limitations in the research process.

Practical implications

What outcomes and implications for practice, application and consequences are identified? Not all papers will have practical implications but most will. What changes to practice should be made as a result of this research/paper?

The findings of this study offer clear, actionable guidance for managers and policymakers. For managers and platform owners, this study provides a diagnostic and strategic framework. The four-layer model can serve as a blueprint for evaluating their own platform's ecosystem potential and for identifying gaps in their strategy.

References

Adner, R. (2017). Ecosystem as Structure: An Actionable Construct for Strategy. Journal of Management, 43(1), 39-58.

Adner, R. (2017). Ecosystem as Structure: An Actionable Construct for Strategy. Journal of Management, 43(1), 39-58.

Cozzolino, A., Corbo, L., & Aversa, P. (2021). Digital platform-based ecosystems: The evolution of collaboration and competition between incumbent producers and entrant platforms. Journal of Business Research, 126, 385-400.

Jacobides, M. G., Cennamo, C., & Gawer, A. (2018). Towards a theory of ecosystems. Strategic Management Journal, 39(8), 2255-2276.

Jovanovic, M., Sjödin, D., & Parida, V. (2021). Co-evolution of platform architecture, platform services, and platform governance: Expanding the platform value of industrial digital platforms. Technovation, 102218.

Lyu, G., Chen, L., & Huo, B. (2019). The impact of logistics platforms and location on logistics resource integration and operational performance. The International Journal of Logistics Management, 30.

Exploring The Antecedents Needed to Build Defence Supply Chain Resilient Capabilities

Zakiah Syamra' Suhaimi[1], Janet Godsell[2]

1: National Defence University of Malaysia, Malaysia; 2: Loughborough University, UK

Purpose of this paper

Consecutive global disruptions from the COVID-19 pandemic to the Russian invasion of Ukraine and, more recently, the US intervention in Venezuela have highlighted the vulnerability of defence supply chains (DSCs). In Malaysia, other factors, such as over-reliance on overseas suppliers, limited economies of scale, technological defence capability constraints, and a lack of strategic procurement approach, have put Malaysia's DSC at risk (Suhaimi & Mohamad Mokhtar, 2023). Moreover, rising cybersecurity threats, the low adoption of industrial digital technologies (IDTs) (i.e., artificial intelligence (AI), autonomous systems, electronic warfare, robotics, unmanned aerial vehicle (UAV)), and a shortage of skilled labour in these IDTs (Ministry of Defence Malaysia, 2026) could further add new layers of risk and vulnerability to its DSC. To achieve the long-term aspiration of the self-reliance principle (MINDEF, 2020; WMG The University of Warwick, 2023), Malaysia developed a National Defence Industry Policy (NDIP) to build a resilient, dignified, innovative and competitive defence industry regionally and globally. Specifically, the policy aims to reduce the over-dependency on foreign technology by strengthening local manufacturing capacity through close collaboration between the public and private sectors (Ministry of Defence Malaysia, 2026). Recognising the importance of this goal, this study seeks to empirically answer the following overarching research question:

"What are the antecedents needed in building resilient DSC capabilities?"

Design/methodology/approach

This study adopts a two-phase mixed-method approach to examine the antecedents needed in building resilient DSC capabilities. In the first phase, data were collected through a survey questionnaire administered to defence firms, in which a survey link was sent via email. The questionnaire measured four main constructs: a) supply chain resilience (SCRes) capabilities, b) SCRes, and c) firm performance. The Malaysian Industry Council for Defence, Enforcement and Security (MIDES) database was utilised to select these firms. The questionnaire was targeted at the top management level or employees with more than three years of experience. To increase the response rate, email reminders and telephone calls were adopted. As a result, 73 usable responses were received, yielding to 58% response rate. Based on the descriptive statistics results, the top and bottom ten companies were selected for the next phase of data collection, semi-structured interviews. The semi-structured interviews are undertaken to seek explanations of the survey results and examine the antecedents of resilient DSC capabilities. This will ensure successful adoption of SCRes capabilities at all three disruption phases, readiness, responsiveness and recovery. Triangulation of survey questionnaire and semi-structured interview data would overcome the bias issues if a single methodological approach is undertaken in this study.

Findings

There were 73 defence firms that participated in the survey. Of this, 65.7% of the firms had fewer than 75 employees and generated less than RM15 million, whilst only 10% of the firms had over 200 employees and earned more than RM50 million. This implies that most of the defence firms were classified as small and medium-sized companies. The largest number of respondents (55%) operated in Klang Valley, with the smallest number of respondents operating in Johor, Melaka, Pahang, and Sarawak. The greatest proportion of the respondents (63%) held executive or senior management positions, whereas 30% held middle management positions and only 7% were in junior management positions. With over 90% of respondents holding managerial positions, the results reflect the credibility and reliability of the study's outcomes. For the descriptive statistics, defence firms demonstrated average performance across all SCRes

capabilities: supply chain planning (3.18), visibility (3.03), collaboration (3.43), resource management (3.31), supply flexibility (3.38), learning (3) and adaptability (3.22). When compared across all disruption phases, the responsiveness phase, which consisted of collaboration, resource management, and supply flexibility, achieved higher scores (3.37). This denotes that defence firms performed better during disruption as compared to pre- and post-disruption. For SCRes, defence firms scored slightly higher (3.8), showing the ability of firms to prepare for, respond to, and recover from an unexpected disruption (WMG The University of Warwick, 2023).

Value

Through a thorough literature review, the study conceptualises SCRes from the context of the defence industry. Unlike previous studies that tend to focus on building the capabilities of SCRes, this study conceptualises it by examining the antecedents needed for achieving a resilient DSC. This study also addresses the lack of existing knowledge on SCRes from the defence perspective. An extensive literature review leads to the development of the SCRes model in the defence industry. This study also offers scope for the industry to make better and more informed decisions on which capabilities are required at each phase of SC disruptions and equip the industry with the antecedents required to combat current and future disruptions.

References

MINDEF. (2020). Defence White Paper - A Secure, Sovereign and Prosperous Malaysia.

Ministry of Defence Malaysia. (2026). NATIONAL DEFENCE INDUSTRY POLICY.

Suhaimi, Z. S., & Mohamad Mokhtar, A. R. (2023). Exploring the elements of supply chain resilience in Malaysia's Defence Industry - A Conceptual Framework. ASEAN Journal of Management and Business Studies, 5(2), 77–82. https://doi.org/10.26666/rmp.ajmbs.2023.2.12

WMG The University of Warwick. (2023). SUPPLY CHAIN RESILIENCE FRAMEWORK AND A METHODOLOGY FOR CREATING SUPPLY CHAIN RESILIENCE INDEX. https://supplychainresiliencehub.com/

Sustainable Strategy in Chocolate Supply Chain in VUCA Context: A Theoretical Integration

Minh Nguyet Nguyen Luu, Anna John, Nicoleta Tipi

The Open University, United Kingdom

Purpose of this paper

Food supply chains increasingly operate under conditions of vulnerability, uncertainty, complexity, and ambiguity (VUCA) driven by climate change, geopolitical instability, regulatory inconsistency, and ever-changing societal expectations (Bennett and Lemoine, 2014; Millar et al, 2018; Setyadi, Pawirosumarto & Damaris, 2025). According to a recent BBC report (Dimitrova, 2026), research on the chocolate supply chain has become increasingly important due to climate-related disruptions such as El Nino events alongside trade pressure and a decline in cocoa farming production. These factors have contributed to rising cocoa and chocolate prices in global markets (Dimitrova, 2026). In major cocoa-producing countries such as Ghana and Cote d'Ivoire, climate change is expected to make cocoa production riskier and increase vulnerability in the regions dependent on it (Parra-Paitan et al, 2024). As a result, the supply chain has become more vulnerable, demanding an improved understanding to better inform policies for supporting farmers and customers (Dimitrova, 2026). Previous research has also demonstrated that the role of climate risk can shape the supply chain's vulnerability in the long run, which reinforces the need for further research on adaptation and resilience and policy adjustment to support producers (Jabbi and Sawitri, 2025). Currently, much of the existing literature addresses individual disruption risks, however further guidance is still needed on how sustainability strategies can be systematically adapted to strengthen supply chain resilience in constantly turbulent environments.

Therefore, this study aims to explore how strategies can be used to enhance sustainable supply chain under VUCA conditions. Ontologically, the purpose of the paper is to develop new theoretical foundations based on a comprehensive integration of three theories: dynamic capabilities, new institutional theory and network theory. The research focuses on the chocolate supply chain, a sector highly exposed to climate risks, global sourcing complexity, and evolvingly stricter regulatory frameworks. Specifically, the study seeks to identify key VUCA challenges affecting the sector, examine how current sustainability practices respond to these challenges, and develop a sustainability driven framework to support supply chain decision making. To this end, this paper develops a set of propositions which will serve as a bridge for further empirical work to be undertaken in the future larger scale project (PhD research).

Design/methodology/approach

This paper adopts a research synthesis methodology (Torraco, 2005) to develop both integrated frameworks that illustrate the interplay among VUCA conditions (vulnerability, uncertainty, complexity, ambiguity) and three theories such as dynamic capabilities theory, new institutional theory, and network theory. This paper synthesises key theoretical contributions from each theory to identify core assumptions, boundary conditions, and underlying mechanisms (Jaakkola, 2020). The first analytical step is going to extract the foundation assumption from the literature of each theory. These assumptions are then compared across the four VUCA dimensions. Through this comparison, the interaction mechanisms from different theories are illustrated under VUCA pressures sustainably. This synthesis process serves as an integrated framework that show how dynamic capabilities, institutional pressures, and network relationships co-shape firm's responses to specific VUCA challenges.

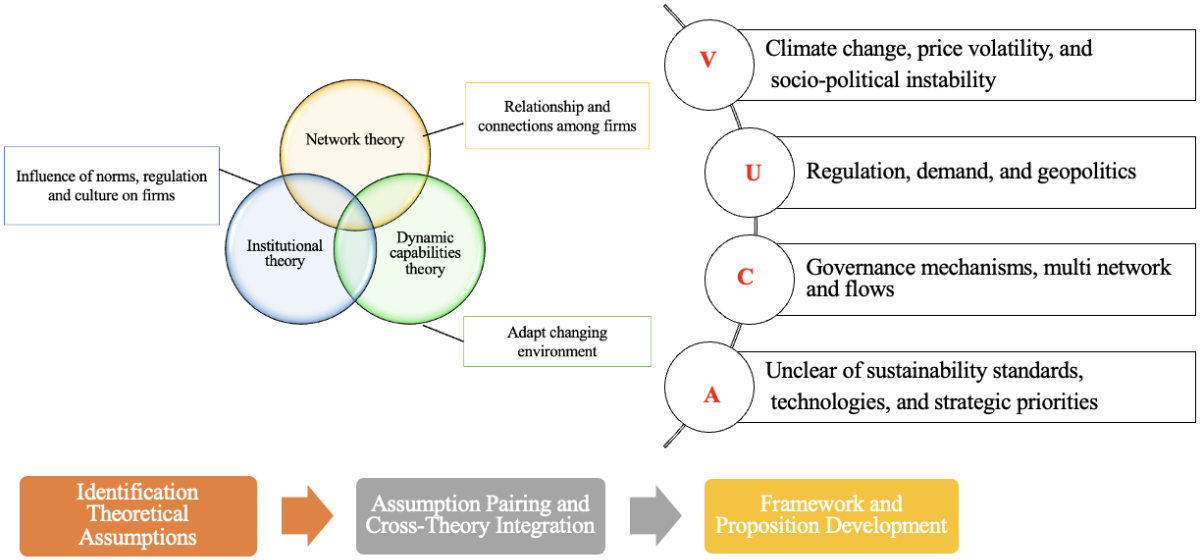


Figure: Visualization in the theoretical approach

Findings

The research synthesis results in an integrated theoretical framework that explains how distinct dimensions of VUCA differently affect the supply chain. This analysis indicates that uncertainty and ambiguity primarily operate at the organisational level whereas dynamic capabilities enable firms to sense weak signals, interpret ambiguous information, and reconfigure resources through learning and adaptation (Teece, Schilke, Hu, & Helfat, 2016). Complexity is identified at a predominantly network level, arising from dense interdependencies, non-linear interactions, and coordination challenges among supply chain interactors (Tipi & El Gazzar, 2021; Greenwood et al, 2011). Built upon the network theory, the synthesis shows that sustainability under complexity depends on relational embeddedness, information flows, and structural positioning within internal organisational networks (Borgatti, Everett, & Johnson, 2018; Bode et al, 2011). Vulnerability associated with sustainability transitions and regulatory changes can be resolved through institutional mechanisms. Institutional pressures define legitimacy thresholds and influence which sustainable strategies are considered viable, thereby shaping organisational responses to rapid environmental shifts (DiMaggio & Powell, 1983; Scott, 2014; John & Lawton, 2018). Therefore, the synthesis demonstrates that these mechanisms are interdependent rather than isolated. Institutional pressures allow the development of dynamic capabilities, while network positions moderate the effectiveness of both capability enactment and legitimacy behaviour (John & Lawton, 2018; Wang et al, 2018). Sustainability under VUCA therefore emerges from the interaction of organisational capabilities, institutional contexts, and network structures rather than from any single theoretical mechanism (Teece, Schilke, Hu, & Helfat, 2016; van der Vegt et al., 2015). From this integrated framework, the study proves a set of theoretically grounded propositions that specify how particular configurations of dynamic capabilities, institutional, and network might enhance sustainable supply chain management under different VUCA conditions.

Value

This paper develops a theory integrating framework for VUCA that explains its operation through multi-level networks. Specifically, it shows how different dimensions of VUCA activate distinct mechanisms across organisational, institutional, and network levels. By linking uncertainty and ambiguity to dynamic capabilities, complexity to network structures, and vulnerability to institutional pressures, this paper shows where existing theories sit within the broader frameworks and how they jointly explain sustainability outcomes. Secondly, the methodology synthesised on this paper contributes to theoretical development by integrating multiple theories

instead of treating them in parallel. It is going to explain how and why theoretical mechanisms interact across levels in complex supply chain environments. Finally, this paper proposes actionable theoretical propositions that provide a foundation for future research in strategic supply chain management. By analysing multi-level phenomena rather than firm-level attributes alone, this paper showcases sustainability transitions and key challenges highlighted in recent logistics and supply chain research.

Research limitations/implications

As a conceptual and theory - driven study, the paper does not focus on an empirical investigation. Future research will empirically examine the proposed framework through qualitative case studies, network analysis, and a mixed method approaches across different chocolate supply chains. Comparative research across different regions, and governance environments is considered to enhance the broader applicability of the results.

Practical implications

Although this paper is conceptual, the integrated framework can offer practical insights for managers and policymakers to navigate their strategies in supply chain under VUCA conditions. Industry managers are encouraged to expand their strategic focus beyond organisational boundaries by actively considering VUCA elements within the geographical contexts of their chocolate supply chains.

References

Ahmed, H.F., *et al.* (2024) 'Supply chain complexity and its impact on knowledge transfer: Incorporating sustainable supply chain practices in food supply chain networks', *Logistics*, 8(1), p. 5.

Bennett, N. and Lemoine, G.J. (2014) 'What a difference a word makes: Understanding threats to performance in a VUCA world', *Business Horizons*, 57(3), pp. 311–317.

Bode, C., Wagner, S.M., Petersen, K.J. and Ellram, L.M. (2011) 'Understanding supply network complexity and resilience', *Journal of Supply Chain Management*.

Borgatti, S.P., Everett, M.G. and Johnson, J.C. (2018) *Analyzing social networks*. 2nd edn. Thousand Oaks, CA: SAGE.

DiMaggio, P.J. and Powell, W.W. (1983) 'The iron cage revisited: Institutional isomorphism and collective rationality in organizational fields', *American Sociological Review*, 48(2), pp. 147–160.

Dimitrova, G. (2026) 'Five factors driving up chocolate prices', *BBC News*, 1 January. Available at: https://www.bbc.co.uk/news/articles/c8r360jyg5lo (Accessed: [add date]).

Greenwood, R., Raynard, M., Kodeih, F., Micelotta, E.R. and Lounsbury, M. (2011) 'Institutional complexity and organizational responses', *Academy of Management Annals*, 5(1), pp. 317–371. https://doi.org/10.5465/19416520.2011.590299

Jaakkola, E. (2020) 'Designing conceptual articles: Four approaches', *AMS Review*, 10(1), pp. 18–26.

Jabbi, E., & Sawitri, K. D. (2025). Supply chain resilience in the cocoa industry amid global disruptions: A comparative case study of Ghana and Côte d'Ivoire.

John, A. and Lawton, T.C. (2018) 'International political risk management: Perspectives, approaches and emerging agendas', *International Journal of Management Reviews*, 20(4), pp. 847–879.

Kareem, S. (2024) *Adaptive sustainable supply chains in a volatile, uncertain, complex and ambiguous (VUCA) environment*. PhD thesis. University of Auckland. https://doi.org/10.13140/RG.2.2.26385.85603

Millar, C.C.J.M., *et al.* (2018) 'Management innovation in a VUCA world: Challenges and recommendations', *California Management Review*, 61(1), pp. 5–14.

Parra-Paitan, C., Meyfroidt, P., Verburg, P. H., & zu Ermgassen, E. K. H. J. (2024). *Deforestation and climate risk hotspots in the global cocoa value chain*. *Environmental Science and Policy*, 158, Article 103796. https://doi.org/10.1016/j.envsci.2024.103796

Richard J. Torraco (2005). Writing Integrative Literature Reviews: Guidelines and Examples. doi**:** 10.1177/1534484305278283

Schilke, O., Hu, S. and Helfat, C. (2024) 'Dynamic capabilities: A review and research agenda', *Journal of Management*.

Scott, W.R. (2014) *Institutions and organizations: Ideas, interests, and identities*. 4th edn. Thousand Oaks, CA: Sage.

Setyadi, A., Pawirosumarto, S., & Damaris, A. (2025). Toward a resilient and sustainable supply chain: Operational responses to global disruptions in the post-COVID-19 era. *Sustainability, 17*(13), 6167. https://doi.org/10.3390/su17136167

Teece, D.J., Peteraf, M. and Leih, S. (2016) 'Dynamic capabilities and organizational agility: Risk, uncertainty and entrepreneurial management in the innovation economy', *California Management Review*.

Tipi, N. and El Gazzar, S.H. (2021) 'Considerations towards a sustainable and resilient supply chain: A modelling perspective', *International Business Logistics Journal*, 1(1), pp. 6–13.

van der Vegt, G.S., Essens, P., Wahlström, M. and George, G. (2015) 'Managing risk and resilience', *Academy of Management Journal*, 58(4), pp. 971–980. https://doi.org/10.5465/amj.2015.4004

Wang, J., *et al.* (2018) 'Management of a holistic supply chain network for proactive resilience: Theory and case study', *Computers & Industrial Engineering*, 125, pp. 668–677.

Inter-Organisational Relationships and Processor-Mediated Supply Chain Learning: A Conceptual Framework for Dynamic Capabilities in Agri-Food Supply Chains

Minh Anh Nguyen, Kwok Hung Lau, Aswini Yadlapalli

RMIT University, Australia

Purpose of this paper

Recent global disruptions have highlighted the vulnerability of supply chains and the capability to recover quickly through learning, particularly in developing economies, where upstream stakeholders – such as smallholder suppliers, processors, or informal actors – are deeply embedded yet often marginalized in formal learning processes (Lissilour, 2025, Tumwebaze et al., 2025). Meanwhile, supply chain learning plays a critical role in enhancing resilience by enabling supply chain actors to anticipate disruptions, coordinate responses, and adapt routines under uncertainty (Scholten et al., 2019). However, the learning happening through hands-on experience and local problem-solving remains underrated (Oelze et al., 2020). One reason is the persistent lack of trust and power imbalances in supply chain relationships, which suppress open communication and learning.

Prior literature has examined the individual effects of both supply chain learning (SCL) and relational capital on supply chain resilience (SCR) by highlighting mechanisms such as learning routines (Scholten et al., 2019), artificial intelligence (AI) - enabled learning environments (Belhadi, 2022; Dai et al., 2025), dynamic learning capabilities (Habibi et al., 2026), and relational enablers (Daghar et al., 2023; Chowdhury et al., 2019), little is known about how relational factors shape the learning mechanism of stakeholders. Given the fact that heterogeneous relational structures influence different learning processes in supply chains, shaping how and what knowledge is exchanged (Pu and Qiao, 2025). Therefore, analysing their combined effects is critical to understanding how supply chains transition toward more resilient configurations over time.

Against this background, this paper aims to develop a conceptual model on examining relationship between supply chain relationship structure (SCRS), SCL, and SCR.

Design/methodology/approach

The development of a conceptual framework grounded in theory would facilitate the examination of the supply chain phenomena under investigation from a generic perspective (Carter and Rodgers 2008). This paper adopts a theory-driven integrative review approach to synthesise insights from the literature on SCL, SCRS, and SCR. Rather than conducting a systematic review for exhaustive coverage, the review of conceptually and theoretical relevant literature identifies key constructs and their relationships necessary for developing a conceptual framework, which is the objective of the study.

Findings

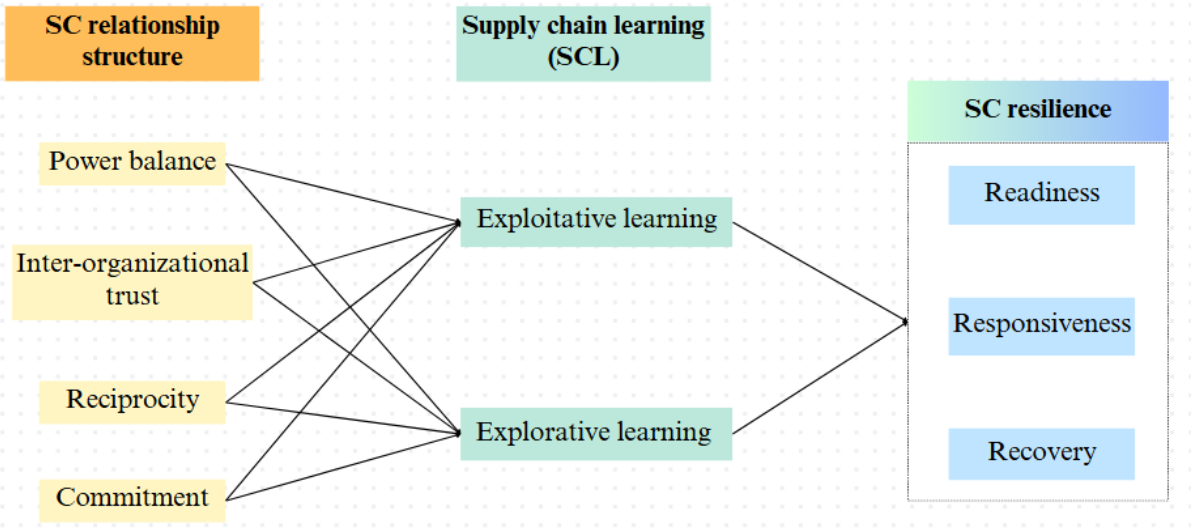
Conceptual framework

This research is anchored on two theoretical foundations. The Organizational Learning theory (OLT) posits that organizations improve their behaviour and performance through experience, knowledge acquisition, and adaptation (Argyris, 1996). In the supply chain context, learning is not isolated within one firm but distributed across multiple actors. SCL represents a networked version of this theory — learning occurs through inter-organizational interactions, knowledge sharing, and joint problem-solving (Silvestre, 2023). Meanwhile, the Social Exchange theory (SET) advocates that interaction between entities or individuals with others are from the expectation of benefits from the relationships (Emerson 1976). In supply chain management,

SET argues that the development of supply chain partnerships is based on the long-term mutual benefits gained from the relationships (Wei et al. 2012). Drawing on SET, trust, commitment, power, and reciprocity are recognised as key attributes of relationships (Wu et al. 2014).

Based on OLT and SET, this research proposes a conceptual framework that connects SCRS including trust, commitment, reciprocity, and power balance with two distinct modes of SCL: (1) exploitative learning, which involves incremental, experiential knowledge acquisition through ongoing transactions, and (2) explorative learning, which fosters deeper capability development and innovation through codified knowledge exchange (Braun et al., 2023). The framework further links these learning modes to three dimensions of SCR, conceptualized in terms of readiness, responsiveness, and recovery – offering a nuanced perspective on how knowledge exchange and relational quality jointly shape resilience outcomes (Chowdhury et al., 2016). A set of theoretical propositions is advanced to capture the relationships between relational structures, learning modes, and resilience outcomes.

Figure 1: Conceptual framework



Source: Author's work

Propositions

We argue that relational capital, built on power balance, trust, and reciprocity, improves SCL by promoting mutual communication and understanding among SC partners, thereby influencing their willingness to engage in knowledge exchange (Zhang et al., 2018). It also reduces relational risks and support interaction, which facilitates both exploitative and explorative learning. On the other hand, high commitment might hinder stakeholders' exploration behaviours (Wang & Zhang, 2022) or impede individual learning (Pillai et al., 2017). Based on the above, we propose the following:

Proposition 1. Greater power balance among supply chain actors is likely to positively influence both explorative and exploitative learning.
Proposition 2. Inter-organizational trust is likely to positively influence both explorative and exploitative learning.
Proposition 3. Reciprocity among supply chain partners is likely to positively influence both exploitative and explorative learning
Proposition 4. Commitment between supply chain actors is likely to positively influences exploitative learning and negatively effects explorative learning.

The framework further distinguishes between two modes of supply chain learning with different implications for resilience. Exploitative learning emphasizes improvement through the adoption of prescribed practices, routines, and standards, relying primarily on explicit knowledge. This learning mode supports operational stability and preparedness but may constrain adaptive capacity. In contrast, explorative learning involves deeper knowledge integration, tacit knowledge exchange, and joint problem-solving, enabling innovation, flexibility, and adaptation in the face of disruptions (Scholten et al., 2019). Based on the above, we propose the following:

Proposition 5. Exploitative learning is likely to positively influences supply chain resilience by enhancing readiness and operational reliability.
Proposition 6. Explorative learning is likely to positively influences supply chain resilience by enhancing responsiveness and recovery capabilities.

Value

This paper makes two key contributions. Firstly, the conceptual framework investigates the constraining effect of asymmetrical partnerships on constraining capacity, which has not been fully examined in the extant literature. Secondly, it contributes to the resilience literature by detailing specific relational structure that connects to resilience via learning-induced capabilities. Finally, it offers a clear typology of supply chain learning, distinguishing between explorative and exploitative modes.

From a practical perspective, the framework provides guidance for supply chain managers and policymakers to move beyond compliance-driven learning and foster relational conditions that enable deeper, more transformative learning across supply chain networks.

Research limitations

This study is conceptual in nature and has not yet been empirically tested. Future research could validate the proposed framework using quantitative approaches and apply it to specific industries or supply chain configurations. Longitudinal studies may also examine how relational structures and learning modes evolve across repeated disruption events.

Keywords: Supply chain learning, relational structures, resilience, exploitative learning, explorative learning

References

Argyris, C. (1996). Organizational learning II. *Theory, method, and practice*.

Belhadi, A., Kamble, S.S., Venkatesh, M., Chiappetta Jabbour, C.J. and Benkhati, I. (2022) Building supply chain resilience and efficiency through additive manufacturing: an ambidextrous perspective on the dynamic capability view, *International Journal of Production Economics*, *249*, 108516

Braun, C. L., Bitsch, V., & Häring, A. M. (2023). Developing agri-food value chains: Learning networks between exploration and exploitation. *Journal of Agricultural Education and Extension*, *29*(4), 417–438.

Carter, C. R., & Rogers, D. S. (2008). A framework of sustainable supply chain management: moving toward new theory. *International journal of physical distribution & logistics management*, *38*(5), 360-387.

Chowdhury, M. M. H., & Quaddus, M. (2016). Supply chain readiness, response and recovery for resilience. *Supply Chain Management: An International Journal*, *21*(6), 709-731.

Chowdhury, M. M. H., Quaddus, M., & Agarwal, R. (2019). Supply chain resilience for performance: role of relational practices and network complexities. *Supply Chain Management: An International Journal*, *24*(5), 659-676.

Dai, J., Geng, R., Xu, D., Shangguan, W., & Shao, J. (2025). Unveiling the impact of the congruence between artificial intelligence and explorative learning on supply chain resilience. *International Journal of Operations & Production Management*, *45*(2), 570-593.

Daghar, A., Alinaghian, L., & Turner, N. (2025). Resilient interorganizational culture in multi-tier supply networks: the "what" and "how". *Supply Chain Management: An International Journal*, *30*(6), 652-680.

Emerson, R. M. (1976), Social exchange theory. *Annual review of sociology*. pp. 335-62

Habibi, F., Chakrabortty, R. K., & Abbasi, A. (2026). The Impact of Supply Chain Networks' Structural Topology and Learning Capabilities on Resilience: a Simulation Study. *IEEE Transactions on Engineering Management*.

Lissillour, R. (2025). Reframing Sustainability Learning Through Certification: A Practice-Perspective on Supply Chain Management. *Sustainability*, *17*(13), 5761.

Oelze, N.; Gruchmann, T.; Brandenburg, M. (2020) Motivating Factors for Implementing Apparel Certification Schemes—A Sustainable Supply Chain Management Perspective. *Sustainability, 12*, 4823.

Pillai, K. G., Hodgkinson, G. P., Kalyanaram, G., & Nair, S. R. (2017). The negative effects of social capital in organizations: A review and extension. *International Journal of Management Reviews*, *19*(1), 97-124.

Pu, G., & Qiao, W. (2025). Relational risk, knowledge sharing and supply chain resilience: the complementary role of blockchain governance and relational governance. *Journal of Knowledge Management*, *29*(2), 301-341.

Silvestre, B. S., Gong, Y., Bessant, J., & Blome, C. (2023). From supply chain learning to the learning supply chain: drivers, processes, complexity, trade-offs and challenges. *International Journal of Operations & Production Management*, *43*(8), 1177–1194.

Scholten, K., Sharkey Scott, P., & Fynes, B. (2019). Building routines for non-routine events: supply chain resilience learning mechanisms and their antecedents. *Supply Chain Management: An International Journal*, *24*(3), 430-442.

Tumwebaze, R. P., Walsh, J. N., & Lannon, J. (2025). Knowledge management in the agriculture sector: a systematic literature review. *Knowledge Management Research & Practice*, *23*(2), 131-148.

Wei, H. L., Wong, C. W. Y. & Lai, K. H. (2012) Linking inter-organizational trust with logistics information integration and partner cooperation under environmental uncertainty, *International Journal of Production Economics, 139*(2), pp. 642-53.

Wu, I. L., Chuang, C. H. & Hsu, C. H. (2014) Information sharing and collaborative behaviors in enabling supply chain performance: A social exchange perspective, *International Journal of Production Economics*, *148*, pp. 122-32

Wang, C., & Zhang, X. E. (2022). Binary effects of exploratory and exploitative learning on opportunity identification: The different moderations of environmental munificence and entrepreneurial commitment. *Asian Business & Management*, *21*(4), 497-524.

Zhang, M., Zhao, X. and Lyles, M. (2018) Effects of absorptive capacity, trust and information systems on product innovation, *International Journal of Operations and Production Management*, *38*(2), pp. 493-512

Supply Chain Resilience Measurement and Strategic Responses in the Volatile Environment

Mei-hui Chen[1], HsinYi Lin[2], Huiting Chih[2], Kune-muh Tsai[3]

1: Chia Nan University of Pharmacy and Science, Taiwan; 2: Industrial Technology Research Institute, Taiwan; 3: National Kaohsiung University of Science and Technology, Taiwan

Purpose of this paper

In recent years, the structure of global industrial supply chains has undergone significant changes due to the impact of the US-China trade war and the COVID-19 pandemic, consequently elevating risks across the entire supply chain. Facing these shifting circumstances, Taiwan's industries find that past business models are no longer sufficient to address potential changes and risks. Only by assessing their own supply chain structural condition—specifically their capabilities and tolerance levels across various aspects—and actively responding to challenges can they maintain their competitiveness in a volatile global environment. To understand the supply chain resilience (SCR) of Taiwan's industries in the face of supply chain risks, the Ministry of Economic Affairs (MOEA) commissioned the Industrial Technology Research Institute (ITRI) to design a questionnaire on SCR and to investigate it across various industries in Taiwan. Over the past three years, we have been studying the SCR of industries such as semiconductors, machinery, textiles, microelectronics, etc. For each of those industries, we first invited 6-12 companies to fill out the questionnaire via https://drscr.org.tw/. After analysis, we further requested 5-6 companies, under their agreement, to conduct a physical visit to clarify and discuss the questionnaire results. We concluded with suggestions for improving supply chain resilience. This paper presents the questionnaire and discussion results for two textile companies, focusing on the supply chain strategies and actions they plan to implement and have already implemented, and on how they could further improve to respond to both short- and long-term risks and uncertainties, including responses to geopolitical turbulence.

Design/methodology/approach STS

The questionnaire was initiated and designed by the MOEA of Taiwan to evaluate the SCR of Taiwan's industries as a reference for formulating industrial development and support programs to strengthen Taiwan's overall resilience. MOEA assigned the questionnaire development project to ITRI, which invited professors and industrial professionals to collaborate. After a year, the project team, using the Delphi Method, delivered the questionnaire design and analysis. To assess overall national resilience, WEF (2012) proposed 5R: Robustness, Redundancy, Resourcefulness, Response and Recovery as the lens of looking at five national-level subsystems (economic, environmental, governance, infrastructure and social). The 5R is one of the fundamental models used to develop our SCR model. Moreover, since the questionnaire is on SCR, in the development stage, the flows of goods along supply chains are also considered as 5 F(lows), starting from (1) product development, (2) demand management, (3) procurement management, to (4) production and (5) order fulfilment. After three rounds of collective critique on questionnaires with experts from the ITRI, industry and academia, the questionnaire for evaluating the SCR of a company was developed. However, the 5R represents a company's implicit capacity, but most of the time it is hard to associate them with managerial and strategic improvement. Thus, ITRI further classified the questionnaire variables into 5 explicit capabilities (5C) as Digital, Analytical, Decision-making, Collaborative, and Sustainability. These capabilities are directly linked to a business's supply chain practices and will primarily be used to represent a company's SCR in the later analysis. In total, there are 144 variables (questions) and they are divided into five constructs (capabilities). Each construct has 1-5 KSF (key success factors) and each KSF has 1-3 KPI (key performance index), while in each KPI, there are 1-15 variables. After filling out the questionnaire, the scores of 5Cs, 5Rs, 5Fs and their respective KPIs and KSFs can be calculated. These scores are very useful for analyzing the strengths and weaknesses of a company’s SCR.

In the past three years, diverse industries were selected for the study. In this paper, we show the results of the questionnaire and physical visits. The representative companies in the industry were selected and invited based on the suggestions from the industry association and professional experts. Most selected ones are publicly listed. After completing the questionnaires, 5-6 companies in the industry are selected again for physical visits. During the physical visit, we were received by high-ranking managers, usually from 2-4 divisions of the company, who instructed their staff to complete the questionnaire.

Findings

We first display the questionnaire analysis results and then discuss with the company one by one what the results mean to them practically and how they could and plan to improve the SCR. Below is a partial list of the SCR of Company A. Besides the 5 Capabilities of the SCR for a business, we will present the SCR from the perspectives of 5Rs and 5Fs, and show their relationships.

Construct of 5 Capabilities	Scores	KSF (key successful factors)	Scores	KPI (key performance index)	Scores
Digital Capability	76.6	Data Collection Capability	82.25	Data Collection Implementation Status	90.00
				Situation Room/Monitoring Center Implementation Status	74.50
		Information Sharing Capability	70.00	Establishment of Supply Chain Information Sharing Platform	70.00
Analytical Capability	70.8	Problem Prediction	73.00	Prediction Mechanism and Analytical Capability	73.00
		Problem Diagnosis	68.44	Recovery Mechanism and Performance	68.44
Decision-making Capability	75.3	Flexibility Capability	70.72	Equipment Resilience Level	70.00
				Operational Flexibility Level	71.25
		Supply Chain Network Design	74.93	Number of Supply Chain Tiers	90.00
				Decentralized Supply Network	70.00
		Backup and Dispatching	78.61	Material Availability Rate	92.67
				Backup Mechanism and Performance	63.75
				Inventory Mechanism	82.00
		Response Speed	74.58	Supply Chain Responsiveness and Cost	86.67
				Supply Chain Agility Performance	62.50
Collaborative Capability	74.1	Risk and Profit Sharing	60.00	Supply/Cooperation Contract Signing	60.00
		Close Partnership	75.06	Proximity to Suppliers and Customers	90.00

Value

This paper examines the SCR of businesses and presents the variables, KPIs, KSFs, and questionnaire constructs developed through the Delphi Method after three rounds of questionnaire consensus involving numerous professionals and professors. In this study, we show the SCR for 5 Capabilities because they are explicit measurements and serve as an illustration of the company's SCR. Other resilience measurements, like 5Rs and 5Fs, can be easily converted to show the implicit measurement (5Rs) or the product flow (5Fs) of the SCR. Two physical visits to the case companies further provide practical meaning to the questionnaire results and how companies may, as a reference, respond to the volatile supply chain environment and geopolitical tension.

Research limitations/implications

The questionnaire was developed with support from the MOEA of Taiwan to measure the industry's SCR. Despite following strict academic standards in developing the questionnaire, it is still influenced by the opinions of governmental officers, which reflects its utility for policy-making. The selected samples are mainly recommended by respective industry associations, with some recommendations from the MOEA, rather than a random selection process. Thus, the result may not reflect the industry's current status quo.

Practical implications

The study's research limitations reflect its practical implications, as governmental officers and industrial professionals were involved in both the questionnaire development and the company selection process. The results, though uncomprehensive, show the SCR of two representative companies and how they respond to the volatilities and risks of the current supply chain environment.

Literature

Vargas, J. and González, D. (2016). Model to assess supply chain resilience. International Journal of Safety and Security Engineering, 6(2), 282–292.

World Economic Forum. (2013). Global Risks Report 2013: Eighth Edition. An Initiative of the Risk Response Network. Geneva: World Economic Forum.

World Economic Forum. (2025). Global Risks Report 2013: 20th Edition. A World of Growing Division. Geneva: World Economic Forum.

Yang, C., Tian, K. and Gao, X. (2025). Supply chain resilience: Measure, risk assessment and strategies, Fundamental Research, 5(2), 433-436.

Keywords: Supply Chains, resilience, risks, geopolical tension, Delphi method

How Supply Chains Can Facilitate Equitable Food Provision – Challenges & Opportunities

Emmanuel Sawyerr[1], Michael Bourlakis[2]

1: University of Glasgow, United Kingdom; 2: Cranfield University, United Kingdom

Purpose of this paper

With a growing global population comes increased demand for food; yet an estimated 1.3 billion tonnes of food is wasted each year, while over 29.6% of the world's population, which is around 783 million people, remain undernourished (UNEP, 2024). In the UK, this contradiction is evident as many households face rising food poverty even as obesity rates continue to increase (O'Brien & Nisbett, 2019). At the same time, there is growing recognition of the scale of food waste across different stages of the supply chain, alongside a renewed interest in redistributing surplus food to support disadvantaged groups (Wascher et al., 2015).

This paper examines the supply of food to disadvantaged communities in the UK, investigating the role that logistics innovation and sustainable supply chain management can play in improving this process. The study is conducted across four locations in the south of England, namely, Tower Hamlets, Brighton and Hove (B&H), Plymouth, and Whitley-Reading. It draws on relevant governmental and institutional documents to benchmark extant knowledge, based on which empirical data is collected to identify opportunities for practical interventions and further research. The objective is to highlight key supply chain issues contributing to food insecurity and diet-related health inequalities faced in these communities, and to generate insights applicable across the UK and other developed economies.

Design

An embedded case study approach was adopted for this study (Yin, 2018). We first conducted a detailed study of food supply chains in Tower Hamlets, B&H, Plymouth, and Whitley-Reading, using secondary data from local councils and central government reports, academic studies on the communities, and publications and websites of community initiative groups. The data were coded using NVivo and analysed for each community to identify geographic characteristics, demographic and foodscape information, diet-related health issues, and existing efforts to address food-system challenges.

We then gathered semi-structured interview data from seventy-two participants, with twenty-four from Plymouth, twenty from B&H, ten from Whitley-Reading and eighteen from Tower Hamlets. We first focused on local charity organisations providing food to marginalised groups. We then interviewed some of their surplus food donors and local government representatives.

Thematic analysis was abductively undertaken in NVivo to vet the findings from the literature review and identify other unique local supply chain-related challenges and new and/or proposed community-based solutions. Cross-case analysis unveiled similarities and differences in challenges and attempted solutions, helping identify opportunities for cross-learning.

Findings

The cross-case analysis highlights a consistent demographic pattern for groups most vulnerable to food poverty and insecurity. These include single-parent households, low-income families, and adults living alone. Additional at-risk groups include households with members facing physical, dietary, or mental health conditions; families with no recourse to public funds; and some pensioners, although the latter group is generally less vulnerable than younger populations.

The role of commercial food supply chain (CFSC) actors in addressing food insecurity has primarily been through charitable redistribution, which is fraught with Can logistical challenges, primarily related to costs, limited capacity and operational inefficiencies. Our study also highlights local food partnerships as critical actors in addressing local food insecurity through

local and regional advocacy and facilitating collaboration among food charities. Community-specific findings are as follows.

Despite high levels of deprivation in B&H, almost 40,000 tonnes of food are wasted annually. While a direct farm-to-consumer intervention failed due to high operational costs, the local food partnership coordinates inter-charity collaborations that lead to meaningful cross-learning and relatively improved operational efficiencies. Of the four cases, B&H was the most effective in addressing local challenges due to better access to data and a pivotal role by its food partnership.

Tower Hamlets borough is one of the most deprived in England, experiencing a high concentration of fast-food outlets. While access to healthy food options is available through both supermarkets and street markets, affordability is a major barrier. The local Council in 2018 established the Tower Hamlets Food Partnership to address food insecurity concerns. With funding from the local council, the partnership works with charities to operate a hub-and-spoke system that has significantly improved logistics efficiency and minimised demand-supply mismatch. However, demand for ethnically-appropriate food options lingers. Funding for this intervention is currently at risk.

The high level of deprivation in Plymouth is also worsened by high levels of obesity in disadvantaged communities. Unfortunately, relevant data on food access, food waste, among others, is woefully lacking, thereby impeding meaningful interventions, despite several efforts. With B&H's comparative success in addressing some of these issues, there are transferable lessons worth exploring.

Whitley is one of the wards in Reading where inequality is starkest, with obesity negatively affecting educational attainment. Unlike Tower Hamlets, access to healthy food is not only financial, but geographical too. Without a local food partnership, collaboration is limited, and relations among charities tend to be adversarial. Like Plymouth, access to relevant data is limited, exacerbating intervention efforts.

Value

This paper examines food insecurity and diet-related health inequalities by exploring foodscapes in four disadvantaged communities in the UK and opportunities for logistics innovation and sustainable supply chain intervention. It exposes the little attention paid to CFSCs and their role in tackling systemic food challenges. There are currently limited effective supply chain strategies to reduce food inequalities. While this is regrettable, it also presents exciting practical and research opportunities to re-examine current theoretical frameworks for flaws and inadequacies, and to explore avenues for reformation and adaptation of extant theories, or new, more equitable and socially inclusive conceptual and policy frameworks.

References

O'Brien, E., & Nisbett, N. (2019). Building a Sustainable Food City: A Collective Approach. *IDS Bulletin*, *50*(2), 111–119.

UNEP. (2024). *Food Waste Index Report 2024*. https://wedocs.unep.org/20.500.11822/45230

Wascher, D., Zasada, I., & Sali, G. (2015). Tools For Metropolitan Food Planning - A New View On The Food Security Of Cities. In N. Borrelli, M. Deakin, & D. Diamantini (Eds.), *The Governance of Food System* (pp. 68–97). Fondazione Giangiacomo Feltrinelli. https://www.researchgate.net/publication/323748427

Yin, R. K. (2018). *Case Study Research and Applications: Design and methods* (6th ed.). Sage Publications, Inc.

When Cities Shake: Localised Humanitarian Logistics in the 2025 Myanmar Earthquake

Nichapa Phraknoi[1], Juliana Sutanto[2], Parskorn Yasawute[3], Savangjit Kanchanakomol[4], Hung Nguyen[1]

1: RMIT University Vietnam; 2: Monash University, Australia; 3: Disaster Relief Training Center, Thailand; 4: Royal Thai Army Nursing College, Thailand

Purpose of this paper

The magnitude 7.7 earthquake that struck Mandalay, Myanmar's second-largest urban centre, on 28 March 2025 caused extensive destruction and a major humanitarian crisis, with more than 4,700 lives lost, over 5,100 people injured, and millions affected (IFRC, 2025). While Myanmar has experienced destructive earthquakes historically, the scale of loss reflects a transformed urban risk environment shaped by rapid urbanisation, infrastructure fragility, and uneven enforcement of seismic standards. Field assessments indicate that structural deficiencies and regulatory gaps amplified collapse severity (Wang et al., 2025). Across ASEAN, rapid urban expansion frequently outpaces governance capacity and disaster preparedness, concentrating populations in hazard-exposed environments, a dynamic recognised in disaster risk governance literature (Tierney, 2014; UNDRR, 2015).

Sudden-onset earthquakes compress operational decision windows, making the first 72 hours critical for survival and placing exceptional strain on humanitarian logistics (HL) systems required to mobilise under uncertainty while protecting responders in unstable conditions. Humanitarian supply chain theory conceptualises disaster logistics as socio-technical systems in which decentralised coordination, redundancy, and adaptive decision-making enhance resilience under disruption (Van Wassenhove, 2006). The Myanmar disaster demonstrates how urban emergencies challenge centralised response models: political constraints and infrastructure disruption limited reliance on international mechanisms, elevating regionally embedded and locally anchored logistics networks.

This study examines how localisation, i.e. the positioning of authority, capability, and contextual knowledge close to affected populations, shapes logistics performance in an urban earthquake response. The conceptual framing integrates disaster resilience and risk governance perspectives with HL theory, viewing urban response systems as distributed resilience architectures where decentralised expertise and networked coordination sustain operational continuity during shock.

Design/methodology/approach

An exploratory qualitative case study investigates HL operations during the earthquake response in Mandalay and Naypyidaw. Case study methodology is appropriate for analysing complex, multi-actor phenomena embedded in operational contexts where boundaries between logistics processes and governance structures are fluid (Yin, 2018). Disaster environments are characterised by uncertainty, rapid decision cycles, and coordination pressures, making qualitative case approaches well suited to capturing situated operational dynamics.

Data collection combines analytic autoethnography, semi-structured interviews, and documentary analysis. Analytic autoethnography provides systematic reflection on practitioner experience to generate theoretically informed insight into coordination pressures, logistics decision-making, and risk management in high-tempo environments (Anderson, 2006). This approach is recognised as valuable where tacit operational knowledge influences system performance.

Semi-structured interviews target responders and coordination actors engaged in logistics and field operations, consistent with qualitative inquiry aimed at capturing diverse experiential perspectives (Braun and Clarke, 2006). Approximately 30 interviews are planned. Unforeseen circumstances in Thailand have temporarily limited access to key informants, and 16 interviews have been completed to date. Despite the reduced sample at this stage, these information-rich

accounts provide timely frontline insight into logistics operations, offering meaningful analytical value while data collection continues.

Participants include logistics control units, medical emergency teams, Urban Search and Rescue personnel, rapid damage assessment specialists, and Myanmar-based volunteers. Documentary sources, including operational reports and verified situation updates support triangulation. Analysis employs iterative thematic coding to identify logistics mechanisms shaping response performance, consistent with qualitative approaches emphasising pattern recognition and interpretive rigour (Braun and Clarke, 2006).

Findings

Preliminary analysis identifies four interlocking logistics mechanisms illustrating how localisation functions as a resilience architecture in urban disaster response.

Proximity-enabled Decentralised Surge Capacity shows that early life-saving mobilisation depended on actors geographically and institutionally close to the disaster zone. Regionally embedded responders deployed faster than distant mechanisms, demonstrating how distributed logistics capacity reduces activation latency in sudden crises.

Adaptive Last-Mile Logistics reveals how infrastructure damage and communication breakdown generated acute situational uncertainty. Responders relied on offline navigation, peer coordination, and contextual judgement when formal information systems degraded, enabling continuous reconfiguration of delivery routes and staging decisions.

Risk- and Safety-Integrated Logistics demonstrates that logistics operations in collapsed urban environments are inseparable from responder safety management. Structural instability transformed mobility decisions into safety-critical processes, exposing how capability gaps propagate operational risk. Political and security uncertainty further shaped safety planning without displacing locally led decision-making.

Regional Coordination as a Localisation Multiplier shows how ASEAN coordination mechanisms, including the AHA Centre and ASEAN Plus Three strengthened national response capacity while preserving decentralised authority. Shared information channels and liaison functions enhanced interoperability and reduced friction across actors.

Collectively, these mechanisms conceptualise localisation as a distributed HL architecture enabling systems to absorb disruption and sustain life-saving action in complex urban emergencies.

Value

This study advances HL theory by reframing localisation as a structural property of resilient supply chains rather than solely a governance reform agenda. The Mandalay earthquake illustrates how decentralised surge capacity, adaptive last-mile operations, and safety-integrated decision processes function as resilience mechanisms under extreme uncertainty, reinforcing theoretical models emphasising agility, redundancy, decentralised authority, and socio-technical coordination in disaster logistics (Van Wassenhove, 2006).

By linking logistics performance to disaster governance and resilience frameworks, the study demonstrates how localised operational architectures convert proximity, embedded knowledge, and network coordination into system-level adaptability. Practically, the findings highlight the importance of embedding structural expertise within deployable logistics teams, investing in offline situational awareness tools, strengthening civilian-military interoperability, and reinforcing regional coordination platforms as localisation infrastructure. Policy implications point toward cross-scale capacity integration connecting municipal preparedness, national logistics systems, and regional governance networks, contributing to emerging scholarship on urban disaster resilience.

References

Anderson, L., 2006. Analytic autoethnography. Journal of contemporary ethnography, 35(4), pp.373-395.

Braun, V. and Clarke, V., 2006. Using thematic analysis in psychology. Qualitative research in psychology, 3(2), pp.77-101.

IFRC, 2025. Operation Update No. 4: Myanmar Earthquake.

Tierney, K., 2020. The social roots of risk: Producing disasters, promoting resilience. Stanford University Press.

UNDRR, 2015. Sendai Framework for Disaster Risk Reduction 2015-2030.

Van Wassenhove, L.N., 2006. Humanitarian aid logistics: supply chain management in high gear. Journal of the Operational research Society, 57(5), pp.475-489.

Wang, T., Zhou, Y., Chen, J., Wang, X., Bi, H. and Wang, X., 2025. Field survey of building damage at Mandalay during 2025 Myanmar Mw 7.7 earthquake. Earthquake Engineering and Engineering Vibration, pp.1-15.

Yin, R.K., 2018. Case study research and applications (Vol. 6). Thousand Oaks, CA: Sage.

Resilience-Driven Supply Chain Management: Toward a Three-Level Control Framework

Naima Rahiel, Sid Ali Addouche, Abderrahman Elmhamedi

Université PARIS 8, France

Purpose of this Paper

Modern supply chains face unprecedented challenges from escalating short-term disruptions natural disasters, cyber-attacks, pandemics and long-term systemic risks including geopolitical turbulence, climate change, and demographic shifts [1]. The COVID-19 pandemic illustrated how systems optimized solely for efficiency catastrophically fail when confronted with demand surges and supply disruptions [3]. Traditional supply chain management approaches optimize for cost minimization, inventory reduction, and capacity utilization under assumptions of stability, proving fundamentally inadequate when stability breaks down [4].

This paper addresses a critical gap: while existing research recognizes the importance of supply chain resilience, most frameworks remain sector-specific or provide only aggregate resilience scores, limiting practical utility for managers who need granular insights into which capabilities to develop, where to invest resources, and how to prioritize improvement initiatives [2]. Furthermore, existing resource allocation approaches typically address single resource categories and focus on normal operations rather than crisis response [5].

The primary purpose is to introduce a paradigm shift toward resilience-driven supply chain management where adaptive capacity takes precedence over static optimization. We develop a comprehensive hierarchical control framework applicable across diverse supply chain contexts, with particular focus on the first level dynamic resource reallocation through internal mutualization demonstrating how intelligent coordination of existing resources can simultaneously improve both crisis resilience and normal-operations efficiency without additional capital investment.

Design/Methodology/Approach

This research employs a multi-method approach combining mathematical modeling, algorithm development, and simulation-based validation. We propose a three-level hierarchical control framework comprising sequential intervention levers operating at different timescales: (1) dynamic resource reallocation (tactical, hours-to-days), (2) operational replanning (operational, days-to-weeks), and (3) topological reconfiguration (strategic, months-to-years).

Focusing on Level 1, we develop three interconnected methodological contributions. First, we construct a function-based performance evaluation model using graph theory where supply chain networks are represented as directed graphs with nodes (facilities) and arcs (resource flows) [6]. Functions are defined as integrated services requiring coordinated combinations of three resource categories: equipment, medications/materials, and staff. Performance metrics employ conjunctive logic missing one critical input prevents entire function execution. Second, we formalize resilience through a parametric mathematical model using hyperbolic tangent functions with seven independent parameters capturing degradation and recovery dynamics, from which six derived indicators enable multi-dimensional diagnosis [7]. Third, we develop priority-based greedy allocation algorithms with complexity $O(|N|^2 \times |T| \times 3)$ suitable for real-time crisis management.

Validation employs discrete-event simulation on a healthcare supply chain network comprising three facilities over 24 time periods, with multiple crisis episodes simulating realistic disruption patterns [8]. Healthcare serves as validation context because it

exemplifies broader supply chain challenges: multiple interdependent resources, service-oriented operations, demand uncertainty, capacity constraints, and catastrophic consequences of failure [3]. Comparative scenario analysis quantifies performance differences between independent operation (Base scenario) and coordinated resource sharing (Flow scenario).

Findings

Simulation results demonstrate that intelligent resource mutualization achieves performance improvements of 40 percentage points during crisis periods without additional capacity investment [8]. Detailed temporal analysis reveals three critical advantages of coordinated resource sharing.

First, recovery speed: the Flow scenario recovers to 90% performance within 3-5 periods after initial shock, while the Base scenario struggles to exceed 50% performance even after 10 periods, representing 2x faster recovery. Second, sustained resilience: the Flow scenario maintains near-perfect performance (90-100%) for extended stable periods, demonstrating that intelligent coordination enables crisis recovery and sustains high operational efficiency [6]. Third, crisis robustness: during subsequent disruptions, the Flow scenario maintains 20-30% functionality while the Base scenario collapses to below 10-15% performance, representing a 200-300% performance advantage.

Analysis reveals that spatial heterogeneity where some nodes operate at high capacity hile others remain underutilized creates the fundamental opportunity for mutualization gains. Resource mutualization transforms network behavior from fragile systems exhibiting catastrophic cascading failures to resilient networks capable of rapid recovery and sustained high performance despite repeated shocks. These findings hold across diverse supply chain contexts including manufacturing, distribution, humanitarian logistics, and service operations, as the mathematical framework remains unchanged while adaptation lies in parameter specification [2].

Value

This research makes three original contributions advancing supply chain resilience theory and practice. First, it introduces a novel function-based performance framework measuring system capability to deliver integrated services requiring coordinated resource combinations shifting focus from resource-level metrics to value-creation capabilities [6]. Second, it develops a parametric resilience assessment approach with seven independent parameters and six derived indicators enabling precise diagnosis of specific organizational weaknesses and targeted interventions, addressing the limitation of existing aggregate resilience scores [2, 7]. Third, it demonstrates that coordination capabilities often yield greater resilience improvements than equivalent investments in additional capacity orders of magnitude in some cases opening new pathways for cost-effective supply chain improvement [4]. The framework's generalizability across manufacturing, distribution, humanitarian, and service sectors establishes both theoretical foundations and practical tools for implementing resilience-driven management [8].

Research Limitations/Implications

Research Limitations

This study focuses exclusively on Level 1 (dynamic resource reallocation) of the three-level hierarchical framework, while complete resilience management requires integration of all three levels. The validation employs simulation on a representative but simplified healthcare network; real-world implementation would face additional organizational, regulatory, and behavioral complexities [3]. The greedy allocation algorithm, while computationally efficient for real-time application, does not guarantee global optimality exact optimization approaches may yield marginal improvements [5]. The framework assumes organizational willingness to share resources, which requires establishing trust, governance structures, and incentive alignment mechanisms.

Implications for Future Research

Several extensions merit investigation. First, formalizing Levels 2 and 3 would complete the framework, enabling integrated multi-level strategies. Second, incorporating exact optimization solvers could benefit strategic planning contexts [5]. Third, extending the framework to stochastic settings would capture demand/supply uncertainty and disruption unpredictability [1]. Fourth, empirical validation across manufacturing, retail, and humanitarian contexts would confirm generalizability beyond healthcare [4]. Fifth, investigating hybrid approaches combining resource mutualization with other resilience strategies could enable comprehensive resilience management [2]. Finally, behavioral research examining conditions under which organizations successfully implement resource sharing agreements would enhance practical applicability.

Practical Implications

Results suggest actionable insights for supply chain practitioners and policymakers:

Invest in Coordination, Not Just Capacity: Intelligent coordination of existing resources often yields greater resilience than capacity expansion at dramatically lower cost [8]. Organizations should prioritize developing coordination capabilities information systems, communication protocols, relationship management rather than solely investing in redundant capacity [4].

Design Flexible Resource Sharing Policies: Organizational policies governing resource sharing significantly impact resilience independent of total resource inventories [6]. Policy reviews examining barriers to internal resource mobility may represent the most cost-effective resilience interventions. Organizations should establish clear governance frameworks defining when, how, and under what conditions resources can be shared.

Activate Mutualization Dynamically: Resource mutualization provides minimal normal-operations benefit but critical crisis value. Rather than maintaining permanent coordination overhead, organizations should design rapid activation mechanisms pre-established protocols, decision authority, communication channels that can be triggered when disruptions occur [7].

Establish Cross-Organizational Mutual Aid Frameworks: The principles extend beyond internal organizational boundaries. Industry associations, regional networks, and governmental bodies can facilitate mutual aid agreements enabling resource sharing across organizations during crises [2].

Address Geopolitical and Systemic Risks: The framework directly addresses both short-term disruptions and long-term systemic risks including geopolitical turbulence [1]. Dynamic

reallocation provides tactical response to immediate disruptions while supporting strategic resilience against long-term uncertainties.

References

R. Agrawal et al., *Progress and trends in integrating Industry 4.0 within Circular Economy*, Business Strategy and the Environment, vol. 33, no. 1, pp. 62–81, 2024.

D. Ivanov, *The Industry 5.0 framework*, International Journal of Production Research, vol. 61, no. 5, pp. 1683–1695, 2023.

L. Keshtkar et al., *Resilience of healthcare supply chains*, International Journal of Production Research, vol. 62, no. 8, pp. 2918–2950, 2024.

S. K. Paul et al., *Key enablers of resilient and sustainable construction supply chains*, Sustainable Production and Consumption, vol. 36, pp. 323–338, 2023.

V. Salehi et al., *Modeling and analysis of oil and gas projects' expenditure*, Journal of Cleaner Production, vol. 356, 131849, 2022.

N. Rahiel et al., *Function-based modeling for reactive optimization*, in Proc. LOGISTIQUA 2025 (IEEE), Casablanca, Morocco, 2025.

N. Rahiel et al., *Mathematical modeling of supply chain resilience*, in Proc. IN4PL 2025 (IFAC), Marbella, Spain, 2025.

N. Rahiel, *Formalisation mathématique de la résilience*, Ph.D. dissertation, Université Paris 8, France, 2025.

SUPPLY CHAIN ANALYTICS

Optimal Fleet Electrification Timing Under Subsidy Phase-Out

Hui-Chieh Li

National Taipei University of Business, Taiwan

Purpose of this paper

The research is motivated by a fundamental gap in the fleet electrification literature, which has focused primarily on static cost structures and policy instruments rather than dynamic timing decisions under policy uncertainty. Existing studies either conduct cross-sectional policy evaluations or develop adoption decision models, but do not examine how deterministic government subsidy phase-out path design influences firm-level transition timing decisions. This gap is critical because subsidy phase-out schedules are announced policy parameters that policymakers can design ex-ante, unlike stochastic market uncertainties, making them directly relevant for policy design. The study has three primary aims. We operationalize real options analysis into policy design parameters, establishing a causal chain from subsidy phase-out trajectories to timing decisions to environmental-economic outcomes. This enables systematic comparison of how policy temporal structure and market volatility factors influence optimal timing decisions. Methodologically, we integrate LSTM demand forecasting with multi-period NPV optimization using a scenario matrix approach that handles multi-dimensional uncertainties across revenue projections, vehicle price trajectories, and subsidy trajectories. This addresses the limitation of static cost-benefit analyses that dominate existing literature. Finally, the study quantifies environmental-economic trade-offs under different subsidy designs using a representative Taiwan logistics case, providing actionable decision tools for net-zero transition policymakers.

Design/methodology/approach

The study develops an integrated multi-period evaluation framework combining LSTM demand forecasting, net present value analysis, and real options theory to evaluate optimal fleet electrification timing across four sequential stages.

Stage 1 integrates historical revenue as a proxy for transportation demand, electric vehicle prices, and government subsidy policies including phase-out schedules.

Stage 2 quantifies three uncertainty sources. LSTM networks with Monte Carlo simulation generate 1,000 stochastic demand trajectories classified into optimistic, baseline, and pessimistic scenarios. Learning curve models project electric truck price reductions at 15% per production doubling. Three subsidy scenarios capture policy variation: continuous support, gradual phase-out to 10% by 2035, and rapid elimination by 2030.

Stage 3 conducts multi-period NPV evaluations treating each year as a discrete investment option. The Total Cost of Ownership framework incorporates differential cash flows across vehicle acquisition, operating costs, carbon emissions, and residual values. Three subsidy, revenue, and price scenarios generate 27 scenario combinations. Sensitivity analyses examine discount rate and carbon price impacts.

Stage 4 identifies optimal transition timing maximizing NPV, quantifies emission reductions, and derives policy recommendations balancing economic efficiency and environmental outcomes.

The framework applies to a Taiwan logistics operator with 70 monthly observations, calibrated using company data and manufacturer specifications.

Findings

The study reveals that subsidy phase-out design dominates fleet electrification timing decisions, shifting optimal transitions by nine years (2026-2035), while revenue variability has minimal impact (0-1 year). All 27 scenarios yield positive NPV ranging from NT$14.81 million to NT$75.86 million, confirming financial viability when properly timed.

Three distinct timing patterns emerge. Continuous support scenarios favor late transitions (2033-2035), yielding highest NPV (NT$68.90-75.86 million) but lowest carbon reductions (449-786 tons). Rapid phase-out scenarios concentrate timing in 2026, achieving maximum emissions reductions (2,338-2,684 tons) but lowest NPV and poorest efficiency (6,300-9,300 NT$/ton CO_2). Gradual phase-out scenarios demonstrate intermediate performance with timing in 2026 or 2030-2031, producing moderate reductions (1,136-1,557 tons) with viable economic returns (22,500-26,000 NT$/ton CO_2).

Cash flow analysis reveals early transition requires higher initial investment (NT$112.52 million) with lower residual value, while delayed transition substantially reduces upfront costs and increases residual value differential. Carbon costs contribute only 2.72% of NPV, while operational savings and residual values contribute 7.6-74.2% and 25.1-92.3% respectively.

Sensitivity analysis shows discount rate increases from 2% to 6% reduce NPV only 7.3% through endogenous timing adjustments, while carbon price variations demonstrate minimal impact at Taiwan levels.

Value

Theoretically, the study operationalizes real options analysis into policy design parameters, establishing a causal chain from subsidy phase-out trajectories to timing decisions to environmental-economic outcomes. Unlike existing studies that focus on stochastic subsidy withdrawal risk (uncertainty about whether subsidies will be revoked), this research examines how deterministic subsidy phase-out path design affects transition decisions—a critical gap because subsidy phase-out schedules are announced policy parameters that policymakers can design ex-ante, unlike stochastic market uncertainties. This enables systematic comparison of how policy temporal structure and market volatility factors influence optimal timing.

Methodologically, the study integrates LSTM forecasting with multi-period NPV optimization, using a scenario matrix to handle multi-dimensional uncertainties in revenue, vehicle price trajectories, and subsidy trajectories. This approach addresses limitations of static cost-benefit analyses that dominate existing literature. The framework demonstrates counter-intuitive resilience through endogenous timing adjustment—as discount rates increase from 2% to 6%, NPV declines only 7.3% because higher rates prompt delayed transitions that reduce initial investment exposure by 65%.

Practically, the study quantifies environmental-economic trade-offs under different subsidy designs using a representative Taiwan logistics case, providing actionable decision tools for net-zero transition policymakers. The research reveals that quantitative assessments of emissions reduction efficiency across alternative subsidy designs have not been previously undertaken, limiting policymakers' ability to evaluate trade-offs between fiscal efficiency and decarbonization urgency.

The paper provides value to three stakeholder groups. For policymakers, it demonstrates that subsidy phase-out design dominates timing decisions, shifting optimal transitions by nine years, and recommends gradual phase-out mechanisms that extend decision windows by 4-5 years while balancing economic viability and emissions targets. For fleet operators, it offers strategic guidance showing that timing flexibility confers financial resilience, with NPV remaining relatively stable despite discount rate variations, enabling operators to focus on policy trajectory assessment rather than interest rate forecasting. For researchers, it establishes that policy temporal structure serves as a more influential lever than market volatility factors in determining commercial fleet transition timing.

Evaluating Logistics Performance in ASEAN Countries: A Novel Dynamic Combined Compromise Solution (CoCoSo) Method Considering Non-Consecutive Series

Shupeng Huang[1], Andrew Potter[2], Daniel Eyers[2], Qinyun Li[2]

1: College of Management Science, Chengdu University of Technology, China; 2: Cardiff Business School, Cardiff University, Cardiff, UK

Purpose of this paper

To ensure the smooth trading and regional integration, the logistics are important. However, the logistics development levels of different ASEAN countries are diverse, leading to difference in logistics effectiveness, costs, and reliability. It can therefore possibly result in logistics inequality and hinder the successful regional integration. To support the identification and measurement of potential regional logistics inequality, the first and foremost step is to accurately evaluate and rank the logistics performance among ASEAN countries. To achieve this goal, this paper attempts to develop a method to comprehensively evaluate the ASEAN countries' logistics performance and support decision-making for relevant stakeholders, including governments, policy makers, and companies in ASEAN area.

Design/methodology/approach

To achieve the research goal, a comprehensive evaluation framework combining hybrid weighting methods and multi-criteria decision-making (MCDM) models is proposed and applied to the logistics performance index (LPI) dataset released by the World Bank. Specifically, equal weighting, entropy weighting, and MEREC (i.e., method based on the removal effect of criteria) weighting methods are simultaneously adopted to derive criteria weights of six dimensions of LPI, and a novel dynamic CoCoSo with non-consecutive series is developed to evaluate the logistics performance of ASEAN countries. The contribution of this method to the existing literature is to effectively handle the issue of the non-consecutive feature in LPI series which are not released in a regular basis. By applying this method, a fair logistics performance comparison among countries and among different periods can be expectedly achieved.

Findings

The hybrid weighting CoCoSo results suggest that Singapore is the country having the highest logistics performance, followed by Malaysia and Thailand. The results also indicate that Lao PDR seems to have the lowest logistics performance by holistically considering its LPI across multiple years based on the CoCoSo results.

Value

To the best of our knowledge, this is the first paper applying a hybrid weighting non-consecutive series dynamic CoCoSo approach to evaluate the LPI of ASEAN countries. The newly proposed method can expectedly capture more information in the LPI dataset to derive a more appropriate performance evaluation. More importantly, it is promising to address the issue of systematic data-missing problem and contribute to the time series analysis literature. Meanwhile, it can bring practical values, and the value of the results can potentially support policy makers to design and implement proper logistics-related import/export policies, as well as inform multi-national companies to design their international trade strategies.

Research limitations/implications

The research implications of this study are twofold. First, this study adopts an ASEAN perspective to analyse the LPI, enriching the theoretic basis of international logistics and advancing the academic literature of international trade. Also, this study provided a framework to evaluate LPI, offering new methodological tool for prospective studies for logistics performance evaluation.

However, the current research is limited by fixed indicators used in LPI static dataset, which might not be able to capture more information from other perspectives.

Practical implications

This study can inform policy makers and practitioners for their decision-making in logistics and international transport. Based on our results, the policy makers can design proper policies to enhance multi-lateral logistics cooperations among ASEAN countries, while practitioners in international companies can use our results and methods to evaluate their business partners in different countries from logistics perspective.

References

Jiang Y, Zhang J, Asante D, et al. Dynamic evaluation of low-carbon competitiveness (LCC) based on improved Technique for Order Preference by similarity to an Ideal Solution (TOPSIS) method: A case study of Chinese steelworks. Journal of cleaner production, 2019, 217: 484-492.

Lin Q, Zhang K, Huang D, et al. Evaluating the impact of Trans-Asian railway on logistics mode selection between Thailand and China: An AHP-TOPSIS approach. Alexandria Engineering Journal, 2024, 98: 147-158.

Yazdani M, Zarate P, Kazimieras Zavadskas E, et al. A combined compromise solution (CoCoSo) method for multi-criteria decision-making problems. Management decision, 2019, 57(9): 2501-2519.

Supply Chain Intelligence for Retrofit at Scale: Diagnosing Implementation Readiness in Delivery-Sensitive Markets

Muhammad D. Abdulrahman, Priyabrata Chowdhury, Shahrooz Shahparvari, Kamrul Ahsan, Kwok Hung Lau, Vinh Thai, Priya Rajagopalan, Dmytro Ostapenko

RMIT University, Melbourne, Australia

Purpose of this Paper

Large-scale residential retrofit is central to national decarbonisation strategies, yet deployment consistently underperforms techno-economic projections. Policy frameworks typically prioritise financial incentives, standards, and consumer engagement, assuming that supply chains can absorb accelerated demand. However, empirical evidence from retrofit and electrification markets suggests that logistics coordination, installer sequencing, and governance misalignment frequently constrain uptake despite favourable economics (Rosenow & Lowes, 2020; Rosenow & Eyre, 2016).

This paper argues that supply-chain readiness constitutes a structural determinant of retrofit scalability and that structured supply chain intelligence is required to anticipate and mitigate implementation risk. Rather than treating supply chains as neutral conduits of policy ambition, the study conceptualises them as active mediators of deployment feasibility. Drawing on transition governance scholarship emphasising implementation conditions in shaping socio-technical pathways (Geels et al., 2016; Wilson et al., 2012), the paper examine the operational interdependencies across retrofit supply-chain domains, identify technology-specific delivery vulnerabilities and, highlights governance asymmetries across value-chain positions.

By advancing a diagnostic intelligence framework, the paper aims to inform strategic decision-making in large-scale building transformation programmes.

Design/Methodology/Approach

The study adopts a structured supply-chain intelligence approach grounded in the Supply Chain Operations Reference (SCOR) framework. SCOR's domain architecture (Plan–Source–Deliver–Return) enables systematic collection and analysis of intelligence across interconnected logistics functions.

Quantitative data were obtained through a practitioner survey covering manufacturers, distributors, retailers, and installers operating within the residential retrofit market. Domain-level performance indices were constructed to measure coordination intensity, perceived fragility, and operational constraints.

To strengthen construct validity and reduce perceptual bias, findings were triangulated with semi-structured industry interviews exploring sequencing complexity, inventory volatility, transport fragility, and warranty-resolution challenges.

The theoretical scope integrates supply-chain governance with energy-transition implementation research. Rather than focusing on optimisation modelling, the approach positions supply-chain intelligence as a diagnostic capability for identifying structural bottlenecks ex ante. This responds to calls for implementation-oriented analysis in energy transitions (IEA, 2023) and extends supply chain intelligence beyond risk monitoring toward policy-feasibility assessment.

The methodological contribution lies in adapting SCOR from firm-level benchmarking to system-level diagnostic intelligence.

Findings

Three core findings emerge. First, retrofit supply chains exhibit tightly coupled operational interdependencies. Warehousing, transport, installer scheduling, and returns handling form a mutually reinforcing system in which disruption in one domain propagates across others. Rapid demand expansion without coordination capacity therefore increases systemic fragility.

Second, scalability varies systematically across technologies. Delivery-sensitive measures - such as heat pumps and high-performance window systems - display greater vulnerability due to transport fragility, sequencing dependency, and higher first-time installation risk. In contrast, warehouse-compatible measures such as insulation align more readily with existing distribution infrastructures. These findings reinforce empirical evidence identifying logistics and coordination barriers in heat pump deployment (Rosenow & Lowes, 2020; Rosenow & Eyre, 2016).

Third, governance asymmetries persist across value-chain positions. Retailers and installers bear customer-facing accountability but lack upstream control over inventory and warranty authorisations. Similar downstream exposure has been documented in retrofit markets (Mahapatra et al., 2013).

Collectively, the findings demonstrate that supply-chain structure actively shapes deployment trajectories. Technology-neutral incentives may unintentionally favour measures with simpler logistics profiles, echoing broader transition research showing that implementation feasibility influences pathway selection (Geels et al., 2017; Wilson et al., 2012).

Value

The paper advances supply chain intelligence by reframing it as a strategic diagnostic instrument for implementation readiness in decarbonisation programmes. It bridges operations management and transition governance scholarship, demonstrating how domain-level intelligence can anticipate bottlenecks before scale-up.

For researchers, the study extends SCOR into policy-level analysis. For policymakers and industry leaders, it provides a structured method for aligning ambition with delivery capacity, thereby reducing systemic risk.

Research Limitations/Implications

The analysis is based on practitioner perceptions within a single national context, which may limit cross-jurisdictional generalisability. Although triangulation mitigates bias, future research could integrate longitudinal logistics data, predictive modelling, and comparative institutional analysis. Further work could also explore digital supply-chain intelligence platforms to enhance real-time coordination.

Practical Implications

Scaling retrofit requires embedding supply-chain intelligence into programme design. Policymakers and industry stakeholders should conduct structured readiness diagnostics prior to demand expansion, identify delivery-sensitive technologies requiring enhanced coordination, align implementation responsibility with operational control and invest in logistics integration, inventory buffering, and sequencing optimisation.

Supply-chain intelligence must therefore move from a reactive monitoring function to a proactive design tool for large-scale transformation programmes.

Acknowledgement:

The authors would like to express their gratitude to RACE for 2030 CRC: Energy Upgrades for Australian Homes (22.H2.S.0365) for funding “WP5 Supply Chain Development” project.

References

Geels, F.W., Sovacool, B.K., Schwanen, T., & Sorrell, S. (2017). The socio-technical dynamics of low-carbon transitions. Joule, 1 (3), 463-479.

IEA (2023). Energy Efficiency 2023. International Energy Agency, Paris.

Mahapatra, K., Gustavsson, L., & Haavik, T., Aabrekk, S., Svendsen, S., Vanhoutteghem, L., Paiho, S., Ala-Juusela, M. (2013). Business models for full service energy renovation of single-family houses in Nordic countries. Applied Energy 112, 1558-1565

Rosenow, J. & Eyre, N. (2016). A post mortem of the Green Deal: Austerity, energy efficiency, and failure in British energy policy. Energy Research & Social Science 21, 141-144.

Rosenow, J., & Lowes, R. (2020). Heating without the hot air: Principles for smart heat electrification. Brussels, Belgium: Regulatory Assistance Project. Available at: https://www.researchgate.net/publication/341654122_Heating_without_the_hot_air_Principles_for_smart_heat_electrification#fullTextFileContent (accessed 19 February 2026).

Wilson, C., Grubler, A., Gallagher, K.S., & Nemet, G.F. (2012). Marginalisation of end-use technologies in energy innovation for climate protection. Nature Clim Change 2, 780–788 (2012). https://doi.org/10.1038/nclimate1576

Hydra-Net: Hybrid Deep Learning Based Routing and Packing Arrangement Network

Dhawal Thakkar[1], Dhanish Ahammed M V[2], Balamurugan Palaniappan[1]

1: Indian Institute of Technology (IIT), Bombay, India; 2: Indian Institute of Science Education and Research (IISER), Mohali, India

Purpose of this Paper

The efficiency of modern logistics operations depends on synchronizing routing schedules with physical cargo loading, a significant computational challenge [1]. Real-world operations require solving the Integrated 3D Loading Capacitated Vehicle Routing Problem with Time Windows (3L-CVRPTW; see Figure 1), where route feasibility depends not just on distance or time but on the geometric constraints of cargo within the vehicle. Sequential heuristics [2] often produce cost-effective yet physically infeasible routes due to packing conflicts, while exact methods falter under the combinatorial complexity of joint routing and packing decisions, creating a clear need for learning-based solvers.

We introduce HYDRA-Net, a novel multi-agent framework designed to resolve the complexities of 3L-CVRPTW. The architecture tackles two core challenges: routing under time windows and 3D packing with vertical stability and containment constraints. Rather than validating packing retrospectively, a practice that triggers costly backtracking, we implement a synchronized inference loop. In this loop, the routing network (TRANSIT-Net) proposes candidate stops that the packing network (STACK-Net) immediately verifies for 3D feasibility. When constraints are violated, a recovery mechanism masks the invalid move and prompts the router to select the next-best feasible alternative. This tight coupling ensures that every generated plan is both cost optimized and physically executable, delivering high-quality logistics solutions in seconds.

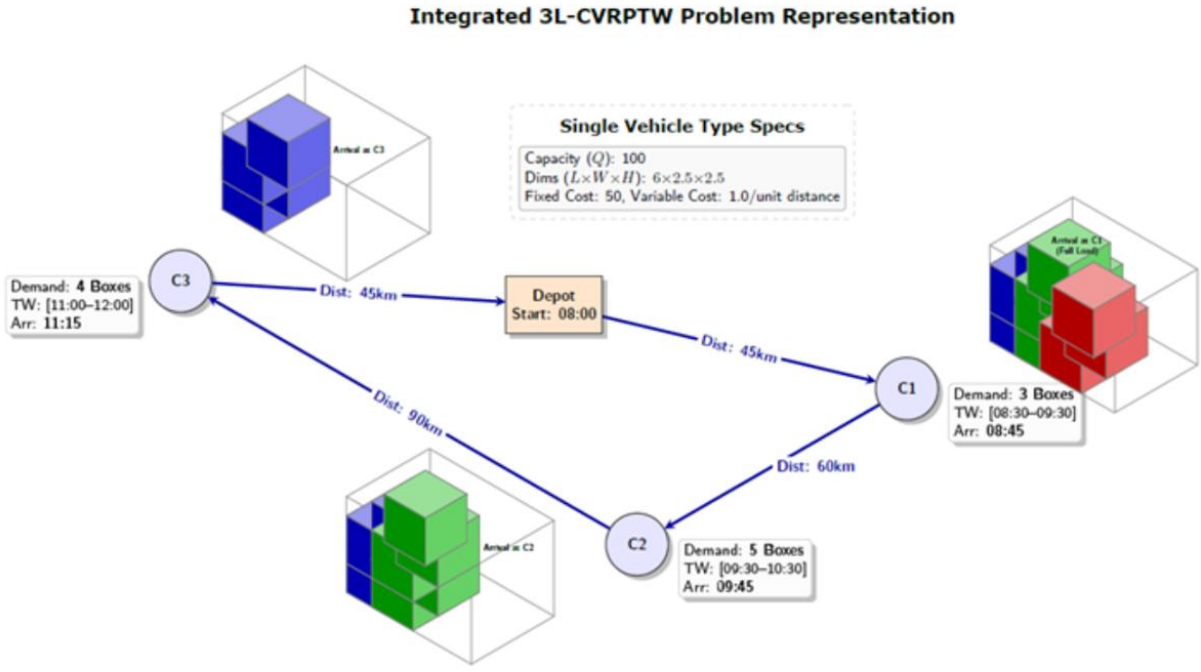


Figure 1: Overview of Integrated 3L-CVRPTW. The diagram illustrates the progressive unloading process along the route. The vehicle starts fully loaded at the Depot. At C1, the Red boxes (C1) are available at the front for unloading. At C2, the Red boxes are gone, making Green boxes (C2) accessible. At C3, only Blue boxes (C3) remain, demonstrating strict LIFO compliance and 3D volume tracking.

Proposed Methodology: The HYDRA-Net Framework

We propose HYDRA-Net, a multi-agent framework for solving 3L-CVRPTW. Recognizing routing and packing as separate sequence prediction problems, we decompose the 3L-CVRPTW into two synchronized Transformer[3]-based agents: TRANSIT-Net (routing engine) and STACK-Net (packing engine). HYDRA-Net orchestrates their interaction to ensure every decision is both logistically efficient and physically executable (Figure 2).

HYDRA-Net employs two agents, each using Transformer architectures (Figure 3). The first agent, called TRANSIT-Net, processes parallel Site, Vehicle, and Time streams augmented by a topological Graph Attention Network (GAT). Its decoder predicts routing triplets (Next Node, Vehicle, Arrival Time) via a shared Cross-Attention Bus, using dynamic masking to enforce capacity and time window constraints. The other agent STACK-Net, manages 3D loading by processing Box Features against a discretized container grid. A GAT analyzes the layout to generate precise item-position pairs, while a Physics Engine mask enforces stability and non-overlap constraints.

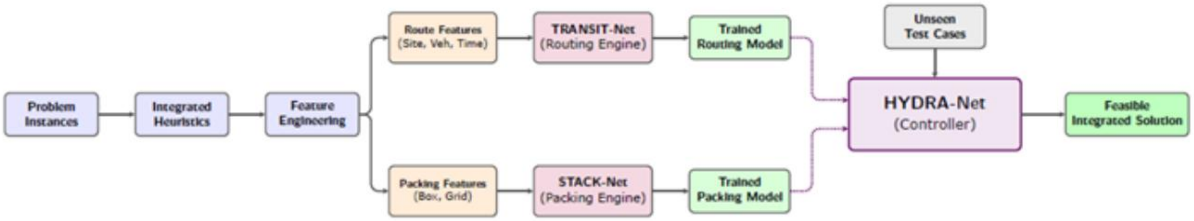


Figure 2: Overview of the HYDRA-Net Framework

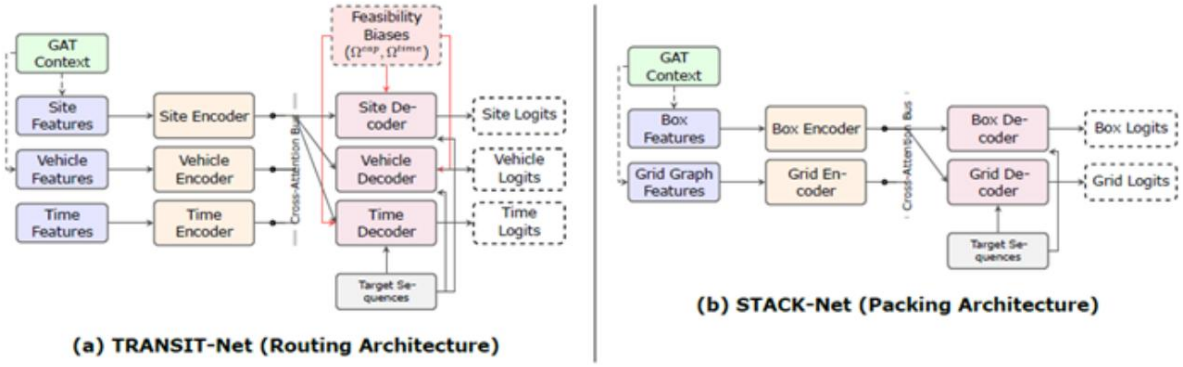


Figure 3: Architecture Overview of HYDRA-Net components. (a) TRANSIT-Net processes Sites, Vehicles, and Time streams enriched by site coordinate context. (b) STACK-Net processes Box and Grid Graph streams enriched by topological context. Both use a shared Cross-Attention Bus to fuse multi-modal representations.

To train TRANSIT-Net and STACK-Net, we developed distinct synthetic data generation frameworks. The serviceable region is modeled as a unit square partitioned into discrete grids. Customer demand comprises sets of 3 to 5 boxes drawn from three distinct cuboid types, serviced by a homogeneous fleet with fixed dimensions (ample availability of vehicles is assumed).

For generating baseline solutions to train TRANSIT-Net and STACK-Net, we use a Hybrid Metaheuristic (Figure 4) with a Cluster-First, Route-Second, Pack-Verify strategy: customers are

clustered via K-Means, routed using Time-Window Aware Ant Colony Optimization, and each route is validated by a 3D packer enforcing containment and stability constraints. Failed packings trigger cluster resizing, forming a feedback loop that guarantees physically feasible training labels.

Our inference approach uses a Propose-Validate-Commit inference loop (Figure 5) that tightly couples routing and packing to avoid infeasible solutions. TRANSIT-Net proposes a candidate triplet (next customer, vehicle, arrival time), which STACK-Net validates for 3D packing feasibility. Valid moves are committed; invalid ones trigger a recovery mechanism that masks the failed action and prompts the next-best alternative, ensuring a physically executable route.

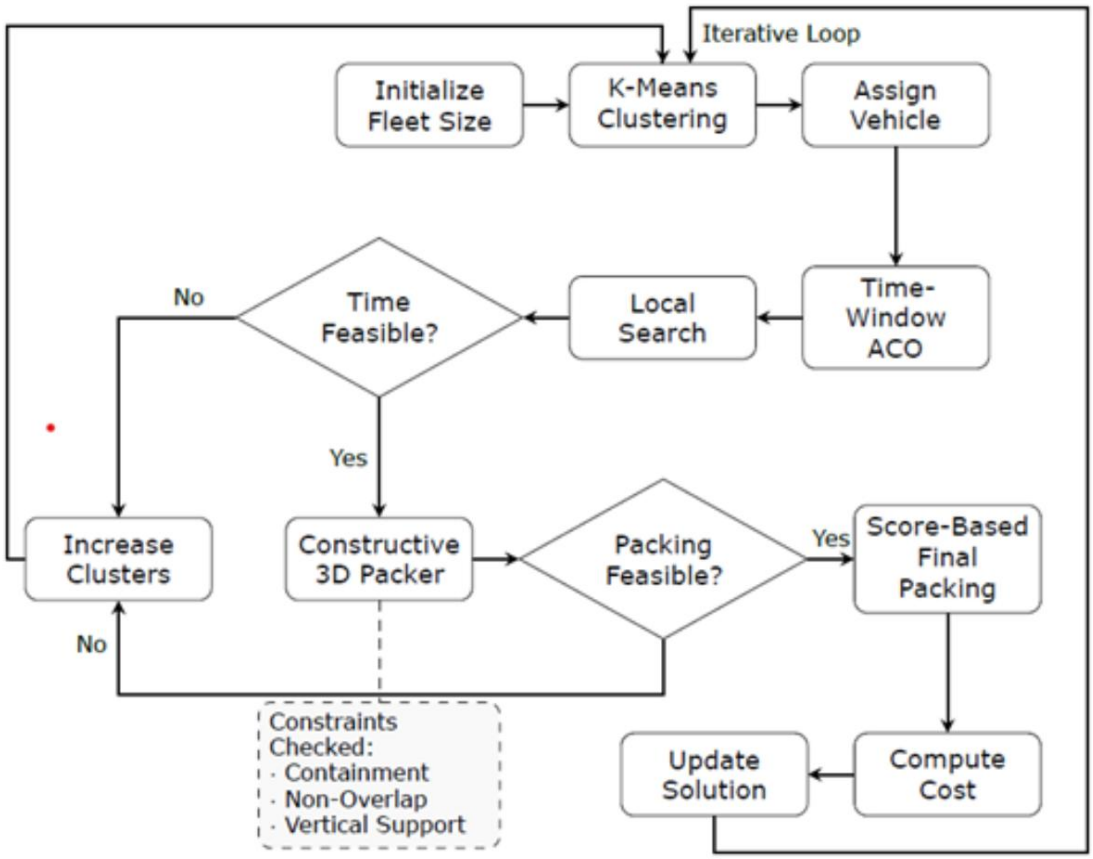


Figure 4: Workflow of the Integrated Hybrid Heuristic. The process employs a specific Pack-Verify stage to ensure physical feasibility before finalizing any route.

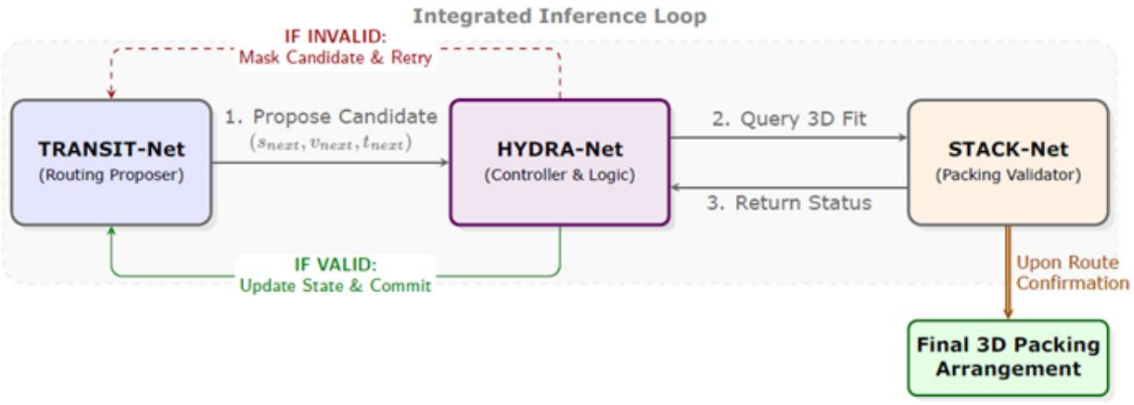


Figure 5: End-to-End Inference Lifecycle of HYDRA-Net. The central controller mediates between the routing proposer and packing validator. Invalid proposals trigger a retry loop (Red), ensuring only physically executable moves are committed (Green).

Findings

Our initial experiments utilized 54,000 synthetic instances to train the respective models, comprising N ∈ {10,11,12} delivery locations, each requiring 3 to 5 items. Demand included cuboids of dimensions 1×1×1, 2×2×2, and 3×3×3, assuming service by a fleet with homogeneous vehicles each with container size 10 × 6 × 6. We used 6,000 held out instances for testing purposes. The principal finding is the successful deployment of a novel multi-agent decision architecture. By assigning distinct optimisation tasks to specialised sub-networks, TRANSIT-Net for routing and STACK-Net for packing, the system coordinates disparate decisions into a feasible executable solution. Training was supervised by our custom integrated heuristic, which was allowed 180 seconds to generate high-quality ground truth solutions. Quantitative analysis confirms that our architecture achieves complete feasibility on unseen test cases, strictly adhering to both delivery time windows and complex 3D packing constraints. Ongoing experiments indicate that HYDRA-Net's solution quality is progressively approaching the solution quality of the heuristics with every training epoch. This confirms that the network is effectively learning the complex operational dependencies. HYDRA-Net generates valid solutions in just 1 or 2 seconds. This dramatic acceleration demonstrates that the multi-agent coordination mechanism effectively balances physical executability with high computational speed, validating its potential for real-time deployment where rapid, constraint-compliant decision-making is critical for logistics efficiency.

Value

Methologically, HYDRA-Net demonstrates that a novel multi-agent framework can effectively orchestrate collaborative decision-making between specialized networks (routing and packing agents in this case) to solve high-dimensional, complex problems previously viewed as intractable for end-to-end learning. By delivering a unified feasible solution (routing and packing) in almost real time, HYDRA-Net helps enable instant, dynamic fleet management. The proposed architecture provides a scalable blueprint for training high-performance models in complex domains where disparate sub-problems must be solved jointly rather than sequentially, representing a significant leap forward in collaborative artificial intelligence systems.

Research Limitations/Implications

While HYDRA-Net consistently produces fully feasible solutions for the complex 3L-CVRPTW, its solution quality is still improving. Future work should investigate self-improvement training loops to iteratively refine the policy beyond initial supervision, aiming to match or exceed heuristic performance.

Practical Implications

Logistics operators can use this framework to replace error-prone sequential planning (of routing followed by packing), with real-time decisions, cutting solution time from minutes to seconds

while ensuring physically feasible routes that prevent loading dock failures and improve fleet volumetric utilization.

References

[1] Rebollo, M., et al. (2024). ”A branch-and-cut algorithm for the 3L-CVRP.” Computers & Operations Research.

[2] Gendreau, M., et al. (2006). ”Tabu search heuristics for the vehicle routing problem with two-dimensional loading constraints.” Networks.

[3] Vaswani, A., et al. (2017). Attention is all you need. NeurIPS.

GLOBALISATION OF SUPPLY CHAINS

Design Drivers for Circular Cold Chain Logistics Using Returnable Transport Items

Irina Harris, Mohammed Fakhrulddin, Dnyaneshwar Mogale, Mohamed M. Naim

Cardiff University, United Kingdom

Purpose of this paper

This research investigates the system-level factors within the Circular Economy that affect the design and operationalisation of the circularity in pharmaceutical logistics, which utilises secondary and tertiary returnable packaging systems, or Returnable Transport Items (RTIs). Such packaging is designed to be long-lasting, reliable, with lifecycle management and system compatibility (Bocken et al. 2016). It serves a critical function to protect products during distribution and enable their effective return for replenishment and reuse. The successful integration of RTIs into logistics design determines the effectiveness of a circular business model that is supported by generic strategies based on cycling (e.g., reuse, remanufacturing, recycling), extending the reusable logistics assets through long-lasting design and repair; intensifying it through the sharing economy and dematerialising the resource through service and solution substitution (Geissdoerfer et al. 2020).

The study focuses on temperature-controlled logistics, which is characterised by rigorous regulatory compliance, advanced active and passive systems, and emerging innovations in packaging design. The core considerations for cold chain performance include the product shelf life, on-time delivery, routing optimisation, inventory levels, innovative technological solutions, temperature predictions, supporting network and enhanced collaboration (Schneikart et al. 2024; Sutar et al., 2026). The aim of this paper is to investigate the critical design drivers for embedding circularity in forward and reverse logistics, as well as how circular economy principles at different stages drive network changes and implementation. The research objectives are to determine the enablers and barriers that affect the adoption and successful implementation of temperature sensitive RTIs in cold chain logistics.

Design/methodology/approach

Semi-structured interviews are conducted with three supply chain and operations managers, a development and production manager and two hub coordinators of an international distribution company. The investigation is structured around the framework by Bradley and Corsini (2023) that has been extended to consider circularity design in supply chain execution. This study adopts a hybrid deductive-inductive approach and considers environmental, economic and social dimensions for the sustainable lifecycle design of reusable packaging in cold chain logistics.

Findings

We have conducted the preliminary analysis of the interview data. The discussions provide valuable insights into a highly specialised international operation with strict operational control. The interviewees emphasise the RTI and supply chain design principles of the circular economy and the ongoing adaptation to customer and regulatory demands to support continuous integration of circularity in reusable temperature-controlled logistics. The success is determined by delivering not only distribution efficiency but also by offering a reliable, consistent performance on time-critical and high-value pharmaceuticals. This directly reflects the ability to solve "difficult problems" while exceeding customer expectations. Although sustainability awareness is increasing, in some cases, customer adoption remains influenced by cost sensitivity and risk aversion. The complex international logistics operations integrate reliable temperature controls, waste elimination through reuse, repair and recycling and risk management strategies.

Value

This study extends the knowledge around innovations in circularity design for pharmaceutical logistics in global distribution using reusable packaging solutions. It investigates the development of sustainable circular business strategies and the key design drivers, in the form of enablers and barriers, of the adoption and successful implementation of temperature-sensitive reusable packaging systems.

Research limitations/implications

Cold chain logistics in the pharmaceutical sector have strict safety and quality requirements. The research considers various stages of the Circular Economy from the RTI design, production, usage (including sorting and cleaning), shrinkage, transportation, recycling/repurposing & end of life stages. Investigating other industries for sector specific characteristics may offer unique challenges for future research.

Practical implications

The managerial implications of this research provide practitioners with insights into how to integrate circular economy principles into the cold chain logistics with returnable transport packaging systems. It highlights the important design drivers across economic, environmental, and social characteristics to support a sustainable supply chain strategy using returnable containers.

References

Bocken, N.M.P., de Pauw, I., Bakker, C. & van der Grinten, B. 2016. Product design and business model strategies for a circular economy. Journal of Industrial and Production Engineering, 33(5), 308-320.

Bradley, C.G., Corsini, L. 2023. A literature review and analytical framework of the sustainability of reusable packaging. Sustainable Production and Consumption 37, 126-141.

Geissdoerfer, M., Pieroni, M.P.P., Pigosso, D.C.A., Soufani, K. 2020. Circular business models: A review. Journal of Cleaner Production 277.

Schneikart, G., Mayrhofer, W., Löffler, C., Frysak, J. 2024. A roadmap towards circular economies in pharma logistics based on returnable transport items enhanced with Industry 4.0 technologies. Resources, Conservation and Recycling 206.

Sutar, G., Dhalmahapatra, K., Chakraborty, S. 2026. Chapter 8 Identifying Critical Factors in Cold Chain Logistics System: A Review. Edited by Yacob Khojasteh, Y., Mousavi Jahan Abadi, S.M. Digital Transformation of Supply Chains: Business Objectives and Applications. International Series in Operations Research & Management Science, Volume 372, Springer 2026.

Modern Slavery Remediation in Healthcare Supply Chains through Blockchain Implementation: A socio-technical systems perspective

Vei Yie Tan, Kamrul Ahsan, Aswini Yadlapalli

Department of Supply Chain and Logistics Management, RMIT University

Purpose of this paper

While blockchain technology is increasingly examined as a means to enhance supply chain transparency, limited research has examined how blockchain may be leveraged to address social sustainability issues like modern slavery. For example, Venkatesh et al. (2020) and Park and Li (2021) examine blockchain associations for social sustainability outcomes at an aggregate level. Within the modern slavery context, blockchain use has been examined in a small number of studies (Marques et al., 2025; Yu et al., 2024). Yet, prior research has insufficiently examined the motivations that drive organisations to implement blockchain for modern slavery remediation, the barriers that constrain implementation, and the levers through which blockchain can be enacted to support remediation. This gap is concerning, as modern slavery operates within complex environments where misaligned motivations, unresolved barriers, or poorly designed interventions can undermine implementation and remediation (Wilhelm et al., 2025). Accordingly, this study aims to examine how blockchain can be implemented to support modern slavery remediation by asking:

1. What drivers and barriers do organisations perceive in implementing blockchain for modern slavery remediation?
2. How can blockchain be effectively implemented to support modern slavery remediation?

Design

The research design involved interviewing two key stakeholder groups: healthcare procurement managers and blockchain experts. The research focuses on the healthcare sector, an underexplored context in modern slavery and blockchain studies, compared with consumer-facing sectors such as fashion, agriculture, and wine (Marques et al., 2025). Australia's reliance on imported goods further exposes the sector, with half of its healthcare organisations sourcing goods from high-risk regions fail to detect modern slavery (Lichtman et al., 2023). This study employs an abductive approach using a socio-technical systems (STS) perspective. The first stage employed deductive logic, drawing on existing literature to establish a theoretical foundation and develop a priori conceptual framework. The second stage adopted an inductive approach aimed at validating the initial framework through empirical analysis of the interview data. Codes were generated directly from the interview transcripts to identify patterns and relationships. Abductive theorising was then undertaken through iterative engagement between the emergent empirical findings and relevant literature, enabling a reinterpretation of STS.

Findings

Healthcare and blockchain participants offered complementary yet divergent views on the implementation of blockchain for addressing modern slavery. Using STS lens, we organise findings into three interacting dimensions. We then developed a blockchain implementation for modern slavery remediation (BIMSR) framework (Figure 1) which identifies a set of drivers that motivate blockchain implementation, including regulatory compliance, reputational concerns, the pursuit of traceability, and the desire for agile risk management. However, these motivations are tempered by implementation challenges such as low organisational readiness, supplier disengagement, data quality and confidentiality, and system integration issues. To overcome these barriers, the framework highlights enabling levers, such as supplier development, incentivised information-sharing, interoperable technologies, and organisational learning, that can foster alignment between blockchain's capabilities in social contexts. Drawing from the STS lens, the framework highlights that the success of blockchain implementation hinges not only on technological aspects but also on complex organisational capacity and stakeholder relationships.

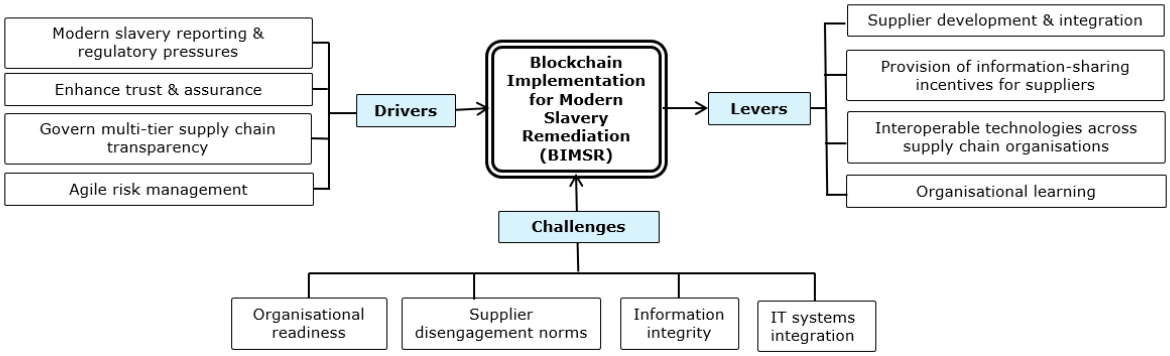


Figure 1. Blockchain Implementation for Modern Slavery Remediation (BIMSR) framework

Value

Extending the modern slavery and blockchain literature, this study provides empirical insights from the under-researched healthcare sector. Combining the identified drivers, barriers, and levers, we presented a multi-dimensional view of blockchain implementation for modern slavery remediation (BIMSR) framework. Using STS lens, the study shows that efforts to implement blockchain for modern slavery remediation are contingent upon how organisations navigate socio-technical frictions, social actors, technological infrastructure, and operational processes rather than on the technology itself. The BIMSR framework theorises this by bringing together a set of drivers (e.g., regulatory and reputational pressures), socio-technical challenges (e.g., concerns over sensitive data disclosure, integration costs, change management burden), and enabling levers (e.g., information-sharing incentives) for modern slavery remediation.

Research limitations

The findings are based on qualitative interviews conducted within the Australian healthcare sector. While this context provides rich insights into a highly regulated and under-researched setting, the results may not be directly generalisable to other industries with different regulatory regimes or labour risk profiles.

Implications

The findings provide insights for healthcare organisations and policymakers seeking to implement blockchain for modern slavery remediation. For healthcare organisations, this includes ensuring interoperability with existing procurement and traceability systems and investing in education and training to build internal digital literacy and cross-functional understanding of blockchain applications. Healthcare organisations must therefore pay attention to the social infrastructure required to effectively implement technology and consider supplier-facing incentive structures, such as preferred supplier status, contract renewal advantages, to encourage upstream participation and reliable information-sharing. Policymakers can play a facilitative role by supporting such initiative for interoperability and data governance, that allow healthcare organisations to encourage collaborative supplier development initiatives.

Keywords: Modern slavery, blockchain technology, socio-technical system lens, healthcare supply chains

References

Lichtman, S., Bhakoo, V., Kach, A., McGaughey, F., Boersma, M., Dinshaw, F., Nolan, J., & Sinclair, A. (2023). Australia's Modern Slavery Act: Is it fit for purpose?

Marques, L., Morais, D., & Terra, A. (2025). More than meets the eye: Misconduct and decoupling against blockchain for supply chain transparency. Production and Operations Management, 34(5), 1057-1075.

Park, A., & Li, H. (2021). The effect of blockchain technology on supply chain sustainability performances. Sustainability, 13(4), 1726.

Venkatesh, V., Kang, K., Wang, B., Zhong, R. Y., & Zhang, A. (2020). System architecture for blockchain based transparency of supply chain social sustainability. Robotics and Computer-Integrated Manufacturing, 63, 101896.

Wilhelm, M., Bhakoo, V., Soundararajan, V., Crane, A., & Kadfak, A. (2025). Beyond compliance-based governance: The role of social intermediaries in mitigating forced labour in global supply chains. Production and Operations Management, 34(5), 1094-1113.

Yu, W., Wong, C. Y., Jacobs, M., & Chavez, R. (2024). Modern slavery supply chain capabilities: the effects of blockchain technology and employees' digital dexterity. International Journal of Operations & Production Management, 45(1), 210-235.

When Complexity Undermines Transparency: Supply Chain Structure and Conflict-Free Mineral Sourcing

Beatrice Bais[1], Guido Orzes[2], Stephan Wagner[1]

1: ETH Zurich, Switzerland; 2: Free University of Bozen-Bolzano, Italy

Purpose of this paper

Despite growing regulatory oversight and stakeholder scrutiny, human rights abuses associated with conflict minerals persist as a significant challenge within global raw material supply chains. Previous studies have highlighted the role of geopolitical conflict and extraction risks in creating supply chain vulnerabilities (Al-Shwaf & Bell, 2025) and the ambiguous effectiveness of corporate social responsibility initiatives in the context of conflict minerals (Arikan et al., 2017). This study examines how structural complexity in the upstream supply chain and mineral-specific geopolitical risks influence firms' ability to trace and source conflict-free minerals. The study emphasizes the role of smelters and refiners as critical nexus suppliers.

Design/methodology/approach

Based on the nexus supplier theory and literature regarding multi-tier supply chain due diligence (Hofmann et al., 2018), this study presents a quantitative research model that links horizontal, vertical, and geographical supply chain complexity to the percentage of conflict-free smelters and refiners. Data were collected through a content analysis of conflict minerals reports filed by electronics manufacturers and were supplemented with financial and environmental, social, and governance (ESG) data from secondary databases. Hypotheses were tested using beta regression models, including robustness checks and mineral-specific analyses.

Findings

The results indicate that greater horizontal and geographical supply chain complexity is significantly associated with a lower proportion of conflict-free smelters and refiners. This confirms earlier evidence that complex, globally dispersed supply networks hinder transparency and sustainability efforts (Kim & Davis, 2016). Geographic complexity has the strongest negative effect, especially for minerals exposed to higher geopolitical instability, such as tungsten. This is consistent with recent insights on the politicization of "conflict-free" sourcing (Rubaii et al., 2025). By contrast, vertical complexity shows no consistent significant relationship.

Research limitations/implications

The study relies on publicly disclosed conflict minerals reports and focuses on the electronics industry, which may limit its generalizability. Nevertheless, the study contributes to the existing literature by combining supply chain complexity, geopolitical risk, and the nexus supplier theory into one empirical framework. This extends previous research on supply chain visibility and conflict mineral governance (Swift et al., 2019).

Practical implications

The findings underscore the need for managers to strategically simplify upstream supply chains, especially by reducing excessive geographical dispersion beyond the smelter and refiner levels. Managing nexus suppliers can enhance traceability and mitigate social sustainability risks. Additionally, policymakers and industry initiatives could benefit from encouraging coordinated approaches that focus on critical chokepoints in mineral supply chains rather than solely on first-tier suppliers.

References

Al-Shwaf, L., Bell, J.E. (2025). Raw material supply risks: Examining extraction and geopolitical conflict. *Transportation Journal*, 64 (2), e70006.

Arikan, O., Reinecke, J., Spence, C., Morrell, K. (2017). Signposts or weathervanes? The curious case of corporate social responsibility and conflict minerals. *Journal of Business Ethics*, 146 (3), 469-484.

Hofmann, H., Schleper, M.C., Blome, C. (2018). Conflict minerals and supply chain due diligence: An exploratory study of multi-tier supply chains. *Journal of Business Ethics*, 147 (1), 115-141.

Kim, Y.H., Davis, G.F. (2016). Challenges for global supply chain sustainability: Evidence from conflict minerals reports. *Academy of Management Journal*, 59 (6), 1896-1916.

Rubaii, K., El-Shewy, M., Griffiths, M. (2025). When "conflict free" minerals go to war. *Political Geography*, 123, 103425.

Swift, C., Guide, V.D.R. Jr., Muthulingam, S. (2019). Does supply chain visibility affect operating performance? Evidence from conflict minerals disclosures. *Journal of Operations Management*, 65 (5) 406-429.

Reinforcing Supply Chain Integration: A Quantitative Assessment of Textile and Garment Sector in Vietnam

Manh Kha Kieu[1], Rajkishore Nayak[1], Irfan Ulhaq[1], Tarun Panwar[2]

1: RMIT University, Vietnam; 2: RMIT University, Australia

Purpose of this paper

This research aims to provide a quantitative assessment of the supply chain integration (SCI) on sustainability performance in the textile and garment (T&G) sector in Vietnam. Despite the established understanding of supply chain and SCI, the paradigm shift of traceability and transparency requirements in the global supply chain outdates previously generated insights (Kieu et al., 2025).

This paper is based on the Uyghur Forced Labor Prevention Act (UFLPA) leveled up the transparency requirements as article level and full supply chain traceability are needed to avoid possible seizure of import shipment to the USA (Brake, 2025; US Customs, 2022). Further, the Carbon Border Adjustment Mechanism (CBAM), Green Claims Directive exacerbated the regulatory complexity (Zhong & Pei, 2024). While previously developed theories can be used in explaining the relationships around SCI with sustainability performance, the current contextual shifts require researchers to reinvent this topic to shed light on this important matter amid global supply chain volatility. To achieve these aims, the authors set three following objectives:

1. Verifying the key drivers of SCI among decision makers in this sector.
2. Confirming the valuable sustainable performance that SCI can bring to the manufacturers in Vietnam, an emerging global market.
3. Providing realistic and practical implications for decision makers in T&G industries to accurately navigate their supply chain strategies.

This research paper identifies context-specific SCI drivers and sustainability effects of integration that are specifically exhibited in a prominent industry in a fast-growing economy.

Design/methodology/approach

This research adopted the quantitative instrument, specifically cross-sectional survey, as the main method in conducting this research. The authors reviewed the Resource-based view theory, Stakeholder theory, and the existing body of knowledge on the current global and Vietnamese context to develop the hypotheses below which are based on the framework shown in **Figure 1**.

H1: Customer pressure (CP) positively correlates with SCI.
H2: Supply uncertainty (SU) positively correlates with SCI.
H3: Resource orchestration (RO) positively correlates with SCI.
H4: SCI positively correlates with economic performance (ECP).
H5: SCI positively correlates with environmental performance (EP).
H6: Network complexity (NC) moderates the relationship between CP and SCI.
H7: NC moderates the relationship between SU and SCI.
H8: NC moderates the relationship between SU and SCI.

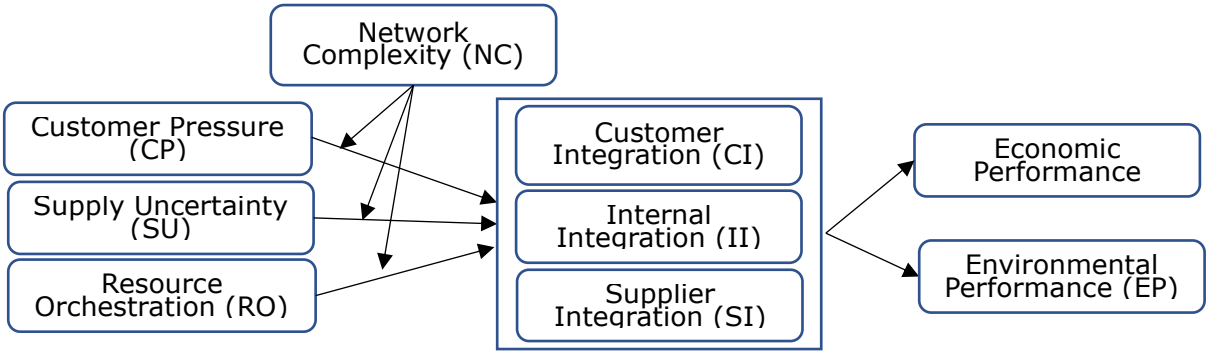


Figure 1 Proposed theoretical framework

The T&G industry in Vietnam is almost fully integrated with four downstream sectors including yarn spinners, fabric makers, garment manufacturers and fashion brands (VITAS 2025). Thousands of mills and manufacturers, covering all the tiers of the supply chain, are primarily located in the Southern part of Vietnam, accounting for about 55% of the total. The Northern region comprises about 30%, while the Central area accommodates the remaining manufacturers (VITAS 2024). Using systematic sampling technique, the authors are collecting responses from 350 companies with similar geographic and sectoral distribution to ensure the results will represent the entire population of T&G industry. Likert measurement scale of 1-5 was used in our questionnaire to collect data for 43 items, grouped into 9 constructs. A pilot study (n=50) was implemented to assess the reliability of the instruments. The main study of 350 responses will then proceed with measurement validity with confirmatory factory analysis (EFA), then hypotheses will be tested with structural equation modeling (SEM) using SPSS-Amos.

Findings

The authors completed collecting and analyzing 50 responses for the pilot test. The preliminary responses showed consistency across measurement instruments as Cronbach's Alpha values meet satisfactory levels. Once additional 300 responses are collected, the authors expect the data analysis to show positive relationships between SCI and sustainability performance including ECP and EP. SCI is validated to reduce operating expenses while increasing revenue and profit, and more importantly, to provide the necessity platforms for supply chain tiers to improve and quantitatively prove their economic and environmental performance.

In addition, the authors are confident to expect strong positive correlation between CP, SU, RO and SCI. It is important to have this validation as it had been believed that customer-related drivers will only affect CI efforts, not the integration across the whole supply chain. With this result, we believe that the customer- or supplier-related drivers do have direct impact on the adoption of all SCI's subdomains, which include customer integration (CI), internal integration (II) and supplier integration (SI). Furthermore, NC is expected to moderate the relationship between CP, SU, RO and SCI.

Value

This paper is unique in two aspects:

1. It fills the gap in the current literature. While global SCI future research trend tends to focus on looking into a specific industry to uncover the effects of its industry-specific context, T&G industry in Vietnam becomes valuable as the country does possess majority of the supply chain (Kieu, 2025). This characteristic ensures the industry-specific content is engaged but the findings can also be further generalized into other areas and industries.
2. The accurate collection of responses to include the right voice from various tiers of T&G supply chain and from various locations across the country.

The findings in this research build literature foundation for future researchers to dive into industry-specific context. The identification of SCI drivers provides industry professionals with valid insights to shape their supply chain decisions and strategies. The sustainability impacts of SCI reassure already adopted manufacturers of their SCI effort while providing added confidence to those who are planning for SCI adoption.

Research limitations/implications

Firstly, this paper collected data only from T&G industry, the findings should be further realigned with other industries' context before any generalization can be made. Future research can investigate SCI adoption across similar industries that have majority of supply chain's presence in Vietnam. Secondly, the T&G industry in Vietnam is matured and has fulfilled global standard for social compliance. Therefore, this research does not include social performance. Future research in emerging industries can investigate this important metric of triple bottom lines thoroughly. Lastly, this research paper only examines the moderating effects of NC on drivers-

SCI relationship. Moderating effects of NC on SCI-performance relationships can be further investigated in future research.

Managerial and Practical Implications

As SCI is proven to be able to reduce operating expenses, increase revenue and profit, and help companies to prove their environmental performance, non-adopters should prioritize SCI adoption. Initial findings show that NC has a negative moderating impact on the relationship between drivers and SCI. Therefore, on one hand, SCI adopters may think about streamlining their supply chain network through supply base and customer base reduction practices to enhance the adoption success rate. On the other hand, managers can adopt SCI in one product line as a pilot project in which the NC is lower prior to companywide adoption.

References

Brake, B.D., 2025. Incoherence in the UFLPA's rebuttable presumption: challenges of supply chain transparency. *SN Business & Economics*, *5*(10), p.152.
Customs, U.S. and Protection, B., 2022. *Uyghur forced labor prevention act* [online] Available at: < https://www.cbp.gov/trade/forced-labor/UFLPA> [Accessed 16 December 2025].
Kieu, M.K., Nayak, R., Akbari, M., George, M. and Panwar, T., 2025. Exploring trajectories in supply chain integration: a systematic analysis of emerging themes. *Management Review Quarterly*, pp.1-60.
VITAS, 2025. VITAS Monthly Newsletters 2025, Hanoi: Vietnam Textile and Apparel Association.
VITAS, 2024. Vietnam Textile and Apparel Industry Directory 2024, Hanoi: Vietnam Textile and Apparel Association.
Zhong, J. and Pei, J., 2024. Carbon border adjustment mechanism: a systematic literature review of the latest developments. *Climate Policy*, *24*(2), pp.228-242.

Defining Humanitarian Logistics Corridors: An Anchor-Based Construct Development Approach

Ali Anjomshoae[1], Ruth Banomyong[2], Puthipong Julagasigorn[3], Paitoon Varadejsatitwong[2]

1: Transportation Institute, Chulalongkorn University, Bangkok, Thailand; 2: Center of Excellence in Connectivity, Thammasat Business School, Thammasat University, Thailand; 3: International College for Sustainability Studies, Srinakharinwirot University, Thailand

Purpose of this paper

Humanitarian operations increasingly depend on time-bound negotiated safe passages to reach vulnerable populations in disasters and conflict-affected areas. International bodies (e.g., the ICRC and the United Nations) commonly refer to these arrangements as "humanitarian corridors," emphasizing their legal–diplomatic role in temporarily enabling protected movement for evacuation and/or the passage of life-saving assistance.

A logistics corridor extends beyond a legal arrangement and constitutes a complex operational system that may involve transport networks, warehousing, inventory flows, cross-border facilitation, service provider coordination, and supporting institutional frameworks. Despite this operational complexity, the term Humanitarian Logistics Corridor (HLC) remains rarely used in academic literature and lacks a formal conceptual definition. Although international organizations employ the term to describe coordinated logistics initiatives involving customs facilitation, pre-positioned stocks, and cross-border operations (BRICS, 2024; IFRC, 2023; WFP, 2025), it is used descriptively rather than theoretically.

This conceptual ambiguity creates a key theoretical gap; humanitarian logistics research remains largely event and operation centric, with limited theorization of the corridor as a distinct unit of analysis. By conceptualizing the HLC, this study opens a theoretical pathway to explain how corridor governance, enabling services, physical links, rules, and multi-actor coordination jointly shape access and performance. The purpose of this study is to conceptualize humanitarian logistics corridors as a boundary-specified subtype within corridor system theory, operating under crisis conditions and analytically differentiated from evacuation and commercial corridor forms.

Design/methodology/approach

This study develops a structured method to construct a working definition of the HLC. The term is explicitly delimited as a corridor system intended to enable the delivery of humanitarian relief supplies to affected populations, while corridors primarily designed for evacuation or safe passage are treated as adjacent but excluded concepts. The definition development follows a three-step process. First, construct delimitation and anchor selection were conducted. Existing usages of "humanitarian corridor" were screened to distinguish relief-supply delivery from evacuation-focused interpretations. Authoritative anchor sources were then selected from transport corridor theory, logistics corridor literature, and humanitarian logistics to extract stable conceptual elements.

Second, attribute synthesis and property classification were performed. Candidate attributes were organized into structural (routes, nodes, gateways), functional (logistics services), governance (coordination, procedures, permissions), contextual (crisis and lifecycle), and purpose-oriented domains. Attributes were classified as necessary or accompanying properties using three criteria: identity (essential to the construct), discrimination (distinguishing HLC from adjacent concepts), and stability (robust across contexts). Only necessary properties were retained for definition construction, supported by explicit inclusion, exclusion, and minimum

structural scope rules. A controlled design matrix was developed to transparently vary definitional dimensions while preserving the necessary-property core.
Third, an initial validation stage was conducted through structured author reflections and expert interviews. The proposed definitions were internally reviewed to ensure logical consistency and clear construct boundaries prior to external validation, followed by semi-structured feedback sessions with one academic expert and four humanitarian logistics practitioners. The purpose of this stage was to evaluate definitional clarity, completeness, discriminability, and practical relevance prior to further refinement.

Findings

The findings derive a baseline definition of a HLC accompanied by two theoretically structured alternatives, all grounded in a shared necessary-property core. The baseline (Balanced) definition conceptualizes HLC as a crisis-activated corridor system integrating transport links and routes, logistics nodes and gateways, enabling logistics services, and institutional arrangements to ensure the sustained delivery of humanitarian supplies into and within affected areas. It emphasizes comprehensive corridor connectivity and coordinated aid delivery during crisis conditions. Across all versions, evacuation- or safe-passage-oriented corridors are explicitly excluded to preserve conceptual discrimination.

Alternative 1 (Lifecycle-inclusive) extends the temporal framing of the construct by incorporating preparedness, response, and recovery phases, positioning HLC as a system established and maintained across the humanitarian lifecycle rather than activated only during crisis onset. Alternative 2 (Authorization-focused) strengthens the governance dimension by foregrounding formal designation, permissions, and coordination mechanisms, particularly relevant in cross-border and conflict settings where access constraints require explicit institutional arrangements.

The findings establish HLCs as a boundary-delineated subtype within corridor system taxonomy characterized by a stable necessary-property core. Across definitional variants, HLCs are shown to integrate transport links and routes, logistics nodes and gateways, enabling logistics services, and formalized institutional arrangements to ensure sustained delivery of humanitarian supplies under crisis conditions. This hybrid institutional–network configuration analytically differentiates HLCs from evacuation corridors, which prioritize civilian movement, and from commercial logistics corridors, which are market-driven and policy-integrated rather than crisis-activated. Variation across the three definitional formulations occurs along two dimensions: temporal scope (crisis-activated versus lifecycle-inclusive) and governance intensity (implicit coordination versus formally designated authorization regimes). Despite this variation, the structural core remains stable, supporting analytical discriminability and boundary clarity.

Value/Originality

This study provides a structured definition of HLC to reduce conceptual drift between legal ‘humanitarian corridors’ and operational logistics arrangements. It extends corridor system theory into crisis governance contexts by conceptualizing humanitarian logistics corridors. Although the term is increasingly used in policy and operational discourse, it remains theoretically underdeveloped and inconsistently applied in academic research. The establishment of clear construct boundaries advances conceptual foundation for performance measurement, resilience assessment, and comparative corridor analysis across crisis contexts. This theoretical extension is supported by a structured construct-development approach that applies anchor-based synthesis and necessary-property logic to corridor system conceptualization.

Research limitations/implications

This study represents an initial stage of construct development and validation. Broader validation across a more diverse group of scholars and humanitarian organizations is required to strengthen representativeness. Moreover, the empirical robustness of the proposed definitions across different crisis contexts remains to be examined. Future research should examine the

applicability of the definitions across diverse disaster and conflict settings and conduct systematic boundary testing.

Practical implications

The proposed definition provides operational guidance for the management of humanitarian logistics corridors in crisis settings. This distinction helps policymakers separate supply-oriented logistics corridors from evacuation passages, reducing mandate ambiguity and improving resource allocation. It supports corridor-level performance assessment by defining what must function for sustained aid delivery, enabling more systematic evaluation of access reliability, service continuity, and resilience.

Inclusive Humanitarian Logistics: Addressing the Needs of Senior Citizens in Flood Response

Nichapa Phraknoi, Thuy Nguyen, Stanley Teck Lee Yap Yap, Thuan Nguyen Hoang

RMIT University Vietnam

Purpose of this paper

Floods are among the most disruptive hazards globally, with rising intensity and unpredictability generating complex humanitarian demands. These pressures are magnified in rapidly urbanising environments, where dense populations and infrastructure constraints increase exposure while complicating emergency logistics. Urban expansion is occurring alongside demographic ageing, developing countries, creating a convergence that heightens the risk of isolation during emergencies and intensifies demands on evacuation, relief distribution, and coordination systems.

While disaster operations often prioritise rapid mobilisation and material distribution, logistics effectiveness also depends on the availability of accessible last-mile delivery for diverse beneficiary groups. Evidence indicates that older adults face persistent barriers in evacuation, shelter access, and relief utilisation due to mobility limitations, chronic health needs, and communication constraints (Phraknoi *et a*l., 2023). As populations age, senior citizens constitute an increasing share of those affected by disasters, and their interactions with evacuation routes, distribution systems, and recovery services demonstrate how beneficiary diversity directly shapes logistics performance.

Vietnam offers a critical setting in which these dynamics intersect: it is both highly flood-prone and rapidly urbanising, with large populations concentrated in low-lying delta and coastal cities. This combination of contexts places sustained pressure on disaster response systems and highlights the need for humanitarian logistics (HL) to exert continuous and sustained pressure on disaster response infrastructure and systems, which underscores and highlights the importance of HL that can deliver timely and equitable aid under volatile conditions.

HL theory conceptualises disaster response as a coordinated system of resource allocation, prioritisation, and last-mile delivery under uncertainty (Kovács and Spens, 2007). Yet prevailing models frequently assume uniform beneficiary capacity, potentially obscuring access disparities (Phraknoi *et al.,* 2023). This paper examines how HL systems can better accommodate seniors' needs during flood response by integrating the lived experiences of older adults with institutional perspectives from government and non-governmental actors. In addition, this study evaluates how inclusive operational adjustments enhance accessibility, coordination, and service continuity without compromising efficiency, positioning demographic responsiveness as a functional dimension of logistics performance and contributing to broader discussions on adaptive and inclusive disaster management (Balcik *et al.,* 2010).

Design/methodology/approach

A qualitative, exploratory design was adopted to examine how HL is enacted in flood-affected environments and how last-mile delivery interfaces with seniors' needs. The study is grounded in HL and vulnerability-informed frameworks, emphasising inclusivity as a vital operational attribute embedded within logistics systems rather than an external social concern (HelpAge International, 2000). This framing supports analysis of evacuation support, relief distribution, and service continuity as interconnected logistics processes shaped by demographic realities.

Data were collected through semi-structured interviews with 35 senior citizens with direct experience of the 2024 flood response and focus group discussions with 22 government and NGO practitioners involved in coordination and delivery to triangulate institutional logistics perspectives with lived experience.

Participants were purposively recruited from flood-prone urban communities in Vietnam. Interviews explored evacuation access, distribution participation, shelter conditions, and recovery support, while focus groups examined prioritisation practices, inter-agency coordination, and operational constraints. Interviews and focus groups were conducted in Vietnamese, transcribed, and translated via the back-translation procedures to ensure accuracy. Data were analysed using inductive thematic coding, supported by NVivo14 software which enabled iterative comparisons across participant groups.

Findings

Initial findings indicate that seniors' needs intersect with HL processes across the following four interacting themes that collectively shape last-mile delivery performance:

(1) **Decentralised Governance Capacity** enables rapid mobilisation and local decision-making, supporting beneficiary identification and tailored evacuation assistance for older residents. Commune-level structures and community organisations facilitate responsiveness but vary in resource depth.

(2) **Coordination and Communication Systems** influence information flow and service synchronisation. Multi-channel alerts improve reach, yet uneven coordination and information saturation can complicate access for seniors with sensory or digital limitations.

(3) **Community Logistics Networks** function as informal extensions of formal response systems. Neighbours and volunteers frequently support evacuation, monitoring, and relief access, compensating for mobility barriers and reinforcing continuity of care.

(4) **Infrastructure, Preparedness, and Demographic Accessibility** shape the material conditions of response. Transport constraints, equipment shortages, and ageing drainage systems affect operational reliability, while preparedness training and shelter arrangements influence seniors' capacity to engage safely with logistics services.

Across the themes, inclusive operational adjustments such as assisted evacuation, predictable distribution schedules, and community-based support were associated with improved access to rescue operations and reduced psychological stress. While data analysis is ongoing, these preliminary patterns suggest that demographic awareness strengthens disaster response management and service continuity without undermining logistical responsiveness.

Value

This study advances humanitarian logistics scholarship by demonstrating how demographic inclusivity functions as a practical determinant of last-mile disaster response performance. By linking seniors' lived experiences with institutional logistics practices, the research reframes ageing as an operational consideration rather than a peripheral vulnerability issue. Initial analysis identifies consistent patterns indicating that decentralised coordination, community logistics networks, and accessibility-focused planning strengthen logistics responsiveness in flood contexts, clarifying how beneficiary diversity shapes operational performance.

Although full synthesis is ongoing and findings should be interpreted as indicative, they provide early empirical insight into inclusive logistics design. This perspective is relevant to researchers examining adaptive logistics, policymakers addressing ageing urban populations, and practitioners seeking to improve equitable disaster response systems within provincial or developing-country contexts. Practically, embedding demographic awareness into evacuation planning, distribution design, and collaboration with community support networks can enhance service continuity for senior citizens without compromising efficiency, offering actionable guidance for strengthening disaster response systems.

References

Balcik, B., Beamon, B.M., Krejci, C.C., Muramatsu, K.M. and Ramirez, M., 2010. Coordination in humanitarian relief chains: Practices, challenges and opportunities. International Journal of production economics, 126(1), pp.22-34. https://doi.org/10.1016/j.ijpe.2009.09.008

HelpAge International. (2000). Older people in disasters and humanitarian crises: Guidelines for best practice, HelpAge International. https://www.helpage.org/silo/files/older-people-in-disasters-and-humanitairan-crises-guidelines-for-best-practice.pdf

Kovács, G. and Spens, K.M., 2007. Humanitarian logistics in disaster relief operations. International journal of physical distribution & logistics management, 37(2), pp.99-114. https://doi.org/10.1108/09600030710734820

Phraknoi, N., Sutanto, J., Hu, Y., Goh, Y.S. and Lee, C.E.C., 2023. Older people's needs in urban disaster response: A systematic literature review. International journal of disaster risk reduction, 96, p.1038. https://doi.org/10.1016/j.ijdrr.2023.103809.

SUPPLY CHAIN SKILLS, TRAINING AND EDUCATION

Work Engagement of Truck Drivers in a Tight Japanese Labor Market : Antecedents and Outcomes

Katsuhiko Hayashi, Sadaaki Sudo

Ryutsu Keizai University, Japan

Purpose of this paper

Amid an increasingly severe labor shortage, improving retention rates and enhancing labor productivity among truck drivers have become pressing issues. Improving drivers' working conditions so that they can enjoy fulfilling and sustainable careers over the long term, while simultaneously achieving higher labor productivity, is an important challenge.

According to existing studies on work engagement (WE), which consists of three dimensions—vigor, dedication, and absorption—workers with high levels of WE tend to derive energy from their work, feel pride and a sense of meaningfulness, and engage enthusiastically and immersively in their tasks. Such workers are also more likely to continue working over the long term and to enhance labor productivity through accumulated experience, skill development, and continuous learning.

The purpose of this study is to examine measures for enhancing drivers' WE by analyzing the factors that influence WE and the effects of WE on related outcomes. Referring to the Job Demands–Resources (JD-R) model, this study examines drivers' individual psychological resources (such as self-efficacy, organization-based self-esteem, and optimism), job resources (including support from supervisors and colleagues and job autonomy), and job demands (both challenging demands that promote skill development and growth and hindering demands). The analysis investigates how these factors affect WE. Furthermore, by analyzing the relationships between WE and outcomes such as job satisfaction and intention to continue working, this study examines whether WE has positive effects on these outcomes. Finally, the study discusses practical measures to enhance WE among truck drivers.

Design/methodology/approach

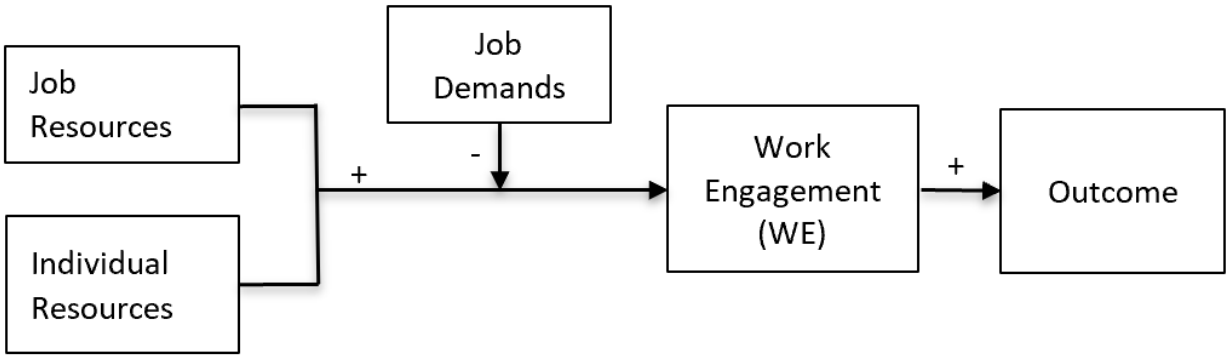
A web-based questionnaire survey, consisting of a screening survey and a main survey, was conducted from February 20 to March 9, 2025. Through the screening survey, 578 full-time truck drivers were selected from a nationwide panel of respondents. Drivers engaged in last-mile delivery, whose working conditions differ substantially, were excluded from the sample. The number of respondents by type of transportation operation is shown in Table 1.

The questionnaire covered items related to years of job tenure and working conditions; work status, workplace environment, and sleep conditions; work engagement (WE); individual resources; job resources; job demands; and outcome variables. WE was measured using the 9-item version of the Utrecht Work Engagement Scale, while the other measures were developed with reference to previous studies.

This study hypothesizes that individual and job resources positively influence WE, while excessive job demands negatively affect WE. It also hypothesizes that WE has positive effects on outcomes (Figure 1.).

Table 1. Number of Respondents

Type of operation	Number
Mainly engaged in long or medium-distance transportation	122
Mainly engaged in short-distance transportation (day trips)	333
Mainly engaged in route delivery	123
Total	578



Source: Based on MHLW (2019)

Figure 1. Expected relationship among factors

Findings

The overall mean score of drivers' work engagement (WE) was 2.28, which was considerably lower than the average score for all occupations in Japan (3.42) reported in MHLW (2019) on a scale ranging from 0 ("never") to 6 ("always"). The mean scores for the three dimensions of WE were also low: 2.19 for vigor, 2.50 for dedication, and 2.16 for absorption.

Responses to items measuring antecedent factors—namely individual resources and job demands—ranged from 2.14 to 2.84, indicating generally low evaluations (scale: 1 = "never feel" to 5 = "always feel"). Similarly, scores for job resources ranged from 2.29 to 2.62, reflecting a low level of perceived availability (scale: 1 = "not implemented at all" to 5 = "well implemented"). Outcome variables also showed relatively low mean values, ranging from 2.46 to 2.98 (scale: 1 = "never feel" to 5 = "always feel").

Multiple regression analyses examining the effects of individual resources and job demands on WE revealed that perceived growth, ease of working, and self-efficacy had relatively high explanatory power (Table 2). With regard to job resources, job assignments reflecting individual preferences and support for balancing work and medical treatment showed strong explanatory power for WE. Furthermore, analysis of the relationship between WE and outcome variables indicated that WE had positive effects on overall job satisfaction, intention to remain with the current workplace, and intention to continue working as a truck driver.

Table 2. The effects of individual resources and job demands on WE

Dependent Variable: Average score of WE	Unstandardized Coefficients		Standardized Coefficients			Collinearity Statistics	
	B	SE	Beta	t	p	Tolerance	VIF
(Constant)	-1.657	0.258		-6.423	<.001		
Satisfaction with ease of working	0.224	0.049	0.183	4.558	<.001	0.446	2.244
High self-efficacy	0.194	0.052	0.151	3.759	<.001	0.447	2.239
High level of job autonomy	0.042	0.042	0.036	1.007	0.314	0.566	1.767
Perceived growth and development through work	0.439	0.051	0.349	8.535	<.001	0.429	2.328
Good interpersonal relationships	-0.018	0.040	-0.015	-0.447	0.655	0.604	1.655

Clear career prospects within the employing company	0.109	0.046	0.089	2.374	0.018	0.514	1.944
Presence of role models in the workplace	0.044	0.043	0.036	1.017	0.310	0.562	1.779
Spending at least half of working hours performing tasks at a high speed	0.070	0.037	0.061	1.923	0.055	0.711	1.407
High concentration of work tasks on oneself	0.042	0.040	0.035	1.068	0.286	0.685	1.459
Sufficient leisure time to recover from work fatigue	0.126	0.042	0.100	2.980	0.003	0.634	1.578
Age group (10-year intervals)	0.115	0.039	0.081	2.958	0.003	0.966	1.036
Gender (female = 1)	0.364	0.208	0.048	1.755	0.080	0.951	1.051
Wage level (per ¥1 million increment)	0.034	0.026	0.037	1.314	0.189	0.906	1.104
Medium- and long-distance transportation dummy	0.120	0.081	0.041	1.493	0.136	0.957	1.045

OLS, ANOVA $p<0.00$, Adjusted $R2=0.587$

Value

This study addressed drivers' work engagement (WE), a topic for which empirical research has been limited, and revealed that drivers' WE is lower than that observed in other industries. It also clarified that drivers' perceptions of individual resources and the adequacy of job resources are generally low. The findings indicate that enhancing individual resources—specifically, a sense of growth, ease of working, and self-efficacy—as well as improving job resources, such as preference-based job assignments and support for balancing work and medical treatment, may contribute to higher levels of WE among drivers. Furthermore, the results demonstrate that higher WE is associated with increased job satisfaction and stronger intentions to remain both with the current workplace and in the driving occupation. These findings suggest that measures aimed at improving WE may serve as an effective strategy for addressing the ongoing driver shortage.

References

Ministry of Health, Labour and Welfare (MHLW) (2019), Toward the realization of a work environment, *Annual Analysis of the Japanese Economy and Labour,* pp. 170–263.

OYAMA Hideki, Kazuya SUZUKI, and Kazuhiro SAKA (2011), Research on the Working Conditions, Fatigue, and Sleep of Truck Drivers : The Problems of Small and Medium-Sized Transport Enterprises Analyzed

by Using a Questionnaire Survey, *J. Science of Labour*, Vol.87, No.2, pp.41-55.

SHIMADA Rie, Junko ISHIZAKI, Kyoko KUROSAWA, and Miyuki SEKI, The Association of Work Engagement and Job Resources among Truck Drivers,

Journal of physical fitness, nutrition and immunology, Vol. 33, No. 1, pp.43-51.

SHIMAZU Akihito (2025), Work engagement: Trends in research and practice in the last 10 years, *Occupational Health Review*, Vol. 37, No. 3, pp. 121-142

Simulation-Based Secured Assessment for Developing Procurement Judgement in Logistics and Supply Chain Education

Tram Nguyen[1], Paul Childerhouse[1], Pete Fernandes[2], Jairus Bowne[2]

1: School of Accounting, Information Systems and Supply Chain, RMIT, Australia; 2: College of Business & Law, RMIT, Australia

Purpose of this paper

Generative AI is reshaping how students produce outputs and intensifying concerns about academic integrity and the authenticity of demonstrated skills (Corbin et al., 2025). In logistics and supply chain management (LSCM) education, this disruption is consequential because graduate capability depends less on content reproduction and more on judgment, trade-off reasoning, and responsive decision-making under uncertainty. This paper presents and evaluates Chain Reaction (CR), a strategic gamification initiative designed as a "secured assessment" that enables authentic skill demonstration in the age of generative AI.

The paper pursues three aims. First, it conceptualises how gamified assessment can function as secured, AI-resilient assessment by shifting evaluation from static outputs to observable decision processes, professional justification, and adaptation under challenge. Second, it reports evidence from a master's-level Strategic Procurement Management course at RMIT Melbourne, examining student perceptions of skill demonstration and engagement alongside qualitative reflections on capability development. Third, it links assessment redesign to Regenerative SC Intelligence, arguing that regenerative-oriented SC require professionals to reason across socio-ecological impacts, resilience, and stakeholder tensions—capabilities better assessed through dynamic, context-dependent tasks than text-only submissions. This paper addresses a gap in secured and AI-resilient assessment literature and offers a transferable model for LSCM programs seeking sustainable responses beyond AI detection.

Design

The study adopts a design-based evaluation approach in an authentic teaching context (Dichev & Dicheva, 2017; Nicol & Macfarlane-Dick, 2006) and uses a low-fidelity SC simulation as a scenario generator, enabling students to iteratively test procurement strategies across progressive supply network challenges. The secured assessment is anchored in a live showcase ("Strategy Pitch") where student teams present their recommended strategy, explain trade-offs, and respond to questions from peers and assessors. This mirrors professional SC governance, where decision-makers must defend choices under scrutiny and pivot as conditions change.

Evaluation triangulates evidence from three channels: (1) observational assessment using a structured rubric assessing alignment between simulation outcomes, theoretical application, and decision rationale; (2) thematic analysis of Strategy Pitch documents to examine how learners internalise constraints, translate theory into action, and justify decisions across cost, risk, and socio-ecological dimensions; and (3) reflective feedback via post-session surveys and Course Experience Survey indicators to capture perceived capability development, engagement, and assessment clarity. Quantitative analysis uses descriptive statistics to summarise response patterns and compare course-level measures across semesters, while qualitative analysis applies iterative coding to surface recurring learning mechanisms. The theoretical scope integrates gamification and feedback theory, authentic assessment, and AI-resilient assessment design (Dichev & Dicheva, 2017; Kapp, 2013; TEQSA, 2023), positioning regenerative SC intelligence as a capability domain requiring adaptive reasoning, resilience-oriented choices, and credible stakeholder communication.

Findings

CR strengthens both perceived learning and the credibility of assessment in an AI-disrupted environment. Quantitative results from the 2025 cohort indicate strong effectiveness: more than 95% of students reported that the assessment enabled them to demonstrate their learning, and over 90% reported high engagement. Compared with the 2024 cohort using a conventional group assessment format, results improved across all five core measures, with the largest gains in clarity of expectations (+0.44) and learning experiences (+0.42). These patterns align with the assessment's transparent structure: students can observe how decisions propagate through outcomes and receive immediate feedback from the simulation context and live questioning.

Student reflections described the game as realistic and hands-on, noting improved understanding of procurement's impact on broader SC performance. Learners reported clearer appreciation of interdependencies, trade-offs, and disruption consequences, aligning with regenerative SC intelligence—balancing performance with longer-term resilience and socio-ecological considerations. Importantly, the live pitch functioned as an AI-resilient "performance moment": while generative AI can assist with generic strategy ideas or drafting, students still had to defend a state-dependent recommendation grounded in their game outcomes and respond to unanticipated challenges. This created a richer, more defensible footprint of professional competence than a static submission alone. Overall, the evidence indicates that gamified secured assessment enables authentic skill mastery by embedding integrity within task design and shifting assessment toward observable, human-centered decision capability.

Value

This paper offers two main contributions. Conceptually, it reframes gamification as a secured assessment architecture that sustains academic integrity and authentic performance measurement (Kapp, 2013) in the era of generative AI, moving beyond its typical positioning as a motivational add-on (TEQSA, 2023). Empirically, it shows that Lo-Fi simulations combined with a live strategy defence can enhance engagement and clarity while enabling credible evaluation of adaptive decision-making. The approach is distinctive in operationalising assessment around navigating uncertainty, requiring professionals to reason across resilience, stakeholder tensions, and socio-ecological trade-offs. The model supports LSCM educators, program leaders, and academic integrity teams seeking scalable, discipline-relevant redesign that is inherently AI-resilient.

Limitations

The evaluation draws on a single course context and relies on self-reported survey data and qualitative reflections, which may be subject to response bias. The Lo-Fi design intentionally avoids automated telemetry, limiting fine-grained behavioural analysis of decision pathways. Future research could use quasi-experimental comparisons across multiple courses and incorporate longitudinal tracking of capability transfer into workplace contexts.

Implications

For educators, CR offers a practical blueprint for AI-resilient, integrity-by-design assessment. For LSCM practice readiness, the model builds competence in strategy formation under disruption, stakeholder communication, and defensible decision-making aligned with regenerative SC intelligence. Institutionally, it shifts attention from AI detection to sustainable, human-centered performance assessment.

References

Corbin, T., Bearman, M., Boud, D., & Dawson, P. (2025). The wicked problem of AI and assessment. *Assessment & evaluation in higher education*, 1-17.

Dichev, C., & Dicheva, D. (2017). Gamifying education: What is known, what is believed and what remains uncertain. *International Journal of Educational Technology in Higher Education, 14*(1).

Nicol, D. J., & Macfarlane-Dick, D. (2006). Formative assessment and self-regulated learning: A model and seven principles of good feedback practice. *Studies in Higher Education, 31*(2), 199–218.

Kapp, K.M., (2013). *The gamification of learning and instruction fieldbook: Ideas into practice*. John Wiley & Sons.

TEQSA (2023). Guidance and resources on assessment and academic integrity in the context of generative AI.

Women Leaders in Apparel Industry: The Case of Vietnam

Aswini Yadlapalli[1], Tram Nguyen[1], Linh Tran Cam Nguyen[2]

1: School of Accounting, Information Systems and Supply Chain RMIT University, Melbourne, Victoria 3000; 2: School of Media Design, University of Economics Ho Chi Minh City, Ho Chi Minh City, Vietnam

Purpose of this paper

Over the past decade women are making significant advancement in economic participation, educational attainment, health, and political empowerment. This progression can be seen in World Economic Forum global gender gap score of 68.8% in 2025 an increase from 68.4% in 2024 (WEF, 2025). Despite the progress, women in managerial roles only accounts for one-third across EU and OECD countries. The portion of women leaders varies across industries, for example in the EU, only 14% of managers in construction and 24% of managers in manufacturing are women (OECD, 2025). Meanwhile, apparel industry considered as female-dominated industry has only 25% of the women are in senior positions (Lindner, 2025). Lack of women executives has contributed to the long-lasting issues of disparities in wages paid to women and men and favouring men over women for high-skilled jobs. Moreover, absence of women executives has heightened the gender-based violence where women are reporting instances of sexual and violent abuses at the workplace (labour behind the label, 2021).

Whilst women leaders in an organisation fuels innovation by bringing valuable perspectives and diversity of thought to the creative process. Particularly, women executives in supply chains improves financial and operating performance by understanding and addressing the customer demands for new products, better service and faster deliveries (Nix and Stiffler, 2016). Moreover, women executives can influence the culture and reputation of the firm and act as brand ambassadors to attract talented women (Stiffler, Watt, & Chumakov, 2020). Promoting women to these leadership positions requires an accurate understanding of the barriers to advancement faced by women, and the strategies used to overcome these barriers (Grullón, 2025; Aung and Hallinger, 2023; Hodges et al., 2015). Against this background, this study aims to investigate the factors that promote women to leadership roles in the apparel industry and their impact on business operations.

Design/methodology/approach

This study adopts an abductive thematic research design, enabling iterative movement between theory and data so that empirical insights can refine and extend existing explanations. The first stage applies deductive reasoning to establish a theoretical foundation and develop an a priori conceptual framework informed by prior literature (Ketokivi & Choi, 2014). In particular, Gendered Organisation Theory (GOT) (Acker, 1990) guides the development of the initial framework by sensitising the analysis to how gender is embedded in organisational structures, practices, and power relations. The second stage uses an inductive approach to contextualise, interrogate, and validate the initial framework through systematic analysis of interview evidence.

Empirical data were collected through semi-structured interviews with senior executives in Vietnam's apparel sector, a context that offers strong theoretical and policy relevance for examining gendered dynamics in global supply chains. Vietnam's apparel industry is a major driver of national economic growth and is projected to reach approximately US$46 billion in export revenue in 2025. The sector contributes around 16% of total exports and employs more than 2.5 million people (Hanh, 2026). Despite being a female-dominated workforce—with women comprising approximately 70–75% of production workers—leadership and ownership positions remain predominantly male. Moreover, as a leading apparel exporter operating within buyer-driven supply chain governance, the industry provides a revealing setting to examine how gendered power relations are shaped, reproduced, and contested across organisational and supply chain levels.

At this stage, participants were selected from four organisations and met the criterion of having more than 10 years of managerial experience. Two firms were large-scale enterprises, each generating over US$400 million in annual revenue and employing more than 10,000 staff. The remaining two were small firms with fewer than 50 employees, mainly outsourcing. Interviews lasted 60–70 minutes, were audio-recorded and transcribed verbatim, and then subjected to open coding and thematic analysis. The coding process was used to surface patterns in gendered organisational processes and to iteratively refine the conceptual framework in line with abductive logic.

Findings

The study finds that women's low participation in senior executive roles in Vietnam's apparel industry is produced and sustained through gendered organisational structures and practices operating within firms and across supply chain relationships. Globally, the apparel sector is marked by a persistent gendered division of labour, with women concentrated in production and lower-tier supervisory roles while men disproportionately occupy management and decision-making positions. As a buyer-driven industry, Vietnam's apparel sector reproduces this pattern, reinforced by commercial practices such as last-minute order changes, discount pressures, and short lead times. These conditions privilege the "abstract worker" ideal - an employee assumed to be continuously available, able to work extended hours, and unencumbered by care responsibilities. In practice, this model systematically disadvantages women, who are less likely to be positioned, socially and organisationally, as able to meet these expectations, thereby constraining their progression into management.

The findings also highlight how Vietnam's broader socio-cultural and institutional context amplifies these dynamics. High power distance norms mean authority is concentrated at the top and seldom challenged, shaping leadership as a domain where hierarchical control and traditional status markers are valued - conditions that tend to favour men's access to senior positions. Consistent with Gendered Organisation Theory (Acker, 1990), women's experiences of inequality are further shaped by the intersection of gender with class, age, marital status, motherhood, and other social positions. In Vietnam, women are culturally constructed as primary caregivers for children and older family members, and this role expectation often translates into organisational assumptions that women are less committed or represent a higher "risk" for promotion. Access to leadership is also mediated by educational background and socio-economic status: women from urban, middle-class, and internationally connected families were perceived as more likely to be considered for leadership roles. Yet many women in the apparel workforce are from rural or working-class backgrounds, limiting their access to executive pipelines and professional networks that facilitate advancement.

Organisational practices within firms further deepen exclusion. In large manufacturers, executives were often physically and socially separated in designated spaces, reducing opportunities for shop-floor women to interact with senior leaders and limiting access to informal mentoring, sponsorship, and visibility - resources that often shape promotion decisions. In smaller Vietnamese apparel firms, promotion processes were described as informal and network-dependent, which can further marginalise women when networks are male-dominated or built through after-hours socialising that women may be less able to participate in. Across both organisational types, participants described advancement as shaped by "best-fit" organisational logics operating under cultural norms, institutional arrangements, and intense global production pressures - logics that tend to reproduce existing gender hierarchies unless actively disrupted.

Notably, respondents emphasised that change is most likely when driven by external forces: regulatory requirements and customer pressures were consistently identified as key catalysts enabling women's promotion into leadership roles. This suggests that, within buyer-driven supply chains, governance and compliance mechanisms can create openings for gender equity - yet without structural redesign of organisational practices, such gains risk remaining partial, symbolic, or contingent on external scrutiny.

Value

This study offers several important contributions. First, it advances leadership scholarship by focusing on the under-researched context of export-oriented apparel manufacturing in Vietnam.

Second, by drawing on GOT, the study conceptualises leadership exclusion not as an individual deficit, but as an outcome of gendered organisational processes, including job design, promotion criteria, intersectionality of factors, and informal networks. Finally, the paper provides policy and managerial relevance by generating insights that can inform gender-inclusive supplier development, leadership pipelines, and capability upgrading initiatives within Vietnam's apparel sector.

Research limitations

This study has several limitations. First, the empirical evidence is based on interviews with senior executives from four apparel firms, which limits the generalisability of findings across Vietnam's diverse apparel sector and across different tiers of global supply chains. Second, focusing on executive perspectives may under-represent the lived experiences of women at shop-floor and middle-management levels; future research should incorporate multi-level and multi-stakeholder data. Third, as a qualitative, cross-sectional design, the study cannot capture how gendered practices and promotion pathways evolve over time, particularly under shifting buyer, regulatory, and labour-market pressures. Finally, interview-based data may be subject to social desirability and retrospective bias; triangulation with organisational documents, workforce/promotion statistics, and ethnographic or observational methods would strengthen validity.

Keywords: Women leaders, Apparel industry, Vietnam, Gender organisation theory.

References

- Acker, J. (1990). Hierarchies, jobs, bodies: A theory of gendered organizations. *Gender & society*, *4*(2), 139-158.
- Aung, P. N., & Hallinger, P. (2023). Research on sustainability leadership in higher education: A scoping review. *International Journal of Sustainability in Higher Education, 24*(3), 517-534
- Grullón, E. (2025). Redefining Female Leadership in the Fashion and Apparel Industry: Equity and Equality, Doctoral dissertation, *Johnson & Wales University*.
- Hanh, V.N. (2026). Investing in Vietnam's Textile and Garment Industry: 2025 Overview and Outlook, https://www.vietnam-briefing.com/news/seizing-investment-opportunities-vietnams-textile-garment-industry.html/
- Hodges, N., Watchravesringkan, K., Yurchisin, J., Karpova, E., Marcketti, S., Hegland, J., & Childs, M. (2015). Women and apparel entrepreneurship: An exploration of small business challenges and strategies in three countries. *International Journal of Gender and Entrepreneurship, 7*(2), 191-213.
- Ketokivi, M., & Choi, T. (2014). Renaissance of case research as a scientific method. *Journal of operations management*, 32(5), 232-240
- https://labourbehindthelabel.org/the-women-who-make-your-clothes/
- Linder, J. (2025), Fashion Industry Gender Statistics, https://rawshot.ai/statistic/fashion-industry-gender
- Nix, N. and Stiffler, D. (2016). Women in Supply Chain, *Supply chain management review,* 20 (5) pp:44-51.
- OECD (2025), Gender Equality in a Changing World: Taking Stock and Moving Forward, Gender Equality at Work, OECD Publishing, Paris, https://doi.org/10.1787/e808086f-en.
- Stiffler, D., Watt, S., and Chumakov, C., 2020, Gartner for Supply Chain 2020- Women in Supply Chain Survey Highlights Consumer Value Chain Progress.
- WEF (World Economic Forum) (2025) Global Gender Gap Report 2025, https://reports.weforum.org/docs/WEF_GGGR_2025.pdf

SECTION TWO: FULL PAPERS

REGENERATIVE SUPPLY CHAINS

Unravelling Supply Chain Integration Amidst Global Uncertainty: New Evidence from an Emerging Economy

Manh Kha Kieu[1], Rajkishore Nayak[1], Irfan Ulhaq[1], Tarun Panwar[2]

1: RMIT University, Vietnam; 2: RMIT University, Australia

INTRODUCTION

Geopolitical tensions, trade conflicts, stringent regulatory framework for traceability and sustainability, supply chain disruptions, changing consumer requirements have been creating tremendous volatility in various industries across the globe, especially the textile and garment (T&G) industry in recent years (European Commission 2021; U.S. Department of Homeland Security 2022; VITAS 2025). In response to these uncertainties, T&G manufacturers are adopting new approaches to not only navigate through this uncertain period but also satisfy these ever-increasing consumer needs (Alom et al. 2024; Alkhudary et al. 2024).

The supply chain performance of T&G industries has been rising steadily with the rapid development of new technologies and management practices. However, due to the resistance nature of humans, the progress of the past two decades has yet to achieve significant milestones. The T&G industry has particularly been affected by global uncertainties because its supply chains are linked through several countries in the world (Alom et al. 2024). Other factors such as rising prices of fertilizers, and raw materials (increased approx. 80-100%), fluctuating cotton prices, low demand for yarns and fabrics and diminishing demand for retailed clothing, have fuelled the challenges. This in turn has urged T&G companies, especially in an emerging country like Vietnam, to adopt supply chain integration (SCI) to co-utilize limited resources (Beeler et al. 2024).

This study aims to examine the SCI landscape in the context of T&G industry in Vietnam by fulfilling the following two objectives: (1) to identify the SCI drivers and trends among the partners at various supply chain tiers, and (2) to examine the relationship between the SCI and firms' sustainable performance. Specifically, the researchers will achieve the research objectives by answering the following two research questions:

RQ1: What factors contribute to the SCI adoption trend among T&G firms in Vietnam?

RQ2: What are the impacts of SCI adoption on sustainability performance among these manufacturers?

This research paper will provide additional insights to the current literature by (1) identifying uncovered drivers that encourage T&G firms adopt SCI practices in this volatile business environment, and (2) evaluating the benefits of SCI adoption in one of the prominent Vietnamese industries, which will establish the rigorous ground for future research in this domain.

LITERATURE BACKGROUND

Supply Chain Integration

SCI describes the forward and backward fully integrated collaboration with partners, including direct and indirect suppliers and customers across the supply chain (Kieu et al. 2025). Supply chain researchers addressed SCI in three different dimensions, which are customer integration (CI), supplier integration (SI), and internal integration (II) (Piprani et al. 2020). CI involves the cooperation between a manufacturer and its clients to make better decisions in order handling, demand projection, production, and delivery plan (Piprani et al. 2020). Companies adopt SI practices to work more closely with their suppliers ensuring the continuity of supply, reducing inventory, planning for capacity, and enhancing innovation (Liu et al. 2020; Yang et al. 2020). Scholars also refer to CI and SI as external integration (EI) (Wei et al. 2021). On the other hand, II connects the internal functions of the company to enhance its operations efficiency in purchasing, production, sales, marketing, and finance by reducing delays, errors, and miscommunication (Yang et al. 2020).

Supply Chain Integration and Sustainability Performance

Shashi (2018) defined "sustainability performance" in supply chain as the collaborative efforts of every tier to improve environmental, social, and economic benefits for all key stakeholders. Economic performance refers to the ability of manufacturers to be efficient and to reduce material, energy consumption, waste treatment costs, revenue and profitability (Nikolaou et al. 2019). Environmental performance represents actions taken by companies to ensure that they care about the future generations by keeping the environment clean (Nayak et al. 2019). Different companies launch different sets of objectives for environmental performance, however, reducing waste and pollution, and reducing environmental impacts are several key measures in environmental performance (Yildiz and Sezen 2019). Scholars evaluate corporate social performance based on evidence that demonstrates companies have initiated social projects to benefit the community, prioritized the well-being of their workforce, and offered opportunities for their employees to learn and progress in their career (Yildiz and Sezen 2019). This article has taken into consideration economic, environmental, and social performance as the key aspects of sustainability performance.

Theoretical Lens

Researchers in SCI domain use resource-based view (RBV) theory and Stakeholder theory (Kieu et al. 2025; Yang et al. 2020). RBV theory looks at how companies acquire or generate resources to build competitive capabilities to achieve sustainable development (Kraaijenbrink et al. 2010). This theory argues that resources and capacity may take a long time to develop, or sometimes they cannot be transacted (Barney 2001). The situation requires external collaboration to ensure a company accesses adequate resources to build its competency. This is especially true in the T&G industry in Vietnam amid ever-changing global business landscapes which impose requirements that companies can no longer individually handle. Stakeholder theory describes the necessity of including stakeholders' values, insights, demands, and opinions to the development of significant initiatives (Nguyen et al. 2021). The principle applies perfectly to the case of SCI where any integration decisions are closely related to either the internal groups or the external suppliers, customers, government, NGOs, and other related stakeholders (Mani et al. 2016). As SCI involves in-depth collaboration across key stakeholders in the entire supply chain, the combination of RBV theory and stakeholder theory was used to explore what drivers in the motivator groups influence the adoption of SCI and how SCI adoption have influenced sustainability performance (Wiedmer et al. 2024).

CONCEPTUAL MODEL AND PROPOSITIONS

Supply chain integration motivators

In SCI context, the stakeholder groups, which include normative motivators, cultural motivators, and regulatory motivators, are the key drivers of SCI and help drive the sustainability performance (Liu et al. 2020; Zhang et al. 2024). The normative motivator group represents the impulse to do the right thing in a specific set of social groups (Zhang et al. 2024). In the supply chain, normative motivators can imply the preference of supply chain stakeholders to do the right thing by collaborating with their direct partners and in some cases, with their indirect ones (Wang et al. 2024). Cultural motivators have enormous influence on how business operates around the world, including how internal and external relationships and cultural values influence SCI adoption decision (Zhang et al. 2024). The influence of Government regulations and legislations, non-profit organizations, and media on the SCI adoption practices is classified as regulatory motivators (Gaur and Mani 2018). **Figure 1** shows the adoption of these motivators in exploring the drivers of SCI adoption practices.

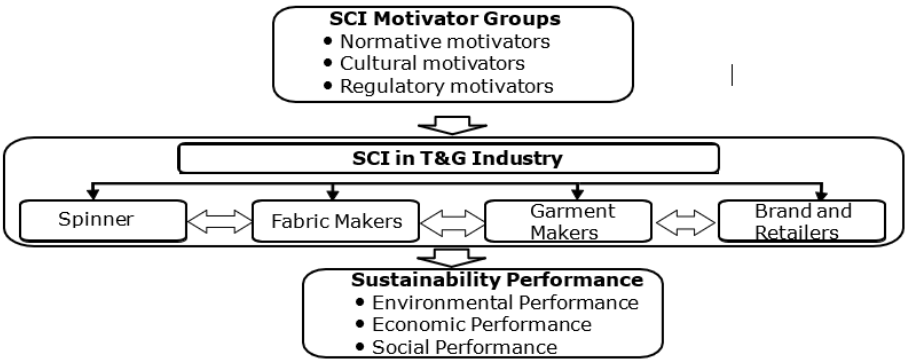


Figure 1: Theoretical model in supply chain integration

Integration enhances firm competitiveness

When examining the current literature of this field, the positive effects of SCI on firms' performance have been strongly grounded by scholars in the supply chain management (Kieu et al. 2025). Recently, scholars have paid increased attention by examining the impact of supply chain practices and integration at macro level on performance of Vietnamese T&G industries (Phan et al. 2020). However, the extant literature does not fully provide the required evidence and managerial implications that support accurate decision making to implement SCI initiative successfully. Very few studies have been conducted to examine the impact of vertical integration on SC performance at firm level. This research aims to explore the specific contributing factors that drive the trend to vertically integrate T&G firms in Vietnam and its impacts on SC performance. The findings of this project will enrich the current literature by providing more insights into this emerging trend among companies in one of the largest industrial sectors in Vietnam.

RESEARCH METHODOLOGY

This research seeks to explore the landscape of SCI within the T&G industry in Vietnam, where new sustainability demands have exerted significant pressure on T&G industries to innovate and consolidate resources through the adoption of SCI. As the authors intend to explore the context-specific contributing factors to this practice and to assess its impact on performance, a qualitative research approach will be the most appropriate (Noor 2008). With these aims, the researchers use semi-structured interviews to collect and analyse the insights from industry practitioners to examine the research propositions and to close the research gap (Ridder 2017).
The researchers carried out 16 semi-structured interviews with owners, directors, and managers which provide an accurate representation of the industry's geographic distribution across the three regions of Vietnam, which are South (9), North (4) and Central regions (3). This ratio was derived from the overall geographic distribution of T&G industry summarized from VITAS's industry directory 2024 (VITAS 2024). The interviewees were chosen from various tiers of T&G supply chain such as spinning mills, fabric makers, garment manufacturers, and fashion brands. The summary is shown in **Table 1** below.

Table 1 Summary of Interviewees

#	Interviewee	Tier	Location	Size (worker)
1	Purchasing director	Spinning	South	450
2	Purchasing manager	Spinning	South	340
3	Owner	Spinning	Central	250
4	Director	Spinning	North	300

5	Merchandise manager	Fabric	South	170
6	Director	Fabric	South	150
7	Deputy director	Fabric	South	200
8	Director	Garment	South	7,000
9	Supply chain director	Garment	South	600
10	Supply chain manager	Garment	Central	10,000
11	Supply chain director	Garment	Central	4,000
12	Sourcing manager	Garment	North	4,000
13	Owner	Garment	North	9,000
14	Merchandising manager	Fashion brand	South	320
15	Sourcing manager	Fashion brand	South	80,000
16	Purchasing director	Fashion brand	North	320

Each interview lasted from 40 minutes to 60 minutes. In addition to the data collected from the interviewees, secondary data was collected from online sources to improve the accuracy. The results were analysed through thematic analysis in NVivo 15 software.

RESULTS AND DISCUSSION

Customer pressure is the strongest driver of supply chain integration

Among various drivers, the pressure from customers is the most important contributor to SCI adoption. Although each tier in the T&G supply chain shares various opinions over the impact of customer pressure on their adoption practices, the authors have identified four key patterns that are shared by interviewees.

Firstly, the pressure from customers to maintain or even reduce costs appears most significant. It is especially true when SP1 shared "*we are facing pressure of price reduction as we do not have yarn dye capacity*". BR02's response: "*we are integrating with upstream suppliers to help them improve quality, operational efficiency*." validates the concerns of upstream suppliers, which refers to their customers' efforts in lowering overall costs of supply. Secondly, supply chain traceability has been an enormous concern among global brands with operations in Vietnam when two fabric mills, FB01 and FB02, continuously emphasized "*we have received increasing pressure from customers about the origin of the materials*". Thirdly, the requirements for sustainable practices among this environmental alert industry have changed and become more stringent with the inclusion of data and evidence. Therefore, the holistic efforts from every supply chain tier from spinning to garment manufacturers are vital to report their sustainability achievements as fabric mill FB01 shared "*our brand customers usually inquired us to incorporate new technologies to access environmental data*".

Supply uncertainty encourages supply chain integration

The participants unitedly shared that supply uncertainty (SU) strongly contribute to their SCI adoption decision. Among numerous elements of SU, the following three ones have been cited as the prominent contributors. First, price volatility, despite certain confidentiality, has a profound impact on the decision of all stakeholders in the T&G industry to integrate with their partners. FB03 shared that "*the yarn price has fluctuated significantly in the last couple of years which make it difficult for fabric makers to control costs*". Second, material supply disruption is another factor that motivates all T&G tiers to integrate. BR01 reassured that falling to integrate with suppliers will lead to supply disruption: "*purchasing executive may not plan well without proper engagement to avoid disruption*". Lastly, product quality has always a part of the discussion with all key stakeholders as it plays a dominant role in maintaining a low total cost including waste and rejection cost. BR03 especially highlighted the needs of integrating with their suppliers to ensure they will have consistent material quality to avoid colour and hand-feel

discrepancies and rejections through a statement: "*the whole supply chain has to work together to ensure quality standards and consistency*".

Resource orchestration demands supply chain integration

Resource orchestration indicates the strategic management and coordination of organizational assets (such as people, capital and technology) to develop distinctive capabilities, effectively combine them, and utilize them to attain competitive advantages. The below patterns captured in the interviews highlight the impacts of resource sharing in SCI adoption at various stages in the supply chain. Firstly, expensive and uncertain new product development (NPD) needs integrated resources. This pattern is supported not only by the upstream stakeholders represented by FB02: "*when customers have new product ideas, they will request us to co-develop the products with them*", but also from the fashion brands BR02's quote: "*the strategy for product development always aligns with market movement and trend*." Secondly, new technology adoption requires integration as GM04 argued that "*the industry needs technological solutions to prove the full supply chain traceability*". As the global these regulations have been evolving rapidly and significantly, the pressure for suitable technological solutions to prepare quantitative environmental data and the evidence for presenting the supply chain traceability has grown rapidly across the whole T&G supply chain in Vietnam (Alkhudary et al. 2024). Thirdly, knowledge transfer encourages companies to integrate as GM06 stated that "*when customers explore Vietnam market, they provide technical assistance*". In addition, SP03 shared "*some U.S. cotton suppliers actively support us with technology knowhows for better spinning operations*". Lastly, fashion brands adopted integration practices because they would like to utilize the suppliers' financial resources in ways that benefit both parties. This influencer is validated with BR 01's sharing: "*we integrate with suppliers to pool resources such as lengthening the account payable time, development and training time*".

Network complexity moderates the relationship between the influencers and SCI adoption

The interviewees exerted agreed opinion over the SCI adoption effort over a concern of the complexity of their supply chain networks. Comments from representatives from all T&G supply chain tiers, represented by GM02: "*our supply chain is very complicated, and this is a problem for us when we are trying to integrate with our suppliers*", indicated that the larger the networks, the more complicated and expensive the SCI implementation would be. "*Since we do not have a lot of suppliers, the coordination will be easier*" agreed by GM06, and supported by GM05 "*with the current scope, we can handle it. The bigger and more complex you are, the harder it would become*". Hence, initially T&G firms are focusing more on integrating with the smaller supply base or smaller integrated entity list, to simplify the collaboration efforts, supply chain tracking, and to maximize information flow and resource sharing. Such intentions were mentioned very clearly by FB01: "*the complexity of tracking the fabric articles or products becomes lesser since our supply base does not include too many yarn suppliers*". More complex networks consume more resources during the coordination, and therefore reduce the ambition to implement SCI, especially when it comes to resource sharing, integration of infrastructure and technology collaboration.

Supply chain integration enhances environmental performance

Leaders of firms in T&G industry in Vietnam shared a consensus about the positive correlations between SCI and environmental performance. Across the supply chain, although each entity exhibits different outcomes of SCI, the researchers have identified two key benefits.
Firstly, manufacturers will implement environmental initiative more effectively. Apparently, the interview's content exhibits a consensus among all key stakeholders with regards to the improved efficiency of their environmental performance. GM01 indicated "*integrating with customers and suppliers help us improve our capacity in sustainability and environmental protection practices*". FB03 also shared "*while doing integration, the top priority is to adopt and implement environmentally friendly practices*". Effective coordination creates stronger and more unified efforts toward sustainability.

Secondly, improved compliance capability has been agreed among the interviewees. SCI enhances the coordination and control over the environmental compliance of the whole supply chain BR03 mentioned that "*suppliers want to join our supply chain have to commit to our environmental standards and should be working toward more environmentally friendly practices*". This is particularly important because the new EU's sustainability regulations require importers, brands and retailers to provide proven quantitative environmental data across the supply chains in their annual sustainability reports, SP04 shared "*integrated mills already have the sustainability documents in place and therefore the request for environmental protection data has been collected and can be provided*". SCI ensures the accountability toward the implementation and record of environmental improvement practices in each tier of this important Vietnamese T&G supply chain.

Supply chain integration enhances financial performance

We also examine the most important area in both academia and industry, which is financial performance improvement. All respondents share a consensus that SCI has a strongly positive influence on financial performance. Companies achieve financial benefits in the three most apparent ways which are presented below.

1. Most interviewees shared the synergized opinion that the most apparent impact of SCI on financial performance is cost reduction, specifically in logistics costs, inventory carrying cost and product rejection rates. GM05 shared with us that "*they very quickly saw the profit because of the lead time reduction and cost saving from minimizing outsourcing activities*". FB02 added "*with more visibility into the supply chain, especially into customers' projection, our firm can strategize our operations more efficiently*". They also witness the reduced lead times and cost reduction not only in their company but in their suppliers and customers.
2. Another benefit of SCI adoption among interviewed companies is increased revenue and resilience. FB01 emphasized that "*win-win partnership during the integration process will bring financial benefits*". All key stakeholders in the Vietnamese T&G industry earns stable profitability, higher revenue while minimizing the potential losses through integrating with externally with their partners. This positive impact is highlighted through the statement of an interviewee from GM01 "*with supply chain integration, while the market is growing, margin will be medium or high, while the market is declining, firms will suffer less or break even*."
3. Brand value and awareness is another benefit SCI brings about with consistency in service quality and delivery. BR01 agreed that "*our business is becoming smoother if we integrate*". BR02 added that SCI enhances the competitiveness and the placement of the firms in its supply chain which allows the integrated companies to reap long-term profitability "*the company is more profitable once we capture the information more efficiently from the market*". It is evident that SCI enhances competitiveness by boosting brand reputation, which supports profit increase and brands' competitive advantage.

CONCLUSIONS, IMPLICATIONS, LIMITATIONS AND FUTURE RESEARCH DIRECTION

Conclusions

This qualitative research paper holistically examined the SCI adoption situation in the T&G industry of an emerging economy. The authors have identified the most influencing drivers of SCI adoption, the moderating effect of supply chain network complexity and the positive impacts of SCI adoption on environmental and financial performance. These qualitative findings help construct a holistic framework of SCI which cover the SCI adoption practices, the drivers and benefits in a fast-evolving industry in a developing country like Vietnam which is presented in **Figure 2**.

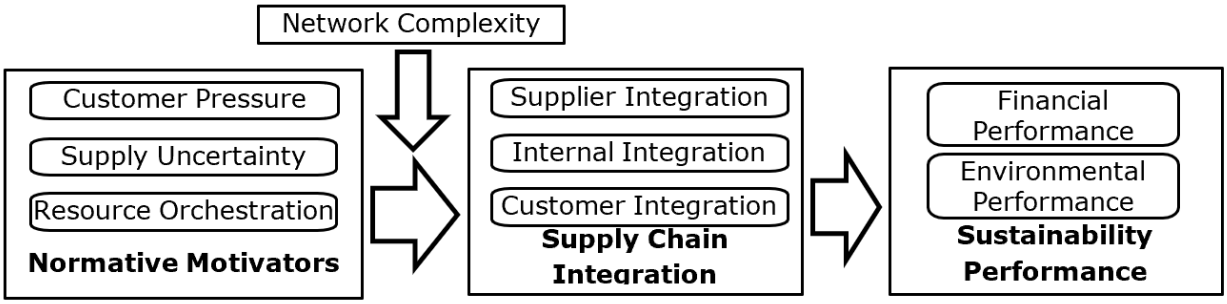


Figure 2 The Proposed Theoretical SCI Framework

In detail, it is noteworthy that customer pressure, supply uncertainty, and resource sharing strongly correlates with SCI adoption among T&G companies which comprises of supplier integration, customer integration and internal integration. The network complexity is found to moderate the relationship between these mentioned driving factors and SCI adoption. In addition, all three facets of SCI have remarkable correlations with financial performance and environmental performance. SCI is also correlated with social performance, but the relationship is not significant because the entire T&G industry in Vietnam already met the social compliance requirements from not only local regulations but international standards.

Implications

From a managerial standpoint, this research paper provides significant implications to industry practitioners in the T&G industry, especially in Vietnam as limited scientific SCI publications have been conducted in this specific context. Managers in T&G firms in Vietnam will be able to narrow their focus into examining customer pressure, supply uncertainty and resource sharing to make rigorous SCI adoption decisions without spending unnecessary efforts in the vast operations of their businesses. The papers provide solid evidence for business leaders in spinning, fabric making, garment manufacturing and fashion brands to spend more efforts in SCI practices to improve environmental performance to meet the more stringent sustainability expectations from their customers to enhance financial performance. The business professionals will also see the holistic picture of important integration practices including CI, SI and II, and will be able to apply suitable ones into their businesses.

Limitations and future research directions

Future research can use quantitative methods to further assess and quantify the impacts of SCI on environmental and financial performance. Secondly, orchestrating resources across the supply chain to provide authenticated environmental performance metrics with the adoption of blockchain can be investigated. Thirdly, although the qualitative findings of this research are best applicable to the T&G industry, other industries may not share similar context and therefore the findings will not be applicable. Future research can examine the adoption of SCI, its drivers and impacts in other industries to develop cross industries' findings in this domain. Additionally, researchers should dive deeper into the roles of SCI in more specific environmental performance, such as carbon neutral targets, efficiency of recycling and upcycling materials. Lastly, although this research has concluded the moderating effect of network complexity, the authors believe there are uncovered moderators and mediators to SCI in this environment. Scholars can explore and identify the important moderators and mediators of SCI and its drivers, as well as SCI and sustainability performance.

ACKNOWLEDGMENTS

We would like to extend our gratitude to the 16 industry professionals who generously contributed their time and insights to our research on SCI in the T&G industry. Their valuable perspectives and experiences have significantly enriched our understanding of this dynamic field.

We sincerely appreciate your expertise sharing, which has been instrumental in shaping the outcomes of this study.

REFERENCES

Alkhudary, R., M. M. Queiroz, and P. Fénièss. 2024. "Mitigating the risk of specific supply chain disruptions through blockchain technology." Supply Chain Forum: An International Journal 25 (1): 1-11.

Alom, S., S. Basu, P. Basu, and R. Joshi. 2024. "Shipment policy and its impact on coordination of a fashion supply chain under production uncertainty." Transportation Research Part E: Logistics and Transportation Review 192: 103778.

Barney, J. B. 2001. "Resource-based theories of competitive advantage: A ten-year retrospective on the resource-based view." Journal of Management 27 (6): 643-650.
Beeler, A., K. A. Schaefer, J. Sestak, and G. Conover. 2024. "Impacts of US countervailing duties on phosphate fertilizers." American Journal of Agricultural Economics 106 (2): 620- 636.

European Commission, 2021. Lex - 52021PC0189 - en - EUR-lex. EUR-Lex. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0189. November 23, 2025.

Gaur, J., and V. Mani. 2018. "Antecedents of closed-loop supply chain in emerging economies: A conceptual framework using stakeholder's perspective." Resources, Conservation and Recycling 139: 219-227.

Kieu, MK., R. Nayak, M. Akbari, M. George, and T. Panwar. 2025. Exploring trajectories in supply chain integration: a systematic analysis of emerging themes. Management Review Quarterly. https://doi.org/10.1007/s11301-025-00490-z

Kraaijenbrink, J., J.C. Spender, and A.J. Groen. 2010. "The resource-based view: A review and assessment of its critiques." Journal of Management 36 (1): 349-372.

Liu, X., C. Qian, and S. Wang. 2020. "When do 3PLs initiate low-carbon supply chain integration?" International Journal of Operations & Production Management.

Mani, V., A. Gunasekaran, T. Papadopoulos, B. Hazen, and R. Dubey. 2016. "Supply chain social sustainability for developing nations: Evidence from India." Resources, Conservation and Recycling 111: 42-52.

Nayak, R., M. Akbari, and S. M. Far. 2019. "Recent sustainable trends in Vietnam's fashion supply chain." Journal of Cleaner Production 225: 291-303.

Nguyen, G.N., V. Mani, M. K. Kha, and T. Papadopoulos. 2021. "Supply chain social responsibility in labour-intensive industries: a practitioner's perspective." Production Planning & Control 1-20.

Nikolaou, I.E., T.A. Tsalis, and K.I. Evangelinos. 2019. "A framework to measure corporate sustainability performance: A strong sustainability-based view of firm." Sustainable Production and Consumption 18: 1-18.

Noor, K. B. M. 2008. "Case study: A strategic research methodology." American journal of applied sciences 5 (11):1602-1604.

Phan, T. H., X. T. Doan, and T. T. T. Nguyen. 2020. "The impact of supply chain practices on performance through supply chain integration in textile and garment industry of Vietnam." Uncertain Supply Chain Management 8: 175-186.

Piprani, A. Z., S. Mohezar, and N. I. Jaafar. 2020. "Supply chain integration and supply chain performance: The mediating role of supply chain resilience." International Journal of Supply Chain Management 9 (3): 58-73.

Ridder, H. G. 2017. "The theory contribution of case study research designs." Business research 10: 281-305.

U.S. Department of Homeland Security, 2022. "Uyghur forced Labor Prevention Act." UFLPA | Homeland Security. Available at: https://www.dhs.gov/uflpa.

VCOSA, 2024. "Vietnam Cotton and Spinning Association Newsletters 2024." Ho Chi Minh: Vietnam Cotton and Spinning Association.

VITAS, 2024. "VITAS Directory 2024." Hanoi: Vietnam Textile and Apparel Association.

VITAS, 2025. "VITAS Monthly Newsletters 2025." Hanoi: Vietnam Textile and Apparel Association.

Wang, Q., X. Liu, M. Hu, and B. Huo. 2024. "A reductionistic or holistic approach? The impacts of fit patterns of supplier and customer integration on company and supply chain performance." International Journal of Production Economics 273: 109265.

Wei, S., J. Yin, and X. Chen. 2021. "Paradox of Supply Chain Integration and Firm Performance: The Moderating Roles of Distributive and Procedural Justice." Decision Sciences 52 (1): 78- 108.

Wiedmer, R., M. Polyviou, and J.P. Paraskevas. 2024. "Does global supply chain integration payoff? The case of maritime shipping firms." Journal of Business Logistics 45 (1): 12350.

Yang, Q., R. Geng, and T. Feng. 2020. "Does the configuration of macro-and micro-institutional environments affect the effectiveness of green supply chain integration?" Business Strategy and the Environment 29 (4): 1695-1713.

Yildiz, Ç. S., and B. Sezen. 2019. "Effects of green supply chain management practices on sustainability performance." Journal of Manufacturing Technology Management 30 (1): 98-121.

Zhang, C., M. Venkatesh, and M. Ohana. 2024. "The impact of normative institutions on socially sustainable supply chain management: the role of individual cultural values." International Journal of Operations & Production Management 44 (4): 790-812.

Systematic Review of The Agricultural Sector Decarbonization Barriers and Mitigation Strategies

Sarunyoo Kanchanasuwan[1], Suriyan Jomthanachai[1], Danuphon Tippong[1], Janya Chanchaichujit[2]

1: Faculty of Management Sciences, Prince of Songkla University, Thailand; 2: Faculty of Environmental Management, Prince of Songkla University, Thailand

INTRODUCTION

Decarbonization and the move to a low-carbon economy have emerged as international imperatives in pursuit (Safonov et al., 2022) of tackling climate change. This conversion is significantly influenced by agriculture as a major emitter of greenhouse gases (GHG) and as a sector that faces high climate change risks (Kamyab et al., 2024). Though low-carbon operations are significantly important, the industry's response to climate challenges remains narrow and uneven (Ji, Li & Zhang, 2024). The situation is worse in developing countries, where the deficiency of resources, technology, and policy support is more salient and constrained (Aydın et al., 2024).

Agricultural decarbonization is known to be a complex issue with fragmented production systems, multiple stakeholders representing various interests involved in agriculture, and the use of emission-intensive inputs, including chemical fertilizers and fossil fuels, and productivity uncertainty caused by varying climates (Yu, Han, & Zhang, 2026). Previous research has indicated the inadequacy of a one-size-fits-all approach and called for context-specific strategies that respond to production systems and supply chain contexts as well as policy environments.

Decarbonization efforts continue to confront numerous obstacles such as financial constraints, low technological maturity, policy and regulatory uncertainties, deficient economic incentives, and knowledge & stakeholder engagement gaps (Noor et al., 2026). Although the literature on decarbonization barriers (or challenges) is abundant for individual mitigation options, systematic research that specifically combines decarbonization barriers with mitigation measures is limited. To fill this gap, this study performs a Systematic Literature Review (SLR) to: i) list the principal barriers to the process of decarbonizing agriculture, and ii) synthesize existing proposed mitigation strategies. Thus, the study aims to answer two research questions: RQ1: What are the main obstacles identified in the literature with regard to decarbonization of the agricultural sector? and RQ2: What proposed facilitative measures can be employed in addressing and removing the barriers?

Design/methodology/approach

This study uses a Systematic Literature Review (SLR) methodology to determine the barriers to decarbonizing the agriculture sector and synthesizes available publications that can benefit future research. The SLR method offers an exhaustive, transparent, and replicable way to systematically examine, review, and synthesize the literature involved.

Sample Article Selection

The search and selection of the articles took into consideration the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines, thus assuring reliable and valid results. The use of the PRISMA framework for this study is presented in Figure 1, outlining the sequence of processes employed to select literature. The Scopus database has been a well-appreciated, comprehensive source of academic publications around the world, as it is one of the biggest and most reputable academic databases.

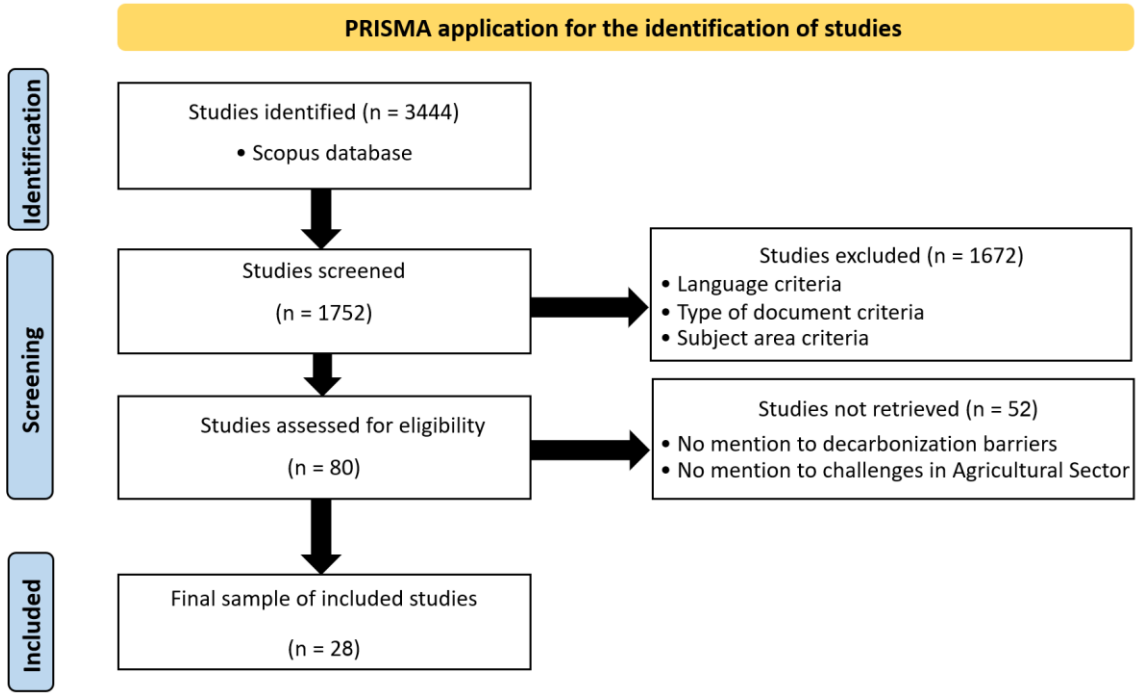


Figure 1. Document selection process following the PRISMA approach

The Scopus database search initially returned 3,444 articles using determinant-related keys ("barrier" OR "driver") with emission reduction terms ("decarboni*" OR "net-zero"). The keywords were used in the titles, abstracts, and keywords of the publications identified. For a more specific scope, the search strategy included agriculture-related terms ("agriculture" OR "agricultural"). Exclusion criteria were also used, such as non-English articles and reports from irrelevant topics. The screening process excluded 1,672 articles, and 1,752 studies were retained for further stages of the review.

Subsequently, 80 articles were assessed for full-text eligibility. During this stage, 52 articles were excluded because they did not explicitly address decarbonization barriers, did not discuss challenges within the agricultural sector, or were overly generic in nature. Following the eligibility assessment, a total of 28 articles met all inclusion criteria and were retained as the final sample for the systematic review.

Findings

Decarbonization barriers in the farming sector were synthesized from 28 studies into five categories: Economic & Investment, Technological & Infrastructure, Policy & Institutional, Knowledge, and Collaboration barriers. The synthesis shows that economic and investment constraints appear as the single most important structural barrier, while technological, policy, and knowledge barriers reinforce themselves to hinder the low-carbon transition. Weak coordination or lack of trust between supply chain actors also limits systemic action. In summary, the table shows that agriculture decarbonization is a systemic and multi-dimensional issue that calls for integrated approaches and coherent policy mixes rather than isolated technological or financial measures.

Barrier Category	Key Issues	Academic Explanation	References
1. Economic & Investment	High upfront costs	High initial costs related to low-carbon technologies, Measurement, Reporting, and Verification (MRV) systems, verification, and implementation	Gross et al. (2026); Singh Peterson et al. (2025); Whitton & Carmichael (2025)

Barrier Category	Key Issues	Academic Explanation	References
		discourage long-term investment and lead actors to adopt only minimum compliance measures	
	Uncertain returns on investment	Volatility in carbon and energy markets increases perceived investment risk, resulting in low adoption rates and persistence of carbon-intensive practices	Gross et al. (2026); Taylor et al. (2025); Singh Peterson et al. (2025)
	Limited access to finance	Smallholders and SMEs face financial constraints and limited access to capital, creating structural inequalities in decarbonization pathways	Puga Sanchez & Manshadi (2025); Akpensuen & Jordana Rivero (2025); Ludlow et al. (2021); Huatuco et al. (2025)
2. Technological & Infrastructure	Low technological	Limited commercial maturity of low-carbon technologies at the farm and rural levels	Puga Sanchez & Manshadi (2025); Hasan et al. (2024); Malogulko et al. (2025) Ludlow et al. (2021); Arsic et al. (2023); Sagues et al. (2020); Pimenow et al. (2025)
	Lack of Infrastructure	Insufficient energy and data infrastructure, along with transport and network constraints, limiting adoption and scalability	Hasan et al. (2024); Malogulko et al. (2025)
3. Policy & Institutional	Policy fragmentation	Inconsistent and fragmented policies generate regulatory uncertainty, reducing investment confidence and slowing decarbonization	Slevin & Barry (2024); Akpensuen & Jordana Rivero (2025); Popova (2023)
	Weak policy integration	Poor coordination across agriculture, energy, and environmental policies leads to implementation gaps	Siddiqi & Wolters (2025); Popova (2023); Shvarts et al. (2022)
	Regulatory burden	New standards and compliance requirements increase adjustment costs when institutional support is insufficient	De Almeida et al. (2025); Acampora et al. (2023)
4. Knowledge	Limited carbon-related knowledge	Insufficient understanding of carbon accounting and mitigation options constrains informed decision-making	Whitton & Carmichael (2025); Felton et al. (2023); Ilesanmi (2024) Tapp et al. (2025); Siddiqi & Wolters (2025)

Barrier Category	Key Issues	Academic Explanation	References
	Behavioral and value-based constraints	Stakeholder values, attitudes, and low policy literacy influence acceptance of decarbonization measures	Syder et al. (2025); Siddiqi & Wolters (2025)
5. Collaboration	Multiple stakeholders across the supply chain	Limited collaboration and governance across stakeholders constrain system-wide decarbonization	Moreira-Dantas et al. (2023); Yadav & Raut (2024); Wu et al. (2025)
	Low trust in carbon markets	Concerns over greenwashing and offset credibility reduce confidence in carbon market mechanisms	Gross et al. (2026); Singh Peterson et al. (2025)
	Limited insetting coordination:	Insetting strategies require significant collaboration among multiple stakeholders across the supply chain, increasing implementation complexity and limiting scalability	Gross et al. (2026); Shvarts et al. (2022); Lee & Yen (2025)

Table 1. Key barriers to agricultural decarbonization

MITIGATION STRATEGIES

A staged supply-chain decarbonization plan: Staging agricultural emissions reduction across supply chains will require strong fiscal support and risk-sharing-type instruments. They include certification cost assistance, carbon labelling schemes, and early-stage carbon offsetting to help shoulder the costs and risks of investment for small-scale farmers. This can help enable more widespread participation and early adoption, before moving onto longer term insetting strategies that require larger amounts of investment and a greater degree of multi-stakeholder engagement (Ludlow et al., 2021; Acampora et al., 2023; Puga Sanchez & Manshadi, 2025; Malogulko et al., 2025; Syder et al., 2025).

Farm-level energy transition strategies: Farm-level energy transition strategies focus on supported investment and infrastructural policies, which include low-interest loans, targeted technical assistance, and integration of farm-based energy production into circular economies. These policy tools promote operational feasibility and curb sectoral fragmentation in agriculture, energy, and waste management (Ludlow et al., 2021; Malogulko et al., 2025; Taylor et al., 2025).

Co-created interventions and sustained companion processes: These are fundamental for translating agricultural decarbonization policies into implementation across agri-food supply chains. Decarbonization in the agriculture sector necessitates mutual changes in production techniques, input utilization, and post-harvest management involving multiple actors. The co-design of interventions involving farmers, processors, and standard-setting bodies allows for low-cost MRV systems to better represent farm realities by simplifying data complexity as well as the regulatory burden. When accompanied by appropriate digital agricultural policies, such interventions also facilitate farmers' access to carbon markets, carbon labelling schemes , and price-based incentives, while persistent technical and institutional support reduces transaction costs and ensures long-term gains. Together, these strategies facilitate the work to be carried out and contribute to the persistence and scale-up of decarbonization in agriculture (Moreira-Dantas et al., 2023; Ilesanmi, 2024; Tapp et al., 2025; Lee & Yen, 2025).

Training to reduce greenhouse gas (GHG) emissions: This is a key process in promoting sustainable decarbonization within the agricultural sector. This is because critical constraints are not about technology deficit, but knowledge and learning deficits (in the sense of available

evidence base), understanding, and ability to use 'carbon' tools on-farm and within agricultural supply chains. Instead, such measures serve to build the "carbon capability" of farmers and other relevant actors. In practical terms, education strategies should include sharing knowledge on sources of GHG emissions and mitigation opportunities at the farm level, on the use of carbon footprint calculation tools, as well as on MRV systems in a simple way that reflects local realities. Such work should be accompanied by low-cost digital tools and participatory learning approaches as enablers for increasing acceptance, lowering barriers to adoption, and maintaining long-term pathways for sustainable agricultural decarbonization (De Almeida et al., 2025; Lee & Yen, 2025; Acampora et al., 2023; Moreira-Dantas et al., 2023).

Overall, this paper shows that a coherent set of policy instruments and a mix consistent with the various transition paths at play is indeed what constitutes a necessary condition for allowing agricultural decarbonization to scale in an effective, fair, and sustainable way in the long term.

CONCLUSION

This research followed a Systematic Literature Review (SLR) methodology and analyzed 28 peer-reviewed papers to synthesize understanding of the barriers and levers of the GHG mitigation process in agriculture. The review found that the decarbonization of agriculture is not only bound by technology and economy, but also a complicated and multi-dimensional structural challenge in economic, technological, policy, and knowledge aspects, as well as agri-food supply chain co-operation.

Structurally speaking, the primary constraints are high upfront investment costs, return uncertainty on investments, and the lack of commercial maturity of low-carbon technologies, especially at the farm and rural levels, as well as suboptimal power and data infrastructure. These constraints place enormous bottlenecks on carbon mitigation potential. Furthermore, policy incoherence, siloed governance structures, and regulatory requirements all serve to undermine investment signals for long-term commitments. Meanwhile, knowledge deficits, low carbon literacy, and a lack of coordination among the many interested parties in agricultural value chains stand in the way of continuity, widespread acceptance, and continued implementation of decarbonization efforts.

The review also indicates that agricultural decarbonization is best achieved through step-wise transition pathways. This pathway should start with short-term risk and cost-mitigation measures, including certification systems and carbon labelling, and move towards deep decarbonization and long-term insetting approaches. To support such initiatives, it is necessary to encourage the greening of energy at the farm level, the co-design of participatory interventions, and the systemic incorporation of bioenergy or waste management as bridges within building the carbon system.

In summary, this paper shows that a systematic review is an essential tool for understanding the complexity of agricultural GHG mitigation. It highlights that designing context-specific and transition-phase-compatible integrated policy mixes is a key condition for generating scalable, equitable, and sustainable decarbonization impacts on farms and in supply chains.

CONTRIBUTION

This research offers a new perspective on existing literature about the significance of reducing carbon emissions in the agricultural sector concerning system-based and transitional approaches that include barriers, strategies, and policy instruments across food supply chains. The advance is introducing CO2 reduction as a succession of transitions with collective dynamics. Therefore, this research has implications for academics, policy makers, and stakeholders in agricultural supply chain sectors as well as practitioners involved in the pursuit of sustainable carbon reduction.

REFERENCES

Acampora, A., Ruini, L., Mattia, G., & Pratesi, C. A. (2022). Circular economy and agri-food supply chains: Pathways towards sustainability. *Resources, Conservation & Recycling, 189*, 106755. https://doi.org/10.1016/j.resconrec.2022.106755

Akpensuen, T. T., & Jordana Rivero, M. J. (2025). Achieving net-zero agriculture in Africa: Perspectives on policies, challenges, and opportunities. *Sustainability Science, 20*(3), 1117–1137. https://doi.org/10.1007/s11625-025-01666-y

Arsic, M., O'Sullivan, C. A., Wasson, A. P., Antille, D. L., & Clarke, J. (2023). Carbon mitigation pathways in agricultural systems. *Frontiers in Sustainable Food Systems, 7*, 17278. https://doi.org/10.31025/2611-4135/2023.17278

Aydın, A., Köroğlu, F., Thomas, E. A., Salvinelli, C., Polat, E. P., & Yıldırak, K. (2026). Carbon Farming in Türkiye: Challenges, Opportunities and Implementation Mechanism. *Sustainability, 18*(2), 891.

De Almeida, A. C. L., Bueno, C., Dale, A., Hay, R., & Jarihani, B. (2025). Agricultural systems transition pathways. *Agricultural Systems, 229*, 104438. https://doi.org/10.1016/j.agsy.2025.104438

Felton, M., Jones, P., Tranter, R., Clark, J., Quaife, T., & Lukac, M. (2023). Policy barriers to agricultural decarbonization. *Land Use Policy, 131*, 106668. https://doi.org/10.1016/j.landusepol.2023.106668

Gross, J. C., Colby, A., Johnson, M. F., & Wardropper, C. B. (2026). Systemic barriers to climate-smart agriculture adoption. *Journal of Rural Studies, 121*, 103940. https://doi.org/10.1016/j.jrurstud.2025.103940

Hasan, A. S. M. M., Kesapabutr, P., & Möller, B. (2024). Bangladesh's agricultural decarbonization challenges. *Environmental Science & Policy for Sustainable Development, 81*, 101511. https://doi.org/10.1016/j.esd.2024.101511

Huatuco, L. H., Candia, J. R., Mathew, R. C., & Porles, G. Z. (2025). Net-zero practices and barriers among regional agri-businesses. *International Journal of Business Performance Management, 26*(8), 1–22. https://doi.org/10.1504/IJBPM.2025.144423

Ilesanmi, J. (2024). Eco-entrepreneurship and low-carbon agriculture. *Journal of Sustainable Development Law and Policy, 15*(2), 298–327. https://doi.org/10.4314/jsdlp.v15i2.11

Ji, M., Li, J., & Zhang, M. (2024). What drives the agricultural carbon emissions for low-carbon transition? Evidence from China. Environmental Impact Assessment Review, 105, 107440.

Kamyab, H., SaberiKamarposhti, M., Hashim, H., & Yusuf, M. (2024). Carbon dynamics in agricultural greenhouse gas emissions and removals: a comprehensive review. *Carbon Letters, 34*(1), 265-289.

Lee, T.-C., & Yen, H.-Y. (2025). Quantifying embodied greenhouse gas emissions in agri-food systems. *British Food Journal*. Advance online publication. https://doi.org/10.1108/BFJ-08-2024-0800

Ludlow, J., Jalil-Vega, F., Schmidt Rivera, X., Garrido, R. A., Hawkes, A., Staffell, I., & Balcombe, P. (2021). Organic waste to energy: Resource potential and barriers to uptake. *Sustainable Production and Consumption, 28*, 1522–1537. https://doi.org/10.1016/j.spc.2021.08.017

Malogulko, Y., Sikorska, O., Ostra, N., & Teptia, V. (2025). Agricultural machinery and decarbonization pathways. *Machinery & Energy, 10*(1), 157–172. https://doi.org/10.31548/machinery/1.2025.157

Moreira-Dantas, I. R., Martínez-Zarzoso, I., de Araujo, M. L. F., Evans, J., Foster, A., Wang, X., & Martin, M. (2023). Multi-stakeholder initiatives and food supply chain decarbonization. *Frontiers in Sustainability, 4*, 1231684. https://doi.org/10.3389/frsus.2023.1231684

Noor, N. A., Pandyaswargo, A. H., Rumbayan, M., & Onoda, H. (2026). Technology Readiness of Biomass Waste-to-Energy in Indonesia: A Multistakeholder Assessment of Anaerobic Digestion of Palm Oil Mill Effluent and Municipal Organic Waste. *Energies, 19*(1), 255.

Pimenow, S., Pimenowa, O., Moldavan, L., Udova, L., & Wasilewski, J. (2025). Renewable energy recovery in agricultural systems. *Energies, 18*(5), 1212. https://doi.org/10.3390/en18051212

Popova, I. (2023). Low-carbon development policies in agri-food systems. *Public Administration Journal, 18*(3). https://doi.org/10.17323/1996-7845-2023-04-02

Puga Sanchez, J., & Manshadi, S. (2025). Powering tomorrow's farms: Energy transition pathways. *Energy Reports, 14*, 3935–3951. https://doi.org/10.1016/j.egyr.2025.11.036

Safonov G, Kozeltsev M, Stetsenko A, Dorina A, Saphonova Y, Semakina A, Sizonov A, Safonov M .(2022). Perspectives of Decarbonization of World Economy in the Context of Implementation of the UN Paris Climate Agreement. *International Organisations Research Journal*, *17*(4), 38-61.

Sagues, W. J., Abbati de Assis, C. A., Hah, P., Sanchez, D. L., & Jenkins, B. M. (2019). Biomass conversion and mitigation potential. *Bioresource Technology, 297*, 122493. https://doi.org/10.1016/j.biortech.2019.122493

Shvarts, E. A., Ptichnikov, A. V., Kokorin, A. O., & Krenke, A. N. (2022). Carbon regulation and agriculture. *Ekonomicheskaya Politika, 17*(5), 54–77. https://doi.org/10.18288/1994-5124-2022-5-54-77

Siddiqi, M. U. A., & Wolters, E. A. (2025). Public perceptions of agricultural climate policies. *Energy & Environment, 35*(2), 228–245. https://doi.org/10.1002/eet.2131

Singh Peterson, L., de Daunton, F., Drysdale, A., Otto, L., & Li, X. (2025). Barriers to carbon-neutral agriculture. *Sustainability, 17*(15), 6847. https://doi.org/10.3390/su17156847

Slevin, A., & Barry, J. (2024). Reconciling climate ambition and agricultural policy. *Environmental Politics, 24*(1), 29–48. https://doi.org/10.1007/s10784-024-09632-2

Syder, A., Baker, S., Bowditch, E., Carlisle, S., Finch, T., & Minter, M. (2025). Visioning low-carbon treescapes. *Ecosystems and People, 21*(1), 2497823. https://doi.org/10.1080/26395916.2025.2497823

Tapp, M., Kate, M., Zhang, S., Sailunaz, K., & Neethirajan, S. (2025). Carbon accounting tools for agriculture. *Sustainability, 17*(21), 9428. https://doi.org/10.3390/su17219428

Taylor, M., McDonnell, N., Davies, P., & Trück, S. (2025). Scaling agrivoltaics: Policy and market pathways. *Sustainability Science, 20*(4), 1499–1517. https://doi.org/10.1007/s11625-025-01668-w

Whitton, J., & Carmichael, A. (2025). Systemic barriers to farmer engagement in climate transitions. *Sustainability Science, 20*(5), 1667–1680. https://doi.org/10.1007/s11625-024-01504-7

Wu, B., Gao, J., Guo, Y., Wang, L., & Zhao, H. (2025). Spatial patterns of agricultural emissions. *Frontiers in Sustainable Food Systems, 9*, 1658655. https://doi.org/10.3389/fsufs.2025.1658655

Yadav, V. S., & Raut, R. (2024). Climate neutrality in agricultural logistics. *International Journal of Logistics Management, 35*(3), 892–915. https://doi.org/10.1108/IJLM-03-2023-0110

Yu, Z., Han, H., & Zhang, F. (2026). Global meta-analysis of bioenergy crops reveals substantial greenhouse gas mitigation potential. *Resources, Conservation and Recycling, 227,* 108777.

Not All Modularity Is Circular: A Logistics Perspective on Loop-Enabled and Loop-Blind Product Architectures

Peder Veng Søberg

Technical University of Denmark, Denmark

ABSTRACT

Purpose of the paper

Regenerative supply chains aim to restore value through reuse, refurbishment, and material recirculation. Product modularization is often assumed to support these outcomes by enabling flexibility, upgrading, and postponement. Yet many "modular" products remain difficult to recover or reintegrate after use. This paper asks when modularity enables regenerative supply chain loops and when it primarily supports forward-flow flexibility.

Design/Methodology/Approach

We develop a conceptual framework that reinterprets established modularity types (bus, sectional, slot, and fabricate-to-fit) from a logistics perspective. The framework introduces the two constructs loop-enabled modularity (LEM) and loop-blind modularity (LBM)—and defines irreversible differentiation as a boundary condition linking product architecture to reverse logistics feasibility. The model is supported with illustrative examples, including industrial finishing and paint as a limiting case.

Findings

The analysis suggests that modularity does not inherently enable circular or regenerative outcomes. Regenerative capability depends on whether customer differentiation remains separable from recoverable value. Accessible interfaces and reversible/separable differentiation support repair, refurbishment, module harvesting, and high-quality recycling (LEM). In contrast, architectures that embed differentiation through irreversible fabrication or finishing processes constrain recovery despite high configurational flexibility (LBM). Postponement can reduce forward-flow waste but does not guarantee regenerative performance unless irreversibility is delayed or externalized into recoverable modules.

Value/Originality

The paper provides a practical classification for evaluating modular architectures based on loop feasibility, thereby strengthening the design–logistics link in regenerative supply chain research.

Keywords: Regenerative supply chain, Modularization, Product architectures, Circularity,

INTRODUCTION

Modern supply chains increasingly aim not only to optimize efficiency but also to support regenerative outcomes through reuse, refurbishment, and material recirculation. While product modularization has long been recognized as a key enabler of flexibility, postponement, and product variety management, its role in enabling regenerative supply chains remains insufficiently conceptualized. Existing modularity research primarily evaluates architectures based on their ability to manage complexity and customization, while implications for circular recovery are often treated as secondary outcomes rather than explicit criteria for distinguishing among modularity types. Industrial practice nevertheless suggests that many "modular" products remain difficult to recover, remanufacture, or recycle despite high configurational flexibility. This paper, therefore, argues that modularity alone is insufficient to support

regenerative supply chains. Instead, the logistics consequences of modular design depend on whether modular architecture enables or inhibits material loops. Building on established modularity typologies, we introduce a distinction between *loop-enabled* and *loop-blind* modularization and develop a logistics-oriented framework explaining how different modularization types influence recovery feasibility, reverse flows, and regenerative supply chain performance.

The distinction is particularly relevant as supply chains move beyond sustainability toward regenerative models that seek to restore value rather than merely reduce harm. From a logistics perspective, regenerative performance depends on the feasibility of disassembly, module recovery, and reintegration into subsequent product life cycles. Yet many widely adopted modular strategies, such as irreversible finishing processes or proprietary interface designs, optimize forward supply chain efficiency while unintentionally constraining reverse logistics. Using illustrative examples, including the boundary case of industrial finishing and paint systems, this paper demonstrates how the same modularity type can either enable or limit circular flows depending on interface accessibility and the reversibility of differentiation processes.

This paper contributes to logistics and supply chain research by showing that modularity does not inherently enable circularity and by introducing a classification that distinguishes modular architectures that support regenerative supply chain loops from those that primarily optimize forward-flow flexibility. First, it extends established modularity theory by introducing the distinction between loop-enabled and loop-blind modularization, allowing existing modularity types (e.g., bus, sectional, slot, and fabricate-to-fit modularity) to be evaluated based on their regenerative supply chain implications rather than solely on configurational flexibility. Second, it provides a logistics perspective on product architecture by showing that interface accessibility and the reversibility of differentiation processes shape whether reverse logistics activities such as refurbishment, module harvesting, and material recovery are operationally feasible. Third, the paper identifies postponement of irreversible processes as a key design–logistics linkage and shows, through illustrative cases including industrial finishing and paint systems, how shifting differentiation from fabrication processes to replaceable modules can transform modular architectures from loop-blind to loop-enabled.

Modularity types

This paper focuses on bus, sectional, slot, and fabricate-to-fit modularity.
Bus modularity uses a common, shared "bus" platform that carries a family of variants or options via plug-in modules that attach to a central backbone. In bus modularity, the core system remains fixed while interchangeable modules (e.g., sensors, interfaces, or functional add-ons) can be swapped or upgraded without redesigning the entire product. This enables mass customization and upgradeability while maintaining a stable core, and can facilitate downstream recovery through standardized module interfaces that support reuse or remanufacturing (Lai, Wang, Jiang, & Jia, 2025).

Sectional modularity divides the product into discrete, semi-autonomous sections or subsystems with clearly defined boundaries and interfaces. Each section can be produced, assembled, or replaced independently, enabling variation and parallel development. Sectional modularity supports flexible configuration of feature sets and simplifies disassembly for repair, upgrading, or recycling, thereby aiding both forward production efficiency and potential loop-closure activities when interfaces are standardized (Cunha, Agard, & Kusiak, 2007; Shamsuzzoha, Helo, Piya, & Alkahtani, 2020).

Slot modularity embeds standardized "slots" or receptacles into a product architecture to accept interchangeable components or modules. Slots define fixed points of interconnection that accommodate a range of modules with common form factors, enabling rapid diversification and easy retrofitting or upgrading. Slot modularity is particularly conducive to scalable variation while maintaining compatibility across generations, which can lower disassembly complexity and support downstream recovery under circular economy objectives (Aydın & Hausman, 2009; Ye, Huo, Zhang, Wang, & Zhao, 2018).

Fabricate-to-fit modularity is a customization paradigm in which product architecture is designed around custom-fit modules produced or adapted specifically for a given customer or application, rather than relying on a fixed set of standard modules. Fabricate-to-fit emphasizes tailoring at the module level to meet unique requirements while preserving the ability to disassemble and recover components later. While it can reduce time-to-delivery and enable high-value customization, it often requires robust interfaces and process agility to maintain potential for reuse/remanufacturing in a regenerative supply chain context (Alochet, MacDuffie, & Midler, 2022).

All four typologies can support circularity when interfaces, disassembly pathways, and data governance are standardized and designed with recoverability in mind. Bus and sectional modularity are often cited as more favorable to loop-closure due to their inherently standardized interfaces and separable modules, whereas fabricate-to-fit offers customization gains that may require stronger reverse-logistics capabilities to realize circular benefits. Slot modularity provides a middle ground, balancing standardization with targeted module placement. These distinctions can inform modeling choices, governance arrangements, and policy incentives in regenerative supply chains (Alochet et al., 2022; Aydın & Hausman, 2009; Lai et al., 2025; Ye et al., 2018).

Prior research has demonstrated that modular product architectures support product variety, postponement, and operational flexibility by decoupling components and enabling recombination across product families. Several studies also acknowledge that standardized interfaces and modular components may facilitate repair, reuse, and recycling. However, these benefits are typically discussed as secondary outcomes rather than as explicit criteria for distinguishing among modularity types. As supply chains move toward regenerative models, modularity must therefore be reconsidered not only as a mechanism for managing forward flows but also as a structural condition that differentially shapes the feasibility and efficiency of reverse and circular logistics processes. Consequently, modularity should not be assumed to be inherently circular. Rather, its regenerative potential depends on how interfaces and differentiation mechanisms are designed.

CONCEPTUAL FRAMEWORK

To clarify the logistics implications of modular product architectures for regenerative supply chains, the following concepts are introduced.

Defining Loop-Enabled, Loop-Blind, and Irreversible Differentiation

Loop-Enabled Modularity (LEM) refers to modular product architectures in which components can be separated, recovered, and reintegrated into subsequent product life cycles without significant loss of functional or material value. LEM is characterized by accessible interfaces, non-destructive disassembly, and compatibility with repair, refurbishment, remanufacturing, or high-quality recycling processes.

Loop-Blind Modularity (LBM) describes modular architectures that support configurational flexibility or product variety but do not enable effective recovery or reintegration of components or materials. In such cases, modularity primarily benefits forward supply chain efficiency rather than regenerative flows.

Irreversible differentiation denotes product variation introduced through fabrication or finishing processes that cannot be economically reversed without degrading component or material quality, thereby constraining circular recovery options.

Table I demonstrates that regenerative potential is not determined by modularity type itself, but by how architectural interfaces and differentiation mechanisms shape recovery feasibility within supply chains.

Modularity type	Loop-Blind (LBM): flexibility only	Loop-Enabled (LEM): regenerative potential
Bus modularity	Plug-and-play variety, but sealed/proprietary modules limit recovery	Standardized, accessible interfaces enable upgrading, harvesting, and refurbishment
Component swapping	Cosmetic variation; modules are disposable and not designed for recovery	Replaceable modules designed for repair, reuse, and secondary circulation
Sectional modularity	Mix-and-match, but short life cycles and weak interface continuity limit reuse	Stable interfaces enable reuse across generations and component-level recovery
Slot modularity	Proprietary or evolving slot standards block reuse and harvesting	Serviceable slots support targeted replacement, remanufacturing, and harvesting
Fabricate-to-fit	Permanent differentiation (e.g., coatings) reduces reversibility and recovery	Regeneration is possible only when differentiation is reversible/separable or supported by dedicated recovery processes
Combinatorial modularity	Variant proliferation increases sorting complexity and undermines reuse	Regeneration is possible only when differentiation is reversible/separable or supported by dedicated recovery processes

Table I: Circular interpretation of modularity types (loop-blind vs loop-enabled)

Conceptual implications for modularity types

The distinction between loop-enabled and loop-blind modularity does not introduce new modularity types but reinterprets established architectures through a logistics and recovery perspective. Classical modularity typologies such as bus, sectional, slot, and fabricate-to-fit modularity primarily describe how components are organized to manage product variety and system complexity. However, these typologies do not inherently determine whether components can be re-entered into supply chains after use. Instead, regenerative potential emerges from how interfaces are designed, how differentiation is introduced, and how disassembly aligns with reverse logistics processes.

Bus and sectional modularity often exhibit characteristics compatible with loop-enabled modularity, as standardized interfaces and separable subsystems can facilitate upgrading, component harvesting, and refurbishment. Nevertheless, such outcomes are not guaranteed. Proprietary interfaces, sealed assemblies, or limited access to modules may transform modular architectures into loop-blind configurations. Similarly, slot modularity may support recovery when interfaces remain stable across product generations, but rapid redesign cycles or incompatible interface evolution can undermine reuse despite high forward flexibility.

Fabricate-to-fit modularity illustrates the strongest tension between customization and regeneration. While it enables late-stage adaptation and customer-specific solutions, differentiation is often achieved through fabrication or finishing processes that embed variation directly into components. When such differentiation becomes irreversible, recovery and reintegration become economically or technically infeasible. Consequently, fabricate-to-fit architectures may shift from loop-enabled to loop-blind depending on whether customization remains separable from the core product structure.

Irreversible differentiation as a logistics boundary condition

From a logistics perspective, irreversible differentiation represents a critical boundary condition for regenerative supply chains. Processes such as coating, bonding, dyeing, or chemical finishing introduce product variation that cannot be removed without degrading material quality or increasing recovery costs beyond viable thresholds. These processes may optimize forward supply chain performance by enabling postponement, aesthetic differentiation, or product protection, yet simultaneously constrain reverse flows.

The concept highlights that circular performance is not determined solely by modular structure but by the point at which irreversibility enters the product lifecycle. When differentiation occurs through recoverable modules, material loops remain feasible. When differentiation is embedded directly into core components, recovery options narrow significantly. Thus, regenerative capability depends on whether modular architectures delay, externalize, or avoid irreversible processes.

Linking modular architecture and regenerative supply chains

To integrate the proposed concepts, Figure 1 presents the relationship between modular architecture, differentiation mechanisms, and regenerative supply chain outcomes. The framework conceptualizes modularity as structurally neutral with respect to circularity: established modularity types can support either loop-enabled or loop-blind outcomes depending on how product differentiation is implemented. In particular, the degree to which differentiation is introduced through reversible, separable modules versus irreversible fabrication or finishing processes determines whether components can re-enter supply chains after use. The figure, therefore, positions irreversible differentiation as a boundary condition linking product architecture decisions to reverse logistics feasibility and regenerative performance.

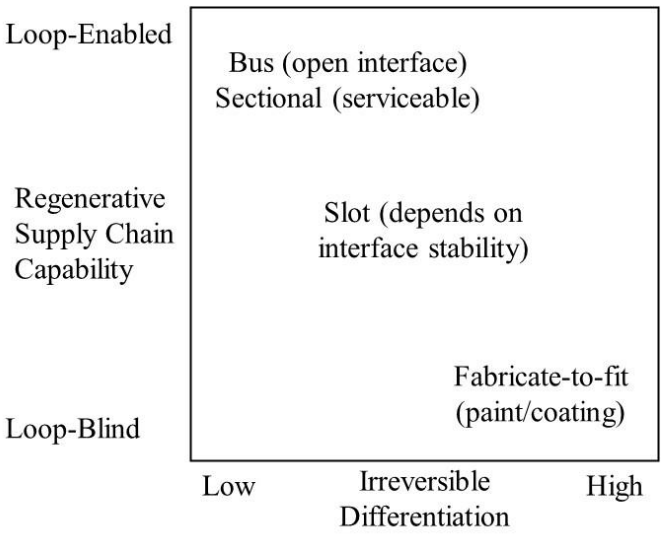


Figure 1: Modularity, differentiation, and regenerative outcomes

Propositions

Based on this framework, three propositions guide the subsequent analysis:

Proposition 1. Modular architectures with accessible and standardized interfaces are more likely to enable regenerative supply chain loops than architectures in which modules cannot be separated without destructive disassembly.

Proposition 2. Product differentiation introduced through irreversible fabrication or finishing processes reduces regenerative recovery potential compared with differentiation implemented through replaceable or separable modules.

Proposition 3. The regenerative performance of modular products depends not only on modular structure but on the alignment between architectural design decisions and reverse logistics capabilities across product life cycles.

The following illustrative examples show how identical modularity types may occupy different positions within the framework depending on interface accessibility and the degree of irreversible differentiation.

Illustrative Examples

Example 1: Bus modularity, upgrade logistics versus disposal logistics

Bus modularity can be configured as either loop-enabled or loop-blind depending on whether the "bus" interface is designed for repeated module extraction and reintegration. In loop-enabled bus modularity, standardized and accessible interfaces support upgrade logistics, where functional modules (e.g., control boards, drives, sensor units) can be replaced during use, harvested after use, and reintroduced through refurbishment or secondary markets. This architecture reduces the need for full-product replacement and shifts value recovery toward component-level flows. In contrast, loop-blind bus modularity may retain the outward structure of plug-in modules but limit recovery through sealed housings, proprietary connectors, restricted access, or short-lived compatibility. In such cases, bus modularity primarily supports forward-flow variety and service differentiation while offering limited feasibility for reverse logistics and reintegration.

Example 2: Sectional and slot modularity—serviceability and interface governance

Sectional modularity often appears conducive to regenerative outcomes because subsystems can be separated and handled independently; however, actual loop capability depends on interface governance and lifecycle continuity. When interfaces are stable across product generations, sections can be repaired, refurbished, or swapped to extend product life and support component harvesting. Similarly, slot modularity can enable targeted recovery by concentrating high-value or failure-prone elements into accessible slots (e.g., power, control, or user-interface units), thereby simplifying diagnosis, disassembly, and module replacement. Conversely, when interface standards change rapidly across generations, or when sections are mechanically separable but electrically or digitally locked, modularity may increase forward configurability without enabling reuse. These cases illustrate that loop-enabled outcomes require not only modular decomposition but also deliberate interface stability, access, and compatibility rules that reduce recovery effort and uncertainty.

Example 3: Industrial finishing and paint as irreversible differentiation

Industrial finishing processes, particularly paint and coatings, illustrate how irreversible differentiation can constrain regenerative supply chain performance even when products appear modular. Painting is commonly used to create late-stage aesthetic differentiation and can support postponement by delaying color commitments closer to demand. Yet coatings typically bond to substrates and are costly to remove without degrading material quality, generating contamination or downcycling risks during recycling. As a result, conventional paint-based differentiation often remains loop-blind. It can reduce forward-flow inventory risk while simultaneously limiting component reuse and high-quality material recovery. Regenerative potential increases when differentiation is externalized into separable elements (e.g., replaceable panels, skins, or covers), shifting variation from fabricate-to-fit processes toward recoverable modules. Alternatively, in settings where coatings are unavoidable, recovery may depend on specialized "chemical-loop" strategies that enable controlled removal or separation, though such solutions may require dedicated reverse logistics infrastructure and may not be feasible across all product categories.

DISCUSSION

The framework developed in this paper suggests that modularity should not be interpreted as inherently supportive of circular or regenerative supply chains. Rather, regenerative performance emerges from the interaction between product architecture, differentiation mechanisms, and

logistics capabilities. While traditional modularity research emphasizes flexibility, customization, and complexity management, the present framework highlights that these same architectural choices may either enable or constrain reverse flows depending on how interfaces and differentiation processes are designed.

From a logistics perspective, loop-enabled modularity shifts value recovery from product-level replacement toward component-level circulation. Accessible interfaces and separable modules reduce disassembly effort, improve predictability in recovery operations, and support refurbishment, upgrading, and secondary-market redistribution. In contrast, loop-blind modularity concentrates value within integrated components, increasing uncertainty and cost in reverse logistics processes and often leading to material downgrading or disposal despite otherwise modular product structures.

A central implication concerns the role of irreversible differentiation. Processes such as coating, bonding, or embedded customization may optimize forward supply chain performance by enabling postponement or aesthetic variation, yet they simultaneously introduce structural barriers to regeneration. The framework, therefore, suggests that regenerative supply chain intelligence requires careful alignment between product design and logistics decision-making. Postponement strategies alone are insufficient if differentiation ultimately becomes irreversible. Regenerative outcomes instead depend on delaying, minimizing, or externalizing irreversible processes so that customer-specific variation remains separable from recoverable product value.

The analysis also highlights governance challenges across product life cycles. Loop-enabled outcomes require interface stability, information transparency, and compatibility across generations to ensure that recovered modules retain functional and economic value. Without such coordination, increasing product variety may unintentionally reduce recoverability by fragmenting module compatibility and increasing sorting complexity in reverse flows. Consequently, regenerative supply chains depend not only on modular decomposition but also on long-term architectural consistency and data integration across actors.

Overall, the framework reframes modularity as a logistics-relevant design condition that shapes the feasibility of regenerative supply chains. Rather than assuming that modular architectures naturally support circularity, firms must evaluate where irreversibility enters the system and how architectural decisions influence recovery pathways across multiple life cycles.

CONCLUSION

This paper examined the relationship between modular product architectures and regenerative supply chain performance by introducing a distinction between loop-enabled and loop-blind modularization. While modularity has traditionally been associated with flexibility, customization, and postponement, the analysis demonstrates that modularity alone does not guarantee circular or regenerative outcomes. Instead, regenerative capability depends on whether product architectures maintain separability between recoverable value and customer-specific differentiation.

By reinterpreting established modularity types through a logistics perspective, the proposed framework shows that identical architectural forms may either enable or constrain reverse flows depending on interface accessibility and the degree of irreversible differentiation embedded in the product. Processes such as industrial finishing and paint illustrate how economically irreversible differentiation can limit recovery options even within otherwise modular systems. The findings, therefore, emphasize the importance of aligning product architecture decisions with reverse logistics requirements when designing regenerative supply chains.

The study contributes conceptually by positioning modularity as a structural condition influencing recovery feasibility rather than as an inherently circular design principle. For practitioners, the framework suggests that regenerative supply chain strategies should focus on postponing or externalizing irreversible differentiation and maintaining interface stability across product life cycles to preserve reuse and refurbishment opportunities.

As a conceptual study, the paper is limited by its reliance on illustrative examples rather than systematic empirical analysis. Future research could test the proposed framework across industries and product categories, examine quantitative trade-offs between customization and recoverability, and explore how digital product information and traceability systems support loop-enabled modular architectures. Advancing such work may help bridge the gap between product design and logistics decision-making in the transition toward regenerative supply chains. Ultimately, modularity is not inherently circular. Regenerative supply chain performance depends on whether architectural decisions preserve the separability of value, enabling components and materials to re-enter supply chains across multiple life cycles.

REFERENCES

Alochet, M., MacDuffie, J. P., & Midler, C. (2022). Mirroring in Production? Early Evidence From the Scale-Up of Battery Electric Vehicles (BEVs). Industrial and Corporate Change, 32(1), 61–111. doi:10.1093/icc/dtac028

Aydın, G., & Hausman, W. H. (2009). The Role of Slotting Fees in the Coordination of Assortment Decisions. Production and Operations Management, 18(6), 635–652. doi:10.1111/j.1937-5956.2009.01039.x

Cunha, C. d., Agard, B., & Kusiak, A. (2007). Design for Cost: Module-Based Mass Customization. Ieee Transactions on Automation Science and Engineering, 4(3), 350–359. doi:10.1109/tase.2006.887160

Lai, X., Wang, N., Jiang, B., & Jia, T. (2025). Effects of Electronic Product Modularity on Recovery Strategy Selection. Rairo - Operations Research, 59(5), 2749–2777. doi:10.1051/ro/2025095

Shamsuzzoha, A., Helo, P., Piya, S., & Alkahtani, M. (2020). Modular Product Architecture to Manage Product Development Complexity. International Journal of Industrial and Systems Engineering, 36(2), 225. doi:10.1504/ijise.2020.110243

Ye, Y., Huo, B., Zhang, M., Wang, B., & Zhao, X. (2018). The Impact of Modular Designs on New Product Development Outcomes: The Moderating Effect of Supply Chain Involvement. Supply Chain Management an International Journal, 23(5), 444–458. doi:10.1108/scm-01-2018-0021

SUPPLY CHAIN INTELLIGENCE

Integrating Heterogeneous Quantitative Data for Prognostic Risk Forecasting in Sea Freight: A Curriculum Learning Early Fusion MoE Framework Drawing on LongCat Flash Omni

Linus Kühl[1], Michael Dircksen[1], Stefan Lier[2], Fries Andreas[3,4], Jost Wiethölter[1]

1: FH Münster, Germany; 2: Fachhochschule Südwestfalen, Germany; 3: Technische Hochschule Köln, Germany; 4: Schmalenbach Institut, Germany

MOTIVATION AND PROBLEM DEFINITION: PROGNOSTIC RISKS IN SEAFREIGHT

Maritime logistics remains the dominant backbone of global trade, yet it is continuously exposed to uncertainty that propagates across port networks and supply chains. Operational disruptions, including congestion, adverse weather, schedule unreliability, and capacity shocks, are typically experienced as measurable outcomes such as arrival delay beyond a service threshold. Alternatively, as excessive anchorage time, missed berthing windows, or elevated safety risk in exposed sea areas. From a decision-support perspective, the most valuable signal is not a retrospective explanation but a *prognostic* risk forecast: the calculated probability that a disruption will occur within a future horizon, together with actionable lead time. To improve robustness under heterogeneity, we employ curriculum learning, i.e., a training strategy that presents easier examples/tasks before harder ones (Bengio et al., 2009).

Recent research has demonstrated that Automatic Identification System (AIS) trajectories enable accurate motion and ETA-related prediction (Nguyen & Fablet, 2021; Saber et al., 2025; Shin & Yang, 2024). Parallel lines of work have shown that port congestion signals are extractable from AIS-derived waiting behavior (Ma et al., 2023) and can be improved when combined with port management information system (PMIS) data (Son et al., 2022). At the macro scale, AIS-based port-call indicators can nowcast trade activity with high timeliness (Arslanalp et al., 2019), motivating the inclusion of economic and trade statistics as slow-moving but informative covariates for regime changes (e.g., demand surges or blank-sailing patterns). However, integrating these heterogeneous quantitative sources into a single forecasting system remains technically challenging due to differences in sampling frequency, latency, noise, missingness, and the need for efficient streaming inference across many vessels and ports.

This paper proposes *SeaRisk-Flash*, a unified framework for prognostic risk forecasting in sea freight that transfers key innovations from LongCat-Flash-Omni (Meituan LongCat Team, 2025) into a maritime time-series context. Specifically: (i) curriculum-inspired progressive training to manage heterogeneity; (ii) jointly encode heterogeneous inputs early to to model cross-source interactions; (iii) a Mixture-of-Experts (MoE) backbone for scalable capacity; and (iv) a modality-decoupled training strategy to address the mismatch between encoder workloads and backbone complexity. While LongCat-Flash-Omni is an omni-modal model designed for real-time audio-visual interaction (Meituan LongCat Team, 2025), the underlying principles can be applicable to sea freight forecasting, where *modalities* correspond to heterogeneous numerical streams rather than images/audio.

This work presents a multi-task, multi-horizon approach for prognostic risk forecasting in sea freight that combines AIS, port usage/PMIS, and macro/trade indicators under explicit constraints. The model uses early fusion and a Mixture-of-Experts backbone with chunk-wise synchronized interleaving to support streaming updates and to handle inputs with different sampling rates in a consistent way. To keep computation manageable and training stable with heterogeneous data, a progressive curriculum learning and a modality-decoupled training strategy that separates modality-specific input encoding from backbone processing is introduced. The transfer of the insights of LongCat-Flash-Omni to the seafreight area is done to evaluate wheather newly developed techniques from other fields can be applied to logistics and have the potential to yield an improvement to the prediction of delays in the outlined case.

LITERATURE REVIEW

AIS-Based Forecasting and Uncertainty

AIS enables vessel movement modeling but is affected by irregular transmission and humanentered fields, raising reliability issues (Harati-Mokhtari et al., 2007). Transformer-based AIS trajectory prediction has achieved strong multi-hour performance via discretized tokenization strategies (Nguyen & Fablet, 2021). In operational forecasting, uncertainty quantification is as important as point accuracy, because decisions depend on risk thresholds; encoder–decoder approaches for trajectory prediction with epistemic/aleatoric uncertainty provide a foundation for probabilistic risk modeling (Capobianco et al., 2022).

Port Congestion and Waiting Behavior

Port congestion manifests as increased queueing in anchorage and extended waiting time before berth. AIS can be used to identify and analyze waiting behavior outside ports (Ma et al., 2023). Hybrid modeling that fuses AIS with PMIS improves congestion forecasting horizons relative to AIS-only signals (Son et al., 2022). These findings motivate port usage streams (berth occupancy, planned arrivals) as explicit inputs rather than implicit effects.

Macro and Trade Indicators from Vessel Traffic

Economic and trade statistics are low frequency but capture regime shifts that strongly condition maritime performance (e.g., utilization-driven congestion). AIS-based port-call indicators can nowcast trade in near real time (Arslanalp et al., 2019), suggesting a principled fusion of micro-level movement (AIS) with macro-level covariates (trade volumes, Purchasing Managers Index, commodity indices). The key methodological constraint is avoiding leakage: macro releases occur with known delays and must be incorporated as vintage-aware, as-of features.

Heterogeneous Time-Series Fusion

General forecasting literature provides strong baselines for multi-horizon forecasting with mixed covariates. DeepAR (Salinas et al., 2020) models probabilistic outcomes over many related series, while Temporal Fusion Transformers (TFT) support static covariates, knownfuture inputs, and interpretable attention/gating (Lim et al., 2021). In maritime settings, recent port/ETA studies often use tree ensembles or deep models per task (Saber et al., 2025), but rarely unify multi-source sequences under early fusion with an efficiency-aware backbone.

Gap and Motivation

The literature indicates that (i) AIS supports strong short-horizon prediction, (ii) port management data extends horizon and context, and (iii) macro/trade indicators condition regime changes. The remaining gap can potentially be filled with an integrated, scalable and streaming-capable *prognostic risk* model that: (a) fuses heterogeneous quantitative streams, (b) supports multi-task/multi-horizon outputs with calibrated uncertainty, and (c) trains efficiently despite data/model heterogeneity. SeaRisk-Flash targets this gap.

PROBLEM STATEMENT

We consider three related forecasting problems: (i) *voyage-level* disruption risk (e.g., late arrival), (ii) *port-level* congestion risk (e.g., high strain) and (iii) *queue* risk (e.g., long queues). At a given decision time t (on a fixed time grid, e.g., hourly), we aim to produce *probabilistic* forecasts for multiple future horizons (e.g., 1h, 6h, 24h, 72h). Concretely, the model outputs calibrated probabilities that a delay threshold is exceeded, that a port congestion index is above a critical level, and that expected waiting/anchorage time is high, using only information available *as of* time t (no look-ahead).

Inputs are heterogeneous streams:

AIS: irregular positions and kinematics, aligned to the canonical time grid.

Port/PMIS: operational port usage signals such as berth occupancy and planned arrivals.

Macro/trade: slow-moving indicators with known release lags (e.g., PMI, trade volumes, commodity prices, exchange rates).

The learning objective is to be defined as multi-task, multi-horizon probabilistic forecasting under missingness and noise.

METHODOLOGY

Data Alignment, Tokenization, and As-Of Semantics

AIS is irregular, PMIS is largely event-driven, and macro/trade indicators are mixed-frequency with publication lags. To fuse these sources without leakage, we first define a canonical time grid $t \in \{1,\ldots,T\}$ at resolution Δ (e.g., 1h) and map every observation to the most recent grid point at or before its timestamp. AIS kinematics are interpolated or forward-filled only within bounded gaps. It is crucial to attach missingness masks and quality flags so the model can down-weight unreliable fields this is depicted in Figure 1 as grey squares / circles. PMIS signals (e.g., berth assignment, queue length proxies, planned arrivals) are aggregated into interval summaries on the grid (e.g., last-hour level, change, and event counts) to preserve operational dynamics while remaining streaming-friendly. Crucially, macro/trade covariates are incorporated with strict *as-of* semantics: at decision time t, the model may only access the latest value that would have been released by then. We therefore store macro data in a vintage-aware form and add explicit release-latency/"age" features alongside calendar embeddings, preventing inadvertent look-ahead when backtesting.

After alignment (canoncical time grid in Fig. 1), it is possible to construct a hybrid quantitative tokenization (cf. discrete AIS representations (Nguyen & Fablet, 2021)) which supports early fusion. Categorical fields (e.g., spatial cell IDs such as H3/Geohash, vessel class, port ID, route/lane ID, and macro regime labels) have to be embedded as discrete tokens, while continuous scalars (e.g., speed, course change, berth utilization, trade growth) have to be normalized and embedded via linear projections. At each time step t, it is now possible to assemble a unified token packet $z_t = [z^{AIS}{}_t, z^{Port}{}_t, z^{Macro}{}_t]$, augmented with explicit missingness indicators, so the downstream backbone can learn cross-source interactions under noise and partial observability.

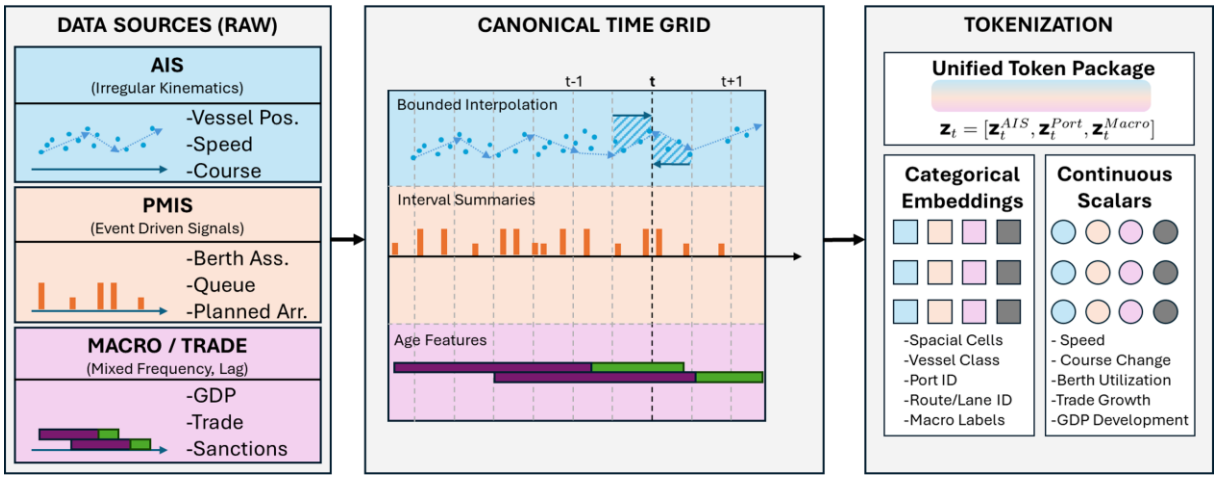


Figure 1: Process overview for data alignment and tokenization to operationalize as-of semantics

SeaRisk-Flash Architecture

SeaRisk-Flash is an early-fusion architecture that turns heterogeneous maritime signals into a single, streaming-capable forecasting system (Figure 2). At each decision time t, the model transforms (i) AIS trajectories and kinematics, (ii) port/PMIS operational state, and (iii) macro/trade context into a shared latent token space, fuses them with a transformer backbone, and emits calibrated multi-horizon risk probabilities for delay, congestion, and queue outcomes. This separation between modality-specific feature extraction and a shared fusion backbone follows the progressive-training and efficiency-aware decoupling principles highlighted in LongCat-Flash-Omni (Meituan LongCat Team, 2025), but is adapted here to time-aligned quantitative streams and high fan-out inference across fleets and ports.

Modality encoders. Each source is first encoded with a lightweight, causal module that respects temporal direction and missingness. The AIS encoder is a causal transformer over the past L time steps of AIS-derived tokens (spatial bins, kinematics, quality flags) with time-aware positional embeddings that include "time-since-last-message" to handle irregular reporting. The port/PMIS encoder represents each port as a port-state sequence (berth occupancy, expected arrivals from schedules/PMIS, and queue proxies such as anchorage density) and uses a small transformer or gated temporal convolution to enable high-throughput updates for many ports. The macro/trade encoder captures slow-moving context via a compact TFT-style gating and variable-selection layer (Lim et al., 2021), separating known-future covariates (e.g., calendar effects) from observed-only series.

Early-fusion MoE backbone. The Mixture-of-Experts (MoE) backbone in the SeaRiskFlash architecture addresses data heterogeneity and computational efficiency in real-time maritime forecasting. By employing a Router Gate to dynamically assign token packets to specialized experts, the model partitions its parameter space to handle divergent streams like high-frequency AIS kinematics, discrete port operational states, and slowmoving macroeconomic indicators. This modularity prevents the optimization conflicts typical of monolithic networks, allowing specific experts to specialize in correlating vessel velocity changes with anchorage density or trade cycles with port throughput. Efficiency is achieved through sparse activation, where only a top-k subset of experts is engaged at any given time. This conditional computation provides a massive theoretical capacity for capturing rare maritime anomalies while maintaining the low latency required for streaming updates. By isolating these specialized functions, the backbone effectively learns non-linear cross-modal interactions, such as the convergence of vessel deceleration, peak berth utilization, and seasonal trade surges—without the risk of signal interference across the network.

Multi-task heads and calibration. For each endpoint $u \in$ {delay,congestion,queue} and horizon h, the model is able to output a logit, yielding probabilities specific to the endpoints. To ensure that the scores are decision-ready, it is possible to apply either post-hoc temperature scaling per task/horizon or a learned calibration layer, and evaluate calibration with tools such as Brier score and reliability error.

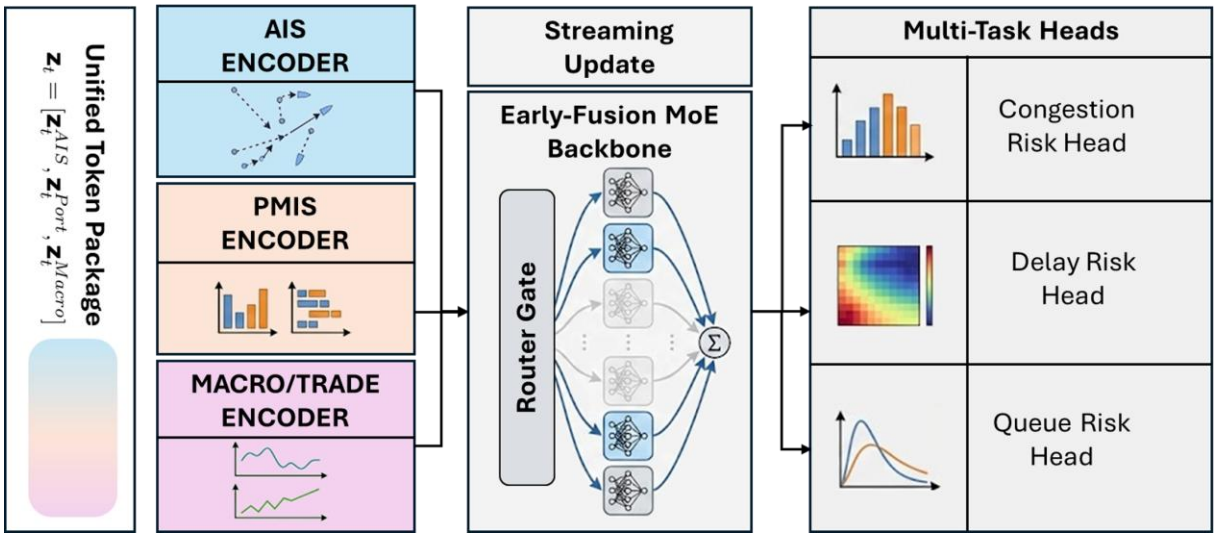


Figure 2: SeaRisk-Flash Archictecture depiction

Chunk-Wise Interleaving and Sparse–Dense Sampling

To support streaming inference, it is advised to build chunk packets over windows of length C (e.g., 1h). Integral is *temporal synchronization*: within each chunk, AIS/port/macro tokens are concatenated in a fixed order and tagged with a chunk timestamp. Similar to chunk-wise interleaving in LongCat-Flash-Omni for streaming audio-visual input (Meituan LongCat Team, 2025), this ensures that new partial evidence (e.g., sudden speed drop near port) can be prefused without waiting for the end of a full voyage segment.

Sparse–dense sampling trades compute for information: when a vessel is within a distance-to-port threshold or when port strain is rising, it is now possible to densify AIS and port updates and otherwise to downsample at sea. This optimizes the compute which is yields high efficiency gains due to the large volume of AIS-Date that would have to be sampled otherwise.

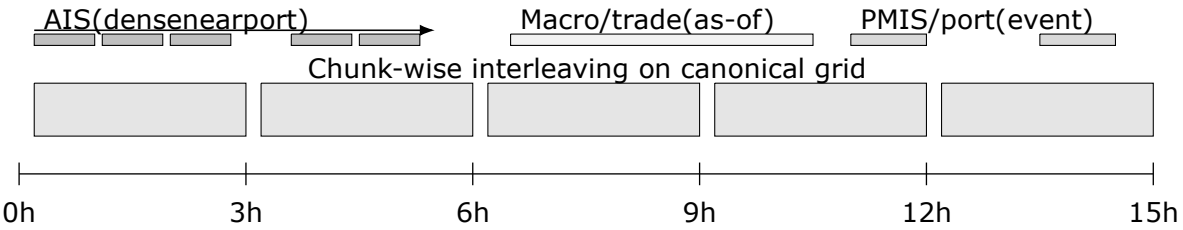


Figure 3: Temporal alignment on a canonical grid with chunk-wise interleaving

Curriculum-Inspired Progressive Training

Following LongCat-Flash-Omni's curriculum strategy for modality heterogeneity (Meituan LongCat Team, 2025), translating this to the seafreight area leads to the follwing progressive schedule:

Stage 0 (AIS foundation): next-step kinematics and short-horizon ETA proxy; objective emphasizes stable sequence modeling.

Stage 1 (AIS + port context): add PMIS and port usage for near-term delay and congestion classification.

Stage 2 (add macro/trade): introduce mixed-frequency indicators with vintage constraints to improve horizon robustness and regime adaptation.

Stage 3 (multi-task annealing): rebalance tasks and port regions; upweight rare congestion and delay tails.

Stage 4 (long-context extension): extend context length to cover multi-leg voyages and multi-port cascades; emphasize stability and calibration.

Modality-Decoupled Training and Streaming Inference

Training compute is dominated by the fusion backbone; the modality encoders are comparatively lightweight but see highly non-stationary batches due to missingness, region-specific sensor availability, and heterogeneous update rates (dense AIS near ports versus sparse macro releases). Accordingly, the most transferable idea from LongCat-Flash-Omni is the *system-level* principle of decoupling modality-specific preprocessing from the shared backbone to stabilize throughput (Meituan LongCat Team, 2025). In SeaRisk-Flash, encoders could precompute and cache embeddings on their natural clocks (e.g., macro/trade embeddings only refresh at release times), while the backbone consumes time-aligned fused packets. This maritime adaptation reduces training and inference stalls caused by variable sequence lengths and intermittent observations, and it allows encoder-specific optimizations (such as caching slow-moving covariates) without changing the backbone learning objective.

Feature Design and Metrics

Table 1 summarizes key inputs and derived metrics and how those can be integrated for a practical implementation of SeaRisk-Flash. The table highlights the advantage of the multimodality of a model that can naturally process inputs from diferent sources with different data structures.

Table 1: Heterogeneous quantitative inputs and engineered metrics used for prognostic maritime risk forecasting.

Stream	Raw signals	Derived metrics (examples)	Update / miss-ingness

AIS	lat/lon, SOG, COG, heading, timestamp; vessel class	grid cell ID; acceleration; turn rate; stop/go ratio; distance-to-port; track quality flags	irregular; missingness mask + time-since-last-msg
Port/PMIS	berth occupancy; planned arrivals; port call events; terminal throughput proxies	port strain index (PSI); queue length proxy; rolling dwell quantiles; utilization slope	event-driven; aggregated to chunks; missingness mask
Macro/trade	trade volumes; PMI; commodity prices; FX; release calendar	growth rates; seasonal decomposition; regime indicator; as-of age; release-lag embedding	low frequency; vintage-aware, no future leakage

DISCUSSION

Why Early Fusion Helps in Maritime Risk

Late fusion often treats AIS, port, and macro inputs as conditionally independent, combining them only at the decision layer. In practice, disruptions arise from interactions: a vessel slowing down (AIS) may indicate congestion only when berth utilization is high (PMIS) and demand regime is elevated (macro/trade). Early fusion lets attention and MoE experts learn such cross-terms directly, which aligns with the early-fusion rationale used for heterogeneous modality integration in LongCat-Flash-Omni (Meituan LongCat Team, 2025).

Operational Deployment Considerations

Streaming latency. SeaRisk-Flash supports incremental chunk updates and sparse–dense sampling, enabling low-latency risk refresh without recomputing long sequences. This is directly analogous to the streaming design principles emphasized in LongCat-Flash-Omni (Meituan LongCat Team, 2025), adapted here from audio-visual interleaving to time-aligned quantitative interleaving.

Data quality and adversarial noise. AIS reliability limitations (Harati-Mokhtari et al., 2007) motivate explicit quality embeddings, outlier filtering, and robust missingness handling. The model should treat AIS fields like destination and ETA as optional, not ground truth.

Economic data lag. Macro/trade indicators can improve horizon stability but must be implemented with strict as-of semantics; otherwise, leakage can artificially inflate backtests. Vintage-aware modeling is thus a central scientific validity constraint.

Limitations

First, this work assumes proprietary PMIS / AIS access. Second, real-world risk endpoints may require domain-specific labeling (e.g., differentiating weather-driven delay from labor disruption). Third, causal identification is not solved: the model forecasts risk but does not, by itself, provide counterfactual recommendations (e.g., reroute vs wait), which is a natural extension.

CONCLUSIONS

This paper presented SeaRisk-Flash, a prognostic risk forecasting framework for sea freight that integrates heterogeneous quantitative sources as AIS, port usage/PMIS, and macro/trade indicators into a unified early-fusion MoE architecture. This framework is outlined in Figure 1 and Figure 2. Inspired by LongCat-Flash-Omni (Meituan LongCat Team, 2025), the framework outlines, how curriculum-inspired progressive training, chunk-wise synchronized interleaving for streaming updates, and a modality-decoupled design to manage heterogeneity and efficiency constraints, can be implemented.

Future work shall focus on evaluation with real multi-port PMIS deployments and AISData, richer external covariates (weather/ocean exposure), and decision-aware learning objectives that directly optimize operational utility.

REFERENCES

Arslanalp, S., Marini, M., & Tumbarello, P. (2019). *Big data on vessel traffic: Nowcasting trade flows in real time* (IMF Working Paper No. WP/19/275). International Monetary Fund. https://doi.org/10.5089/9781513521121.001

Bengio, Y., Louradour, J., Collobert, R., & Weston, J. (2009). Curriculum learning. *Proceedings of the 26th Annual International Conference on Machine Learning (ICML)*, 41–

48. https://doi.org/10.1145/1553374.1553380

Capobianco, S., Forti, N., Millefiori, L. M., Braca, P., & Willett, P. (2022). Recurrent encoderdecoder networks for vessel trajectory prediction with uncertainty estimation. https: //arxiv.org/abs/2205.05404

Harati-Mokhtari, A., Wall, A., Brooks, P., & Wang, J. (2007). Automatic identification system

(AIS): Data reliability and human error implications. *Journal of Navigation*, *60*(3),

373–389. https://doi.org/10.1017/S0373463307004298

Lim, B., Arik, S. Ö., Loeff, N., & Pfister, T. (2021). Temporal fusion transformers for interpretable multi-horizon time series forecasting. *International Journal of Forecasting*,

37(4), 1748–1764. https://doi.org/10.1016/j.ijforecast.2021.03.012

Ma, J., Zhou, Y., & Zhu, Z. (2023). Identification and analysis of ship waiting behavior outside the port based on AIS data. *Scientific Reports*, *13*, 11267. https://doi.org/ 10.1038/s41598-023-38080-2

Meituan LongCat Team. (2025). Longcat-flash-omni technical report. https://arxiv.org/abs/ 2511.00279

Nguyen, D., & Fablet, R. (2021). Traisformer – a transformer network with sparse augmented data representation and cross entropy loss for AIS-based vessel trajectory prediction. https://arxiv.org/abs/2109.03958

Saber, S. M., Thowai, K. Z., Rahman, M. A., Hassan, M. M., Bari, A. B. M. M., & Raihan, A. (2025). High-accuracy prediction of vessels' estimated time of arrival in seaports: A hybrid machine learning approach. *Maritime Transport Research*, *8*, 100133. https: //doi.org/10.1016/j.martra.2025.100133

Salinas, D., Flunkert, V., Gasthaus, J., & Januschowski, T. (2020). Deepar: Probabilistic forecasting with autoregressive recurrent networks. *International Journal of Forecasting*,

36(3), 1181–1191. https://doi.org/10.1016/j.ijforecast.2019.07.001

Shin, G.-H., & Yang, H. (2024). Vessel trajectory prediction at inner harbor based on deep learning using AIS data. *Journal of Marine Science and Engineering*, *12*(10), 1739. https://doi.org/10.3390/jmse12101739

Son, J., Kim, D.-H., Yun, S.-W., Kim, H.-J., & Kim, S. (2022). The development of regional vessel traffic congestion forecasts using hybrid data from an automatic identification system and a port management information system. *Journal of Marine Science and*

Engineering, *10*(12), 1956. https://doi.org/10.3390/jmse10121956

Voyage-Level Arrival Delay Risk Prediction for the Port of Los Angeles–Long Beach via Fusion of AIS Trajectory Features and PortWatch Port Day Indicators

Linus Kühl[1], Michael Dircksen[1], Stefan Lier[2], Fries Andreas[3,4], Jost Wiethölter[1]

1: FH Münster, Germany; 2: Fachhochschule Südwestfalen; 3: Technische Hochschule Köln; 4: Schmalenbach Institut

INTRODUCTION: RISK CLASSIFICATION OF INBOUND VESSEL DELAYS

Maritime logistics delays can propagate through supply chains via missed transshipment connections, terminal storage congestion, production interruptions, and last-mile schedule disruptions. For major gateways such as the Port of Los Angeles–Long Beach, inbound arrival variability can translate directly into berth scheduling uncertainty, labor planning risk, equipment allocation inefficiency, and downstream inland logistics impacts. Because these cascades are nonlinear and time-sensitive, the value of prediction is frequently realized through *earlier* risk identification rather than perfect point estimates. Accordingly, this paper focuses on a binary, decision-oriented endpoint: whether an inbound voyage is likely to experience an *unusually high arrival delay* relative to a baseline ETA.

A key methodological challenge in operational risk modeling is that relevant predictors are distributed across heterogeneous data modalities and spatial/temporal scales. We consider two complementary and widely accessible sources:

1. **AIS data:** time-stamped vessel positions and kinematics. AIS (automatic identification system) is designed to automatically provide position and identification information to other ships and coastal authorities (International Maritime Organization, n.d.). NOAA MarineCadastre distributes processed AIS vessel traffic data obtained from the U.S. Coast Guard AIS network (NOAA Office for Coastal Management / MarineCadastre, n.d.-b).
2. **PortWatch macro indicators:** PortWatch is an open platform to monitor and simulate disruptions to maritime trade flows (International Monetary Fund, 2023). IMF work further describes port-level PortWatch data and its use for trade nowcasting (International Monetary Fund, 2025).

Over an expanded, temporally realistic study horizon (March–April 2025) with a strict time split, *does fusing port-day activity indicators with AIS-derived voyage features improve voyage-level delay-risk prediction relative to single-source models*? We treat this as an empirical question and interpret results in terms of information content and scale mismatch (voyage vs. day), as well as operational considerations such as threshold policy and probability calibration under prevalence shift.

Why risk classification rather than delay-time regression. Two practical considerations motivated a binary risk target. First, operational users often need triage-oriented decisions (e.g., "prioritize this inbound vessel for monitoring") rather than precise minutelevel estimates. Second, voyage-level delay distributions are heavy-tailed and asymmetric, which can make stable point prediction difficult over moderate horizons; a quantileanchored risk definition provides a robust deployment-oriented first step.

We make three main contributions: **(1) Reproducible data fusion pipeline:** a staged workflow that (i) downloads and filters NOAA MarineCadastre daily AIS data (NOAA Office for Coastal Management / MarineCadastre, n.d.-a), (ii) constructs voyage instances via geofences, (iii) fetches PortWatch daily port indicators via an ArcGIS REST query interface with pagination and explicit error handling (Esri, n.d.), and (iv) produces deterministic datasets, metrics, and

figures; **(2) Evaluation beyond point estimates:** ROC-AUC (Bradley, 1997), PR-AUC with discussion of class imbalance sensitivity (Davis & Goadrich, 2006), and Brier score as a proper scoring rule for probabilistic forecasts (Brier, 1950; Gneiting & Raftery, 2007), augmented with bootstrap confidence intervals and paired bootstrap comparisons to quantify uncertainty in fusion gains; and **(3) Operational diagnostics:** analysis of threshold-dependent behavior (default vs. Youden-optimal), calibration summaries (e.g., reliability slope/intercept), rolling backtests for temporal robustness, and ablations to isolate which PortWatch feature groups add value. This paper moves from introduction + data/label definition to a methods section that engineers voyage features from NOAA AIS and optionally fuses them with IMF PortWatch indicators, then fits (mainly) logistic regression models. It then reports held-out (Apr 16–30, 2025) performance and calibration, followed by threshold/operational trade-off analysis, and concludes with the insight that AIS-derived features are the strongest baseline for ranking delay risk into LA–Long Beach, while adding PortWatch provides only modest, statistically uncertain gains over AIS alone.

RELATED WORK

AIS has enabled broad research on vessel movement modeling, including travel-time prediction and ETA estimation using machine learning and trajectory features, with recent AIS-based ETA models validated at specific ports and waterways (Zhang et al., 2024). Our work differs by (i) targeting a binary *delay risk* label derived from a simple baseline ETA (emphasizing risk classification rather than absolute ETA) and (ii) explicitly studying multisource fusion with port-day context.IMF PortWatch monitors and simulates maritime trade disruptions (International Monetary Fund, 2023); IMF methodology for nowcasting trade from space motivates the use of port-level signals as covariates for downstream analytics (International Monetary Fund, 2025). We use one PortWatch dataset (Daily Port Activity Data and Trade Estimates) and integrate it at the port-day level. We use logistic regression as a transparent baseline for binary prediction (Hosmer et al., 2013). Because the test positive rate can differ from training prevalence under time splits, we report PR-AUC in addition to ROC-AUC; PR curves are often more informative under skew (Davis & Goadrich, 2006). We also report Brier score, originally proposed for probabilistic forecast verification (Brier, 1950) and later framed within strictly proper scoring rules (Gneiting & Raftery, 2007).

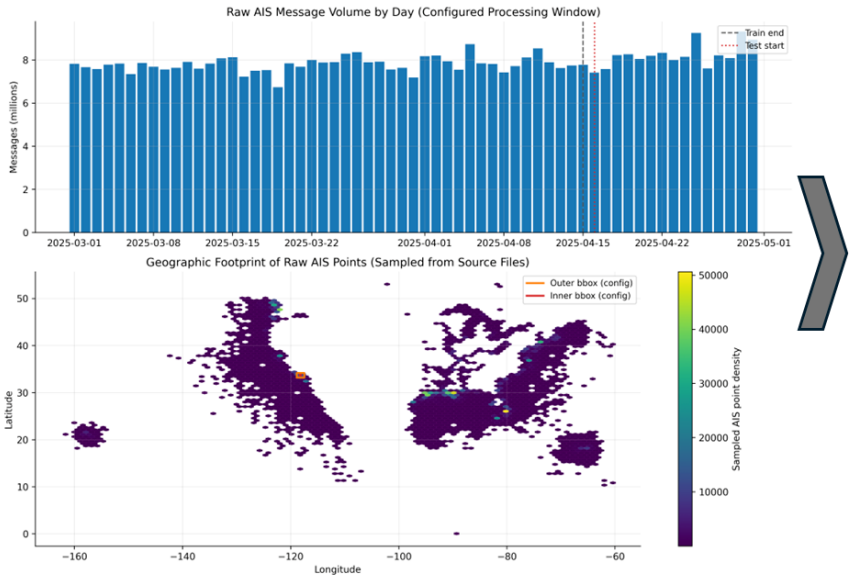
DATA

Study setting and time window.
Port: Los Angeles–Long Beach (PortWatch portid=port664).

Period: March 1–April 30, 2025.

Unit of analysis: inbound voyage instance (per MMSI inbound episode).
To reduce temporal leakage (e.g., using future-day PortWatch context), we use a strict time split: (i) Train: March 1–April 15, 2025, (ii) Test: April 16–April 30, 2025.

AIS data (NOAA MarineCadastre). NOAA MarineCadastre distributes U.S. vessel traffic data derived from the U.S. Coast Guard AIS network (NOAA Office for Coastal Management / MarineCadastre, n.d.-b). For reproducibility and manageable compute, we use daily AIS files for 2025 distributed as compressed CSV (.zst) (NOAA Office for Coastal Management / MarineCadastre, n.d.-a). We download March 1–April 30, 2025 (61 daily files). To ensure optimize compute, we stream-decompress each daily file and apply schema normalization (mapping aliases into canonical columns such as MMSI, BaseDateTime, LAT, LON, SOG, COG, Heading). We then filter rows to an *outer analysis bounding box* around Los Angeles– Long Beach (latitude 33.20–34.20; longitude −118.90 −−117.50) before saving per-day Parquet files. Daily filtered files are concatenated into a single filtered table for voyage construction. In this run, the combined filtered table contains 14,045,615 AIS points and 2,736 unique MMSI values. A visualization of the daily AIS message volume, geographical distribution and the effect of the applied measures to optimize compute is depicted in Figure 1 and Figure 2.

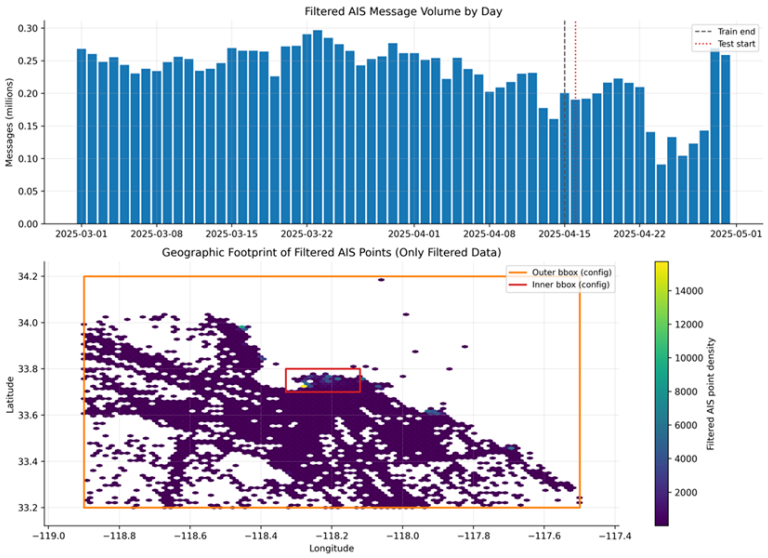


Pre-Filtered Raw AIS Data without geographical scope

482,278,858 Datapoints (Geo-Visualiuation heatmap generated of a random sample of 1,2m. Datapoints)

Raw Data from https://coast.noaa.gov/htdata/CMSP/AISDataHandler/2025/index.

Figure 1: Raw AIS Data in the full dataset provided by the US-Coastguard



Filtered AIS Data

14,045,615 Datapoints Inside of the defined bboxes, yielding a overal reduction of 97 percent from the initial, raw dataset.

Figure 2: Filtered AIS data based on geographical criteria (Zoom on the defined bboxes for the Los Angeles Area)

PortWatch data (Daily Port Activity Data and Trade Estimates). PortWatch is positioned as an open platform to monitor and simulate disruptions to maritime trade (International Monetary Fund, 2023). We retrieve daily port activity and trade estimate fields for Los Angeles–Long Beach via the dataset's ArcGIS FeatureServer using the REST query operation (Esri, n.d.). We use a ports catalog endpoint for discovery/validation of the port identifier and a daily indicators endpoint for the date-indexed fields. Records are fetched using resultOffset/resultRecordCount pagination until exhaustion; ArcGIS error payloads are trapped and raised as explicit runtime exceptions. PortWatch returns one row per day in-range (61 rows), providing complete date coverage for the merge key. We use a subset of indicators consistent with the modeling specification: portcalls and portcall breakdowns (e.g., cargo/container/tanker) plus import/export totals and category totals (container and tanker).

DATA PROCESSING PIPELINE

Figure 3 summarizes the end-to-end workflow from raw data acquisition to evaluation and diagnostics. Relevant steps are described in this chapter in more detail.

Geofence-basedvoyageinstances: We use two rectangular geofences (latitude/longitude bounding boxes) as a minimal, reproducible proxy for "approach" and "arrival" states: (i) Outer approach box: starts the prediction window at first entry. and (ii) Inner arrival box: defines the arrival event at first entry. For each vessel (MMSI), AIS points are time-sorted and we detect outer-entry transitions (outside→inside). To avoid repeated counting of nearidentical episodes, we require at least a 6-hour gap between candidate outer entries. We then search forward from each candidate for the first inner entry and retain episodes that reach the inner box within 48 hours. Points lacking required structural fields (MMSI, timestamp, latitude/longitude) are dropped prior to voyage extraction.

Baseline ETA and delay computation and train-anchored binary delay-risk label: Because reported ETA fields in AIS are often missing or inconsistent, we use a simple physics baseline computed at outer entry. Let *d* be the haversine distance from outer-entry point to a fixed inner-box center; let *v* be the speed over ground (SOG) in m/s. To prevent degenerate ETAs, we clamp SOG to at least 1 knot.

$$\widehat{T}_{\mathsf{eta}} = \frac{d}{\mathsf{max}(v, v_{\mathsf{min}})}, \qquad \Delta = \frac{t_{\mathsf{arrive}} - (t_{\mathsf{outer}} + \widehat{T}_{\mathsf{eta}})}{60}.$$

This baseline is deliberately simple; its purpose is to produce a reproducible delay label without relying on proprietary schedules. The resulting delay is best interpreted as *excess time beyond a straight-line, constant-speed arrival estimate*, not necessarily "terminal delay". We define delay risk as exceeding a high-delay threshold τ learned from training data only: $y = \mathrm{I}[\Delta > \tau]$, $\tau = Q_{0.75}(\Delta \mid \text{train})$.

This anchors the operational meaning of "unusually delayed" to historical performance and avoids leakage of test outcomes into the label definition.

AIS trajectory features (voyage-level). Over a 120-minute window after outer entry (or until arrival), we compute summary statistics intended to capture early approach behavior and reduce susceptibility to late-voyage noise. The modeled AIS feature set includes: point count and duration; SOG mean/std/min/max; fractions of time below 1 and 3 knots; course and heading variability (excluding invalid heading code 511); geometric proxies such as tortuosity and route straightness change; stop-go proxies (episodes and fraction time stopped); acceleration/deceleration summaries; an anchorage-dwell proxy (stopped while 5–25 km from inner center); a local traffic density proxy (unique MMSI within a 30-minute bin around outer entry); and distance to inner center at outer entry.

PortWatch indicators (port-day level): We join daily PortWatch fields to each voyage by the date of outer entry (e.g., total portcalls with category breakdowns, and import/export totals with container and tanker categories). Conceptually, these variables encode day-level throughput/operational pressure that may shift the *baseline risk* for all voyages on that day.

Models and rationale: We use logistic regression as a transparent baseline for binary classification (Hosmer et al., 2013). Logistic regression is appropriate here because:

- It directly outputs probabilities and supports calibration analysis.

- Coefficients offer interpretability (directional effects).
- It is robust and easy to reproduce in a notebook or CLI setting.

We train three variants: AIS-only, PortWatch-only, and fused. Features are standardized and the classifier uses a fixed random seed (random_state=42) and a high iteration cap (max_iter=2000) to ensure convergence. In addition to the full fused set, we evaluate targeted PortWatch ablations (e.g., portcalls-only, trade-total, trade-container, trade-tanker blocks) to test which port-day signals contribute incremental value.

Evaluation metrics and uncertainty:

- **ROC-AUC** as a threshold-independent discrimination measure (Bradley, 1997).
- **PR-AUC** because the positive class can be rare and PR curves can be more informative under class imbalance (Davis & Goadrich, 2006).
- **Brier score** as a proper scoring rule for probabilistic forecasts (Brier, 1950; Gneiting & Raftery, 2007).

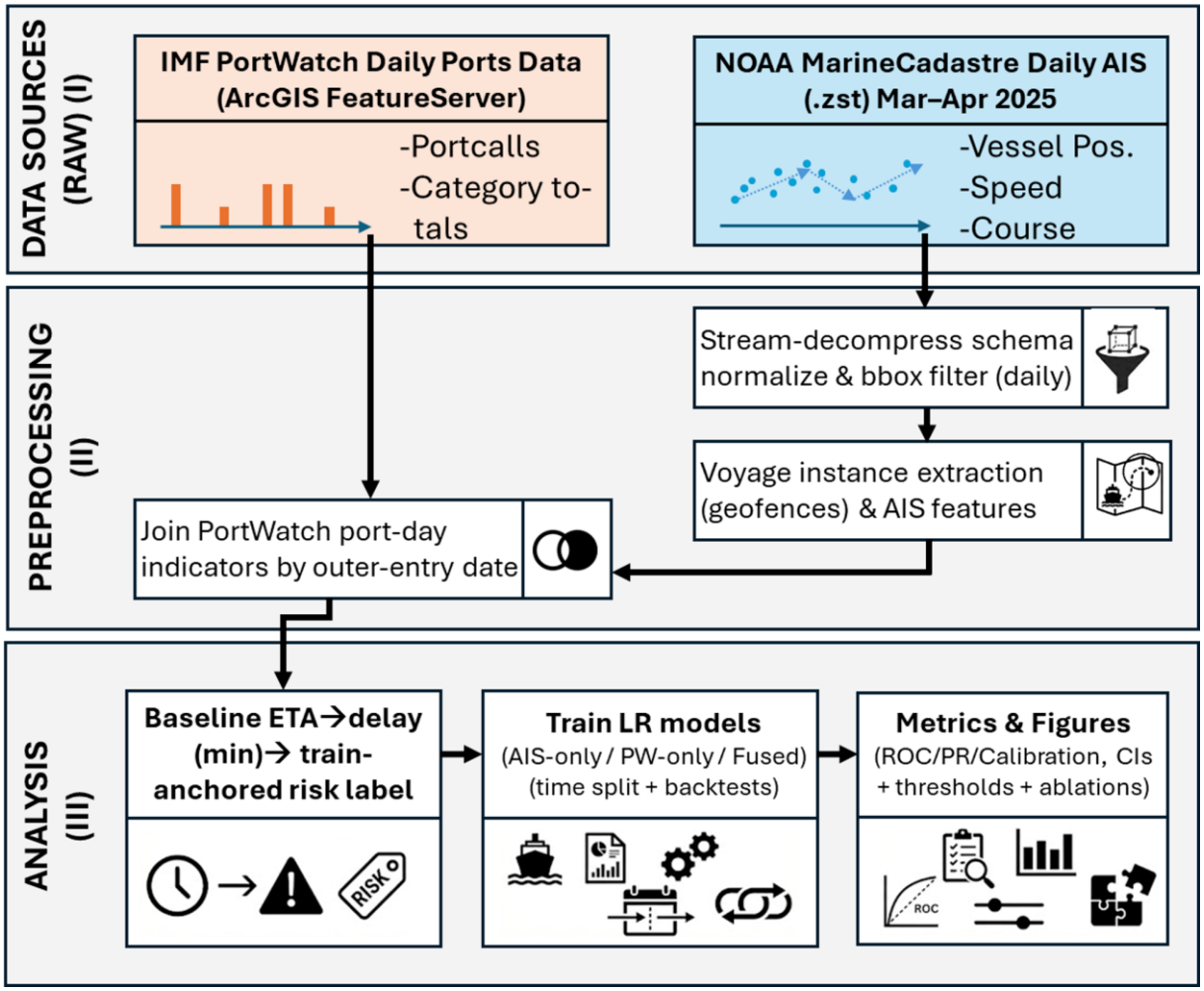


Figure 3: Reproducible pipeline for fusing AIS microdata and PortWatch port-day indicators into a voyage-level delay-risk prediction task with uncertainty and operational diagnostics

RESULTS

Dataset summary: A total of 1,291 voyage instances were available for analysis from 2025-03-01 to 2025-04-30. Using a predefined temporal split, 1,143 voyages were assigned to training (2025-03-01 to 2025-04-15) and 148 to testing (2025-04-16 to 202504-30). Delay-risk prevalence was 25.0% in the training period and 36.5% in the test period, indicating a temporal label shift. This split design was retained to better reflect deployment-like generalization under evolving traffic and operational conditions. Additional visualizations of the Dataset are shown in the appendix.

Predictive performance: Table 1 reports test performance (April 16–30, 2025). Table 2 adds 95% bootstrap confidence intervals (2,000 resamples) for each metric.On the held-out test set, fused AIS+PortWatch achieved the highest point-estimate discrimination. AIS-only was close, while PortWatch-only was substantially weaker. Brier scores are showing that fused and AIS-only were clearly stronger than PortWatch-only. Paired bootstrap comparisons supported this: fused vs PortWatch-only showed clear improvements, whereas fused vs AIS-only differences were small and not statistically clear in this period.

Table 1: Held-out test performance (point estimates). AUC/AP measure discrimination; Brier measures probabilistic accuracy/calibration.

Model	ROC-AUC	PR-AUC	Brier
AIS-only	0.753	0.624	0.195
PortWatch-only	0.542	0.394	0.239
Fused	0.771	0.649	0.197

Table 2: Held-out test performance with 95% bootstrap confidence intervals.

Model	ROC-AUC (95% CI)	PR-AUC (95% CI)	Brier (95% CI)
AIS-only	0.753 (0.676, 0.828)	0.624 (0.514, 0.737)	0.195 (0.168, 0.223)
PortWatch-only	0.542 (0.449, 0.638)	0.394 (0.327, 0.478)	0.239 (0.227, 0.250)
Fused	0.771 (0.698, 0.840)	0.649 (0.541, 0.751)	0.197 (0.167, 0.227)

Temporal Robustness and Heterogeneity: Rolling temporal backtests (30-day train,

7-day test, four windows) preserved model ranking over time: mean ROC-AUC was 0.785 ± 0.052 for fused, 0.780 ± 0.049 for AIS-only, and 0.546 ± 0.060 for PortWatch-only. Mean PR-AUC followed the same pattern (fused 0.658 ± 0.069; AIS-only 0.639 ± 0.081; PortWatch-only 0.470 ± 0.061). Subgroup analyses showed heterogeneity by traffic density and weekday, with wider uncertainty in smaller strata. These results are useful for monitoring and follow-up analysis but should be interpreted cautiously.

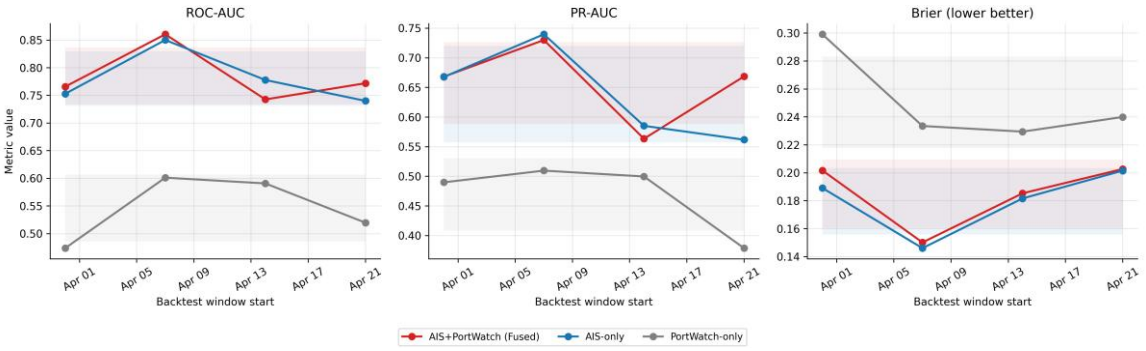


Figure 4: Rolling-window temporal backtest performance (Rolling 30-day train, 7d backtest)

Interpretation of the results: The results show that AIS-derived features provide the dominant predictive signal for voyage-level delay risk. Fusion with PortWatch indicators clearly improves over PortWatch-only modeling, while gains over AIS-only are modest in this evaluation period. Temporal backtests support robustness of this ranking. For operational use, model selection should be paired with explicit threshold tuning, and raw probabilities should be recalibrated before direct risk communication. Two conclusions can be drawn from the interpretation of the results:

(1) AIS micro-features provide the dominant voyage-level separation. AIS-only achieves strong discrimination (ROC-AUC 0.753; PR-AUC 0.624), consistent with the mechanism that per-voyage delay risk is influenced by local behaviors (slowdowns, maneuvering variability, stop-go dynamics, and holding/anchoring proxies) that are directly observable in near-port AIS trajectories.

(2) Port-day indicators are weak alone, and provide at most modest incremental discrimination when fused. PortWatch-only performs substantially worse than AISbased models. Fusion yields the highest point estimates for ROC-AUC/PR-AUC, but paired bootstrap intervals for Fused minus AIS-only cross zero, indicating that incremental discrimination gains are modest and statistically uncertain in this horizon. This aligns with the scale-mismatch hypothesis: PortWatch covariates are constant within each day, so they can shift day-level baseline risk but cannot explain which *specific* voyage becomes delayed among multiple vessels sharing the same day-level conditions.

DISCUSSION

Scientific validity of the label

A central methodological choice is that delay is computed relative to a simplified baseline ETA. This is appropriate for a reproducible study because it avoids reliance on proprietary schedules, but it also changes the interpretation of "delay":

- The label reflects *excess travel time* relative to an idealized motion model, not necessarily berth waiting time.
- The empirical delay distribution is heavy-tailed, with many voyages arriving earlier than the baseline (negative delays) and a long positive tail; a quantile-defined risk label targets the operationally relevant tail while avoiding unstable point prediction.

Nonetheless, systematic slowdowns, holding patterns, and approach behavior (which may correlate with congestion or operational constraints) remain meaningful operational risk signals.

Threats to validity and reproducibility

Endpoint/schema volatility. Web-service schemas and ArcGIS endpoints can change over time. To address this, the data-access layer uses explicit port discovery (ports catalog query), paginated retrieval, and strict error handling for ArcGIS payloads (Esri, n.d.). Production-grade fusion should additionally implement schema version checks and automated field validation to reduce silent breakage.

Prevalence shift under times splits. Training and test prevalence differ materially (25.0% vs. 36.5%). Such shift can degrade threshold stability and probability calibration even when AUC remains strong. This motivates (i) reporting PR-AUC alongside ROC-AUC (Davis & Goadrich, 2006), (ii) calibration diagnostics and proper scoring rules (Brier, 1950; Gneiting &

Raftery, 2007), and (iii) explicit threshold policy analysis, since a fixed 0.5 threshold can behave poorly under distribution shift.

Uncertainty and dependence. Even with a larger test set than short demos, metric estimates remain uncertain and model comparisons can be sensitive to the dependence structure of predictions. Bootstrap confidence intervals and paired comparisons provide practical uncertainty quantification; more formal AUC comparison tests exist (e.g., DeLong) (DeLong et al., 1988), but assumptions and dependence should be considered.

Scale mismatch: voyage vs. day. PortWatch features are port-day aggregates. Without within-day variation, such features can only modulate day-level baseline risk. Ablation and importance results suggest that some PortWatch signals (e.g., export-related indicators) contribute measurable but secondary context; richer contextualization may require higher-frequency port state proxies or multi-port network spillover indicators (International Monetary Fund, 2023, 2025).

Implications for logistics risk management

Operationally, discrimination, calibration, and threshold policy play different roles:

- High ROC/PR performance supports *ranking* and triage (which voyages to inspect or prioritize).
- Calibration quality supports *probabilistic decision-making* (choosing thresholds based on cost trade-offs).
- Threshold selection controls workload and miss burden; Youden-optimal thresholds can shift a model from recall-oriented behavior to higher-specificity alerting, which may be preferable when false-alert costs are high.

Our results suggest that AIS features are foundational for voyage-level risk ranking, while PortWatch can provide contextual increments that are beneficial in some regimes but should be validated with uncertainty and monitored under temporal shift.

CONCLUSION

We presented a reproducible study of voyage-level arrival delay risk prediction for inbound traffic to Los Angeles–Long Beach by fusing NOAA MarineCadastre AIS trajectory features with IMF PortWatch port-day indicators over March–April 2025. On a strict held-out split (April 16–30), the fused logistic regression achieved ROC-AUC 0.771 and PR-AUC 0.649, while AIS-only achieved ROC-AUC 0.753 and PR-AUC 0.624; paired bootstrap comparisons indicate that fusion decisively outperforms PortWatch-only but provides only modest, statistically uncertain discrimination gains over AIS-only in this horizon. Calibration diagnostics show over-confident probability scaling (slopes < 1) for all models, and threshold analyses demonstrate that operational behavior depends strongly on the chosen decision policy. The resulting pipeline and diagnostics provide a practical template for extending to longer horizons, multiple ports, enriched exogenous covariates (e.g., weather and labor signals), and more expressive models, while maintaining reproducibility and interpretability.

REFERENCES

Bradley, A. P. (1997). The use of the area under the roc curve in the evaluation of machine learning algorithms. *Pattern Recognition*, *30*(7), 1145–1159. https://doi.org/10.1016/S0031-3203(96)00142-2

Brier, G. W. (1950). Verification of forecasts expressed in terms of probability. *Monthly Weather Review*, *78*, 1–3. https://doi.org/10.1175/1520-0493(1950)078<0001:VOFEIT>2.0.CO;2

Davis, J., & Goadrich, M. (2006). The relationship between precision–recall and roc curves. *Proceedings of ICML*. https://doi.org/10.1145/1143844.1143874

DeLong, E. R., DeLong, D. M., & Clarke-Pearson, D. L. (1988). Comparing the areas under two or more correlated receiver operating characteristic curves: A nonparametric approach. *Biometrics*, *44*(3), 837–845.

Esri. (n.d.). *Query (feature service layer) — arcgis rest api documentation*. Retrieved February 4, 2026, from https://developers.arcgis.com/rest/services-reference/enterprise/query-feature-service-layer/

Gneiting, T., & Raftery, A. E. (2007). Strictly proper scoring rules, prediction, and estimation.

Journal of the American Statistical Association, *102*(477), 359–378. https://doi.org/10.1198/016214506000001437

Hosmer, D. W., Lemeshow, S., & Sturdivant, R. X. (2013). *Applied logistic regression* (3rd ed.). Wiley.

International Maritime Organization. (n.d.). *Ais transponders (solas regulation v/19 carriage requirements)*. Retrieved February 4, 2026, from https://www.imo.org/en/ourwork/safety/pages/ais.aspx

International Monetary Fund. (2023, November 15). *Imf and university of oxford launch*

"portwatch" platform to monitor and simulate trade disruptions. Retrieved February 4, 2026, from https://www.imf.org/en/news/articles/2023/11/13/pr23390-imfuniversity-oxford-launch-portwatch-platform-monitor-simulate-trade-disruptions

International Monetary Fund. (2025). *Nowcasting global trade from space* (IMF Working Paper No. 2025/093). https://doi.org/10.5089/9798229009294.001

NOAA Office for Coastal Management / MarineCadastre. (n.d.-a). *Ais data handler: Daily ais files for 2025 (ais-yyyy-mm-dd.csv.zst)*. Retrieved February 4, 2026, from https:

//coast.noaa.gov/htdata/CMSP/AISDataHandler/2025/index.html

NOAA Office for Coastal Management / MarineCadastre. (n.d.-b). *Vessel traffic (ais): Overview and provenance (u.s. coast guard ais)*. Retrieved February 4, 2026, from https:

//www.coast.noaa.gov/digitalcoast/data/vesseltraffic.html

Zhang, Y., et al. (2024). Automatic identification system-based prediction of tanker and cargo estimated time of arrival in narrow waterways. *Journal of Marine Science and*

Engineering, *12*(2), 215. https://www.mdpi.com/2077-1312/12/2/215

APPENDIX

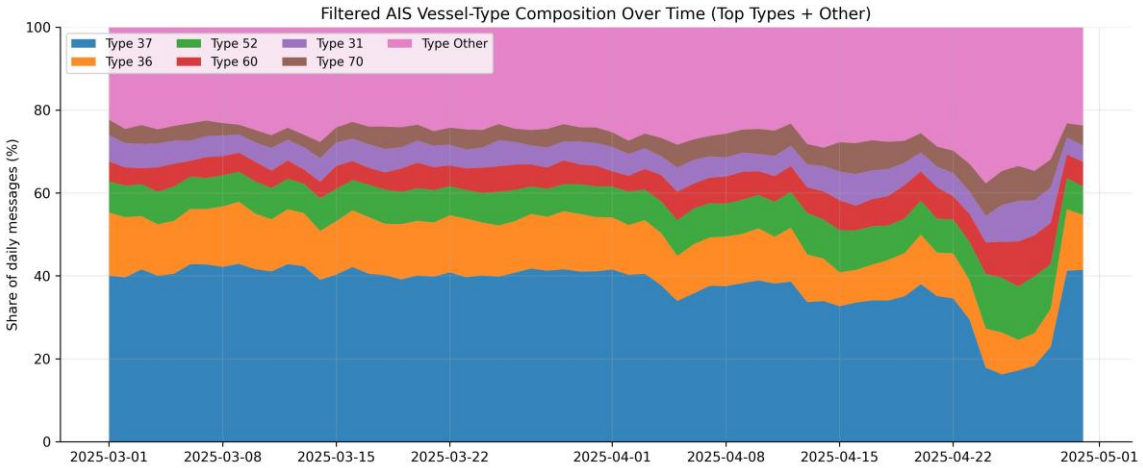


Figure 5: Filtered AIS Vessel-Type Composition Over Time (Top Types + Other)

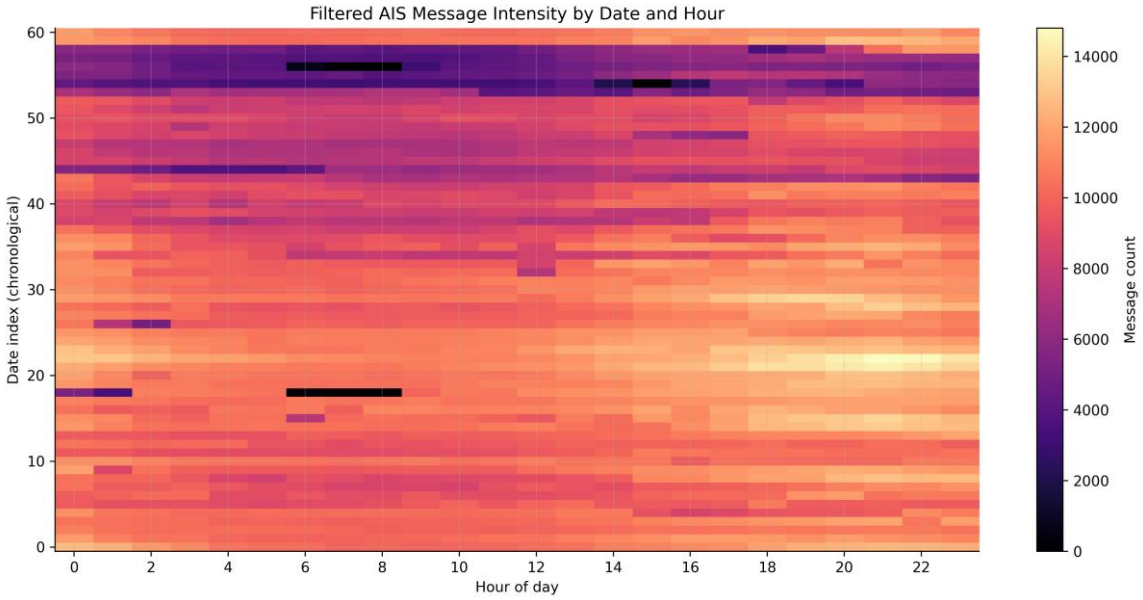


Figure 6: Filtered AIS Message Intensity by Date and Hour

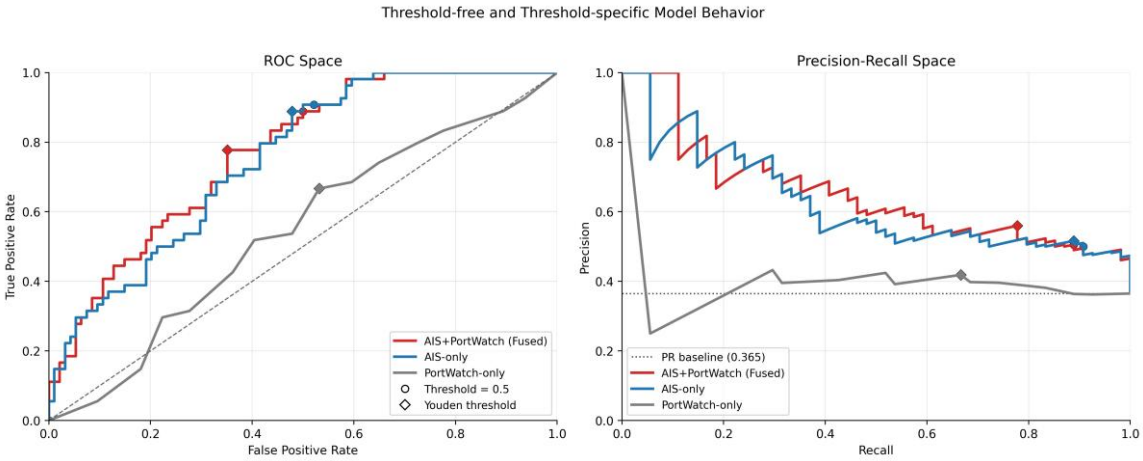


Figure 7: ROC curves on the held-out test split (April 16–30, 2025)

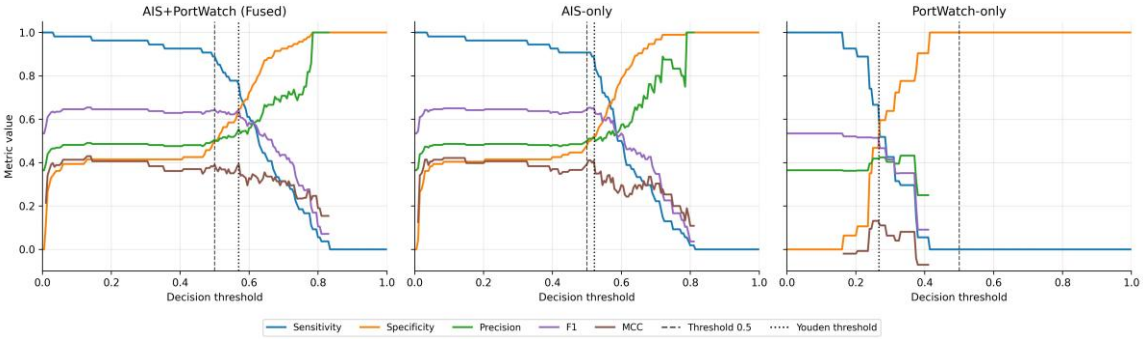


Figure 8: Threshold Frontier Across Key Operating Metrics

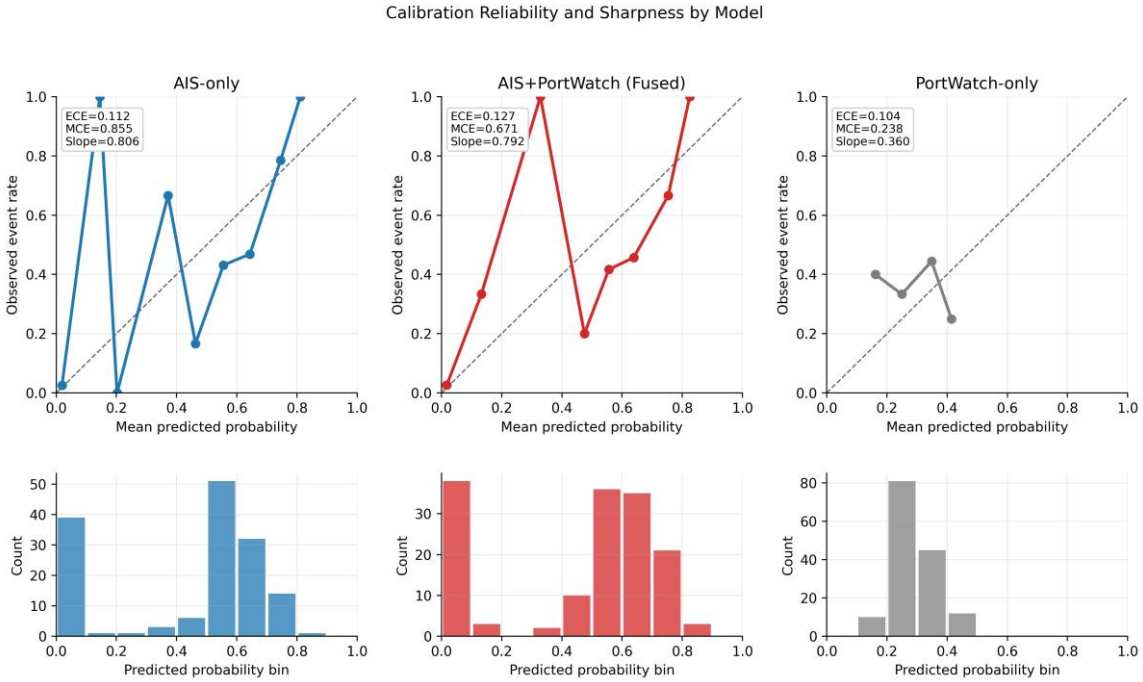


Figure 9: Threshold Frontier Across Key Operating Metrics

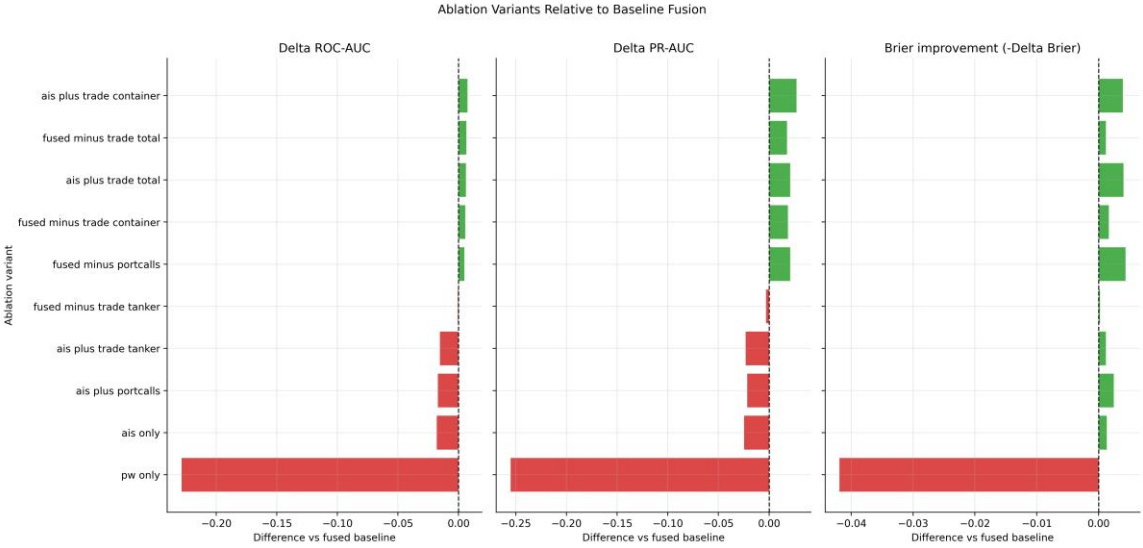


Figure 10: Ablation Impact Waterfall

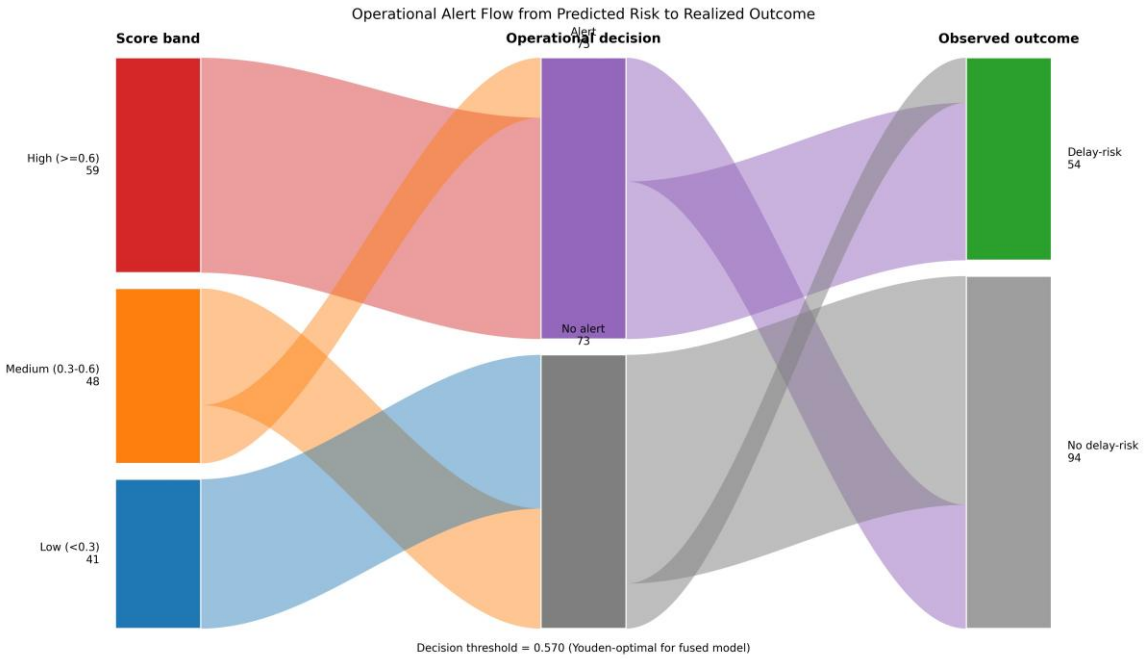


Figure 11: Ablation Impact Waterfall

Configuring Digital Twin Readiness for Regenerative Supply Chain Intelligence: Evidence from Indonesia's Shrimp Supply Chain

Anggriani Profita[1,2], Lin Wu[3], Kim Tan[1]

1: Nottingham University Business School, University of Nottingham, United Kingdom; 2: Faculty of Engineering, Mulawarman University, Indonesia; 3: Nottingham University Business School China

INTRODUCTION

Aquaculture has become the fastest-growing source of aquatic food globally and is increasingly central to meeting rising protein demand as capture fisheries stagnate (FAO, 2024). As environmental degradation, resource scarcity, and social inequities intensify, supply chains are no longer expected merely to minimise harm, but to actively sustain long-term socio-ecological viability. This shift has catalysed growing interest in regenerative supply chains, which emphasise adaptive capacity, collaborative governance, and value creation that supports both economic and ecological systems over time (FAO, 2024). Achieving such ambitions depends fundamentally on supply chain intelligence, understood as the capability to generate, integrate, and act on information across interconnected actors in support of informed and responsible decision-making.

Indonesia occupies a pivotal position in this transformation as the world's second-largest fish producer, where aquaculture plays a critical role in national food security, export earnings, and rural livelihoods (Tran et al., 2017). Future growth in fish availability is expected to rely heavily on aquaculture expansion, positioning the sector as a strategic pillar of economic development amid increasing environmental and market pressures (Henriksson et al., 2017). These dynamics intensify the need for supply chains that are not only productive but also resilient and capable of supporting regenerative ambitions.

Within Indonesia's aquaculture sector, shrimp is the most economically significant commodity, contributing approximately 0.31 per cent to national GDP and accounting for over 30 per cent of total fishery export earnings (BPS-Statistics Indonesia, 2023). Indonesia competes directly with technologically advanced producers such as China, Vietnam, and Thailand (Love et al., 2021; Mosallanezhad et al., 2021). Concurrently, the sector remains vulnerable to disease outbreaks, environmental stressors, and production variability, underscoring the need for coordinated and intelligence-driven decision-making across the supply chain.

However, persistent structural constraints continue to limit coordination. Fragmented production structures, geographically dispersed farms, and smallholder dominance hinder consistent quality and traceability (Pathumnakul et al., 2009; Azizah et al., 2020). Limitations in monitoring, documentation, and food safety assurance, combined with continued reliance on fragmented paper-based systems, weaken export performance. Traditional pond layouts and management practices further raise concerns regarding environmental efficiency and social impacts in coastal communities (Azizah et al., 2020; Bestianta, 2022). These conditions suggest that even foundational "less harm" objectives remain difficult to achieve consistently, let alone regenerative aspirations.

Digitalisation has therefore emerged as a proposed pathway toward improved coordination and sustainability. Under the FAO's Blue Transformation agenda, digital technologies are promoted as enablers of regenerative aquaculture through improved resource efficiency, environmental monitoring, and traceability (FAO, 2024). Technologies such as Internet of Things devices and data-driven decision platforms increasingly facilitate real-time insights and collaborative management across value chains (Verdouw et al., 2021; Wolfert et al., 2017). However, in Indonesia, adoption remains uneven and fragmented, concentrated among better-capitalised actors with limited interoperability and weak cross-actor integration (Azizah et al., 2020).

Within this evolving landscape, digital twin technology has gained attention as an advanced form of supply chain intelligence. By integrating real-time data, analytical models, and simulation capabilities, digital twins enable prediction, scenario analysis, and adaptive decision-making (Fuller et al., 2020; Tao et al., 2019). Although successful in manufacturing and logistics contexts (Ivanov & Dolgui, 2020; 2021), their applicability in smallholder-dominated aquaculture systems remains uncertain. Digital twins require high-quality data, interoperable infrastructures, and governance mechanisms that enable collective use across heterogeneous actors, revealing a substantial gap between technological potential and sectoral readiness.

Existing research provides limited guidance for addressing this challenge. Technology readiness studies frequently examine technological, organisational, or environmental factors in isolation, overlooking readiness as a relational and system-level condition. Digital twin research remains largely grounded in advanced manufacturing contexts, with limited multi-actor empirical investigation. Moreover, linear, variable-oriented methods dominate the literature, obscuring causal complexity and limiting understanding of how combinations of conditions may jointly enable readiness. Consequently, it remains unclear how configurations of digital twin readiness underpin regenerative supply chain intelligence in socio-ecologically sensitive production systems.

This study, therefore, aims to identify and interpret configurations of digital twin readiness that enable regenerative supply chain intelligence in Indonesia's shrimp supply chain. Accordingly, the paper addresses the following research question: What configurations of digital twin readiness enable regenerative supply chain intelligence in a socio-ecologically sensitive supply chain? Adopting a configurational, multi-actor approach, the study contributes conceptually by reframing readiness as an intelligence capability, methodologically by integrating thematic analysis, Pareto analysis, and fuzzy-set qualitative comparative analysis (fsQCA), and empirically by providing evidence from Indonesia's shrimp supply chain.

METHODOLOGY

Research Design and Case Context

To examine how configurations of digital twin readiness enable regenerative supply chain intelligence, this study adopts a qualitative multiple-case design. Qualitative inquiry is appropriate for exploring complex and evolving socio-technical phenomena in which readiness is not yet fully operationalised and underlying mechanisms are not directly observable (Creswell & Creswell, 2023; Bryman et al., 2021). Rather than measuring implementation outcomes, the study investigates how readiness conditions are perceived, interpreted, and configured across interconnected actors.

A case study approach is suitable for examining contemporary phenomena embedded within real-life contexts, particularly where the boundaries between technological change and institutional conditions are intertwined (Yin, 2014; Stake, 1995). Consistent with a critical realist orientation, the design seeks to uncover the generative mechanisms and structural constraints that shape digital twin readiness across multiple levels (Easton, 2010; Fletcher, 2017). This perspective aligns with the study's framing of regenerative supply chain intelligence as an emergent, system-level capability rather than a firm-level attribute.

The empirical setting comprises Indonesia's shrimp supply chain, a socio-ecologically sensitive production system characterised by smallholder dominance, fragmented coordination, and uneven technological capability. Given its economic significance and exposure to environmental risks, the sector provides a critical context in which regenerative ambitions depend on effective cross-actor intelligence.

A multiple-case structure was employed to capture configurational variation across supply chain tiers (Yin, 2014). Three analytically distinct cases were defined according to core echelons: upstream (hatcheries and feed suppliers), midstream (shrimp farmers), and downstream (intermediaries, distributors, and cold storage operators). An embedded design was adopted,

with individual actors serving as units of analysis within each case. This structure enables both within-case depth and cross-case comparison, allowing examination of how readiness conditions vary, align, or conflict across actor roles and regional contexts (Creswell & Poth, 2025).

To capture contextual heterogeneity, the cases were bounded across four major shrimp-producing provinces: Lampung, West Java, West Kalimantan, and South Sulawesi. These regions were purposively selected to reflect variation in infrastructure, institutional support, and market access relevant to digital transformation. By bounding cases at the actor and regional levels within a defined study period, the design supports analytical generalisation and systematic comparison of readiness configurations in a complex supply chain environment (Yin, 2014; Easton, 2010).

Data Collection

Data were collected through 30 semi-structured interviews conducted between February and May 2024 across three supply chain tiers. The sample comprised upstream actors (n = 7), midstream actors (n = 17), and downstream actors (n = 6), distributed across four major shrimp-producing provinces: Lampung (n = 6), West Java (n = 8), West Kalimantan (n = 7), and South Sulawesi (n = 9).

Purposive sampling was employed to select participants with operational, technical, or managerial responsibilities relevant to digital technology adoption and supply chain coordination (Creswell & Poth, 2025). This ensured the inclusion of actors directly engaged with infrastructural constraints, coordination mechanisms, and emerging digital practices across tiers.

Interviews were conducted in natural settings using a semi-structured protocol organised around actor roles, supply chain coordination, current digital technology use, adoption drivers and barriers, and organisational readiness for future technologies. The interview guide was informed by technological, organisational, and environmental dimensions of technology adoption, enabling systematic exploration of infrastructural capabilities, inter-actor dependencies, and perceived pressures shaping digital transformation. Interviews lasted 45-60 minutes, were audio-recorded with informed consent, and were transcribed for systematic analysis. To ensure confidentiality, participants were anonymised using coded identifiers indicating actor type and province (e.g., F1L for Farmer 1 in Lampung; D1WK for Distributor 1 in West Kalimantan).

Analytical Strategy: Integrated Workflow

To identify configurations of digital twin readiness that enable regenerative supply chain intelligence, this study employed an integrated three-phase analytical workflow linking qualitative exploration with configurational explanations.

Phase 1: Thematic Analysis
Interview transcripts were analysed using thematic analysis to identify readiness factors across technological, organisational, and environmental domains (Braun & Clarke, 2006). This phase generated a structured matrix of empirically grounded readiness conditions derived from actor narratives across supply chain tiers.

Phase 2: Pareto Analysis
To reduce analytical complexity and focus on the most influential conditions, a Pareto analysis was applied to rank readiness factors by frequency and cross-actor relevance. This step identified the "vital few" conditions with the greatest empirical salience while maintaining transparency in the factor selection process.

Phase 3: fuzzy-set Qualitative Comparative Analysis (fsQCA)
The prioritised factors were calibrated into fuzzy sets and analysed using fsQCA. Unlike linear, variable-oriented methods, fsQCA examines conjunctural and asymmetric causation, enabling identification of multiple combinations of conditions sufficient for digital twin readiness (Ragin, 2008; Fiss, 2011).

Together, this sequential integration links qualitative depth, empirical prioritisation, and configurational reasoning. The workflow ensures that identified readiness pathways remain grounded in actor perceptions while capturing causal complexity and equifinality in a socio-ecologically sensitive supply chain. Figure 1 summarises the integrated analytical workflow.

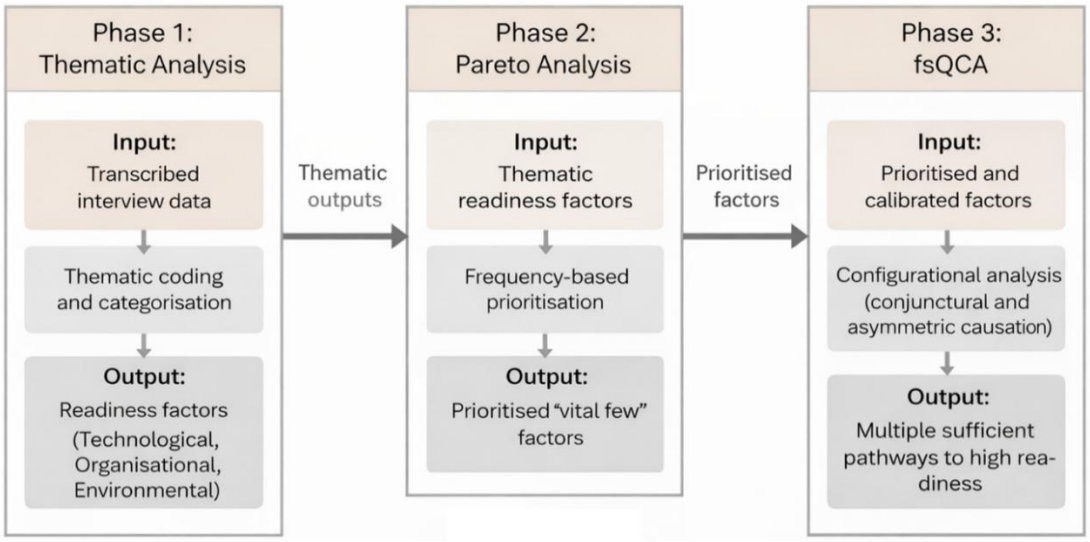


Figure 1. Integrated Analytical Workflow

RESULTS AND DISCUSSION

The thematic analysis identified 45 digital twin readiness factors across technological, organisational, and environmental domains, reflecting infrastructural capabilities, managerial alignment, workforce preparedness, and ecosystem influences. Pareto prioritisation reduced this set to 23 empirically salient factors, accounting for the majority of cross-actor mentions. To facilitate configurational analysis, these prioritised factors were conceptually aggregated into four high-order conditions: Technological Readiness (T), Organisational Readiness and Resilience (O), Workforce Capability (W), and Ecosystem Influence (E). This aggregation preserved empirical richness while reducing analytical complexity, enabling examination of how combinations of internal and external readiness conditions jointly produce regenerative supply chain intelligence. A more detailed presentation of the thematic and prioritisation procedures is available in Profita et al., 2025).

Configurational Overview

The fsQCA results reveal three sufficient configurations of digital twin readiness that enable regenerative supply chain intelligence: 1010 (T•~O•W•~E), 0010 (~T•~O•W•~E), and 0111 (~T•O•W•E). All three pathways demonstrated high consistency (≥ 0.88) and remained stable under robustness checks, including stricter PRI thresholds (≥ 0.80), frequency cut-offs, and province-level jackknife tests. Overall solution consistency remained above 0.90, with individual raw coverage values ranging from 0.19 to 0.23, indicating that each configuration explains a meaningful share of observed readiness outcomes.

The results confirm equifinality: multiple distinct combinations of conditions can jointly produce digital twin readiness in a socio-ecologically sensitive supply chain. No single condition reached the threshold for necessity, underscoring that readiness does not emerge from isolated factors but from conjunctural interactions among technological, organisational, workforce, and ecosystem dimensions.

Notably, Workforce Capability (W) appears in all three robust configurations, suggesting that human capital and adaptive capacity are foundational elements of readiness across contexts. By contrast, technological infrastructure (T), organisational alignment (O), and ecosystem support

(E) serve as either substitutable or complementary conditions, depending on the pathway. These findings indicate that regenerative supply chain intelligence emerges through alternative structural arrangements rather than a single dominant digital transformation model.

Pathway 1: Technological–Workforce Reinforcement (1010)

The 1010 configuration (T•~O•W•~E) represents a readiness pathway driven primarily by technological awareness and workforce capability, in the absence of strong organisational coordination or ecosystem support. This pathway was observed mainly among upstream and midstream actors in Lampung and West Kalimantan, with isolated cases in West Java. Actors in this configuration consistently emphasised the importance of usable technology, data quality, and individual competence as prerequisites for digital transformation, even where formal structures and external collaborations remained underdeveloped.

The underlying mechanism is practice-led adaptation. Respondents described how readiness develops through hands-on experimentation with digital tools for feed management, water quality monitoring, or record keeping, often on a small scale and without organisational mandates. Workforce learning and technological familiarity precede formal investment or system integration, indicating that readiness initially emerges cognitively and experientially rather than structurally.

This pathway demonstrates that early-stage digital twin readiness can materialise through bottom-up learning processes. Although regenerative supply chain intelligence remains limited at this stage, technological-workforce reinforcement establishes the foundational capabilities that enable the subsequent development of organisational alignment and ecosystem integration.

Pathway 2: Workforce-Centric Readiness (0010)

The 0010 configuration (~T•~O•W•~E) represents a workforce-centric pathway in which digital twin readiness is driven almost exclusively by human capability, without strong technological infrastructure, organisational coordination, or ecosystem support. This pathway emerged as the most recurrent configuration, with the highest raw coverage (0.23), indicating that it explains the largest share if observed readiness outcomes across actors and provinces. It was particularly visible among farmers and distributors in West Java, South Sulawesi, and Lampung.

The mechanism underpinning this configuration is capacity-led substitution. In these contexts, workforce learning orientation, digital literacy, and proactive experimentation compensate for limited systemic support. Actors reported engaging with digital applications informally through peer learning, trial-and-error practices, and incremental skill development rather than through formal investment programmes or structured governance frameworks. Readiness, therefore, originates from individual motivation and adaptive competence rather than institutional design.

This pathway highlights that human capital is the pivotal catalyst for early-stage digital transformation in socio-ecologically sensitive supply chains. Although technological sophistication and organisational integration remain underdeveloped, workforce capability initiates the cognitive and behavioural shifts necessary for regenerative supply chain intelligence to emerge. Training, knowledge dissemination, and learning-oriented cultures this become critical levers for advancing readiness in resource-constrained environments.

Pathway 3: Networked Readiness (0111)

The 0111 configuration (~T•O•W•E) reflects a networked readiness pathway characterised by strong organisational alignment, workforce capability, and ecosystem engagement, despite relatively limited emphasis on technological sophistication. This pathway was most evident among downstream actors, particularly distributors in South Sulawesi and Lampung, where readiness was shaped through coordination mechanisms, relational trust, and inter-organisational collaboration rather than advanced digital infrastructure.

The mechanism underlying this configuration can be described as collaborative orchestration. In these contexts, actors leverage structured planning, shared accountability, and stakeholder partnerships to coordinate information flows and operational processes. Ecosystem influence, through industry benchmarks, alliances, and innovation trends, reinforces organisational commitment and collective learning. Workforce participation supports the operationalisation of these collaborative arrangements, enabling coordinated adaptation even where technological systems remain basic.

This pathway demonstrates that regenerative supply chain intelligence can emerge through relational and governance-based mechanisms rather than solely through technological advancement. Organisational resilience and ecosystem alignment provide a substitute foundation for digital transformation, illustrating that socio-ecologically sensitive supply chains may advance toward regeneration through collective coordination before full technological integration. Trust-based networks and institutional partnerships thus act as strategic enablers of scalable digital twin readiness.

Cross-Pathway Insights: The Triple-C Readiness Model

Synthesising the three sufficient configurations, the findings suggest that digital twin readiness in socio-ecologically sensitive supply chains can be conceptualised as a layered but non-linear architecture, captured in the proposed Triple-C Readiness Model. Rather than representing fixed stages, the model identifies three interrelated readiness layers: Cognitive Readiness, Capability Readiness, and Coordination Readiness.

Cognitive Readiness refers to awareness, digital literacy, and experimentation, and foundational trust-building. This layer is most visible in the technological-workforce reinforcement pathway (1010), where actors cultivate familiarity with digital tools before institutional integration. Capability Readiness reflects structured competence, financial planning, adaptive routines, and workforce preparedness, corresponding strongly to the workforce-centric pathway (0010), in which human capital substitutes for systemic infrastructure. Coordination Readiness involves inter-organisational alignment, shared data norms, and ecosystem engagement, exemplified by the networked readiness pathway (0111), where relational governance enables system-level intelligence despite limited technological sophistication.

Importantly, these layers are cumulative but not sequential. Actors may overlap, substitute for, or recombine readiness dimensions depending on their structural positions and resource constraints. The Triple-C model, therefore, reframes readiness as a dynamic configurational capacity rather than a binary condition. It explains how regenerative supply chain intelligence emerges through alternative structural arrangements that activate adaptive learning, operational capability, and relational coordination across actors.

CONCLUSION

This study examined what configurations of digital twin readiness enable regenerative supply chain intelligence in a socio-ecologically sensitive supply chain. Drawing on qualitative evidence from Indonesia's shrimp industry and applying an integrated configurational workflow, three sufficient readiness pathways were identified: technological-workforce reinforcement (1010), workforce-centric readiness (0010), and networked readiness (0111). The findings confirm equifinality, demonstrating that regenerative supply chain intelligence does not depend on a single transformation model but emerges through alternative conjunctural arrangements across technological, organisational, workforce, and ecosystem dimensions.

The principal contribution is the articulation of the Triple-C Readiness Model, which conceptualises readiness as a layered but non-sequential architecture comprising Cognitive, Capability, and Coordination readiness. Rather than a static checklist of prerequisites, readiness is reframed as a dynamic configurational capacity through which actors mobilise awareness, operational competence, and relational alignment. In socio-ecologically sensitive systems, regenerative supply chain intelligence materialises when these layers interact coherently,

enabling adaptive learning, resource optimisation, and cross-actor coordination. This perspective advances digital twin readiness theory by situating it within system-level regenerative transformation rather than solely within firm-level adoption.

From a digital transformation strategy standpoint, workforce capability emerges as a foundational catalyst across pathways. Investments in digital literacy, structured training, and adaptive routines can initiate readiness even under infrastructural constraints. However, sustained regenerative outcomes depend on progression toward coordination readiness, where organisational alignment and ecosystem collaboration enable scalable intelligence. Strategic interventions should therefore recognise substitutability and complementarity among readiness dimensions rather than assume linear technological upgrading.

The findings should be interpreted in light of several limitations. The study is context-specific to Indonesia's shrimp supply chain, which may constrain transferability. The cross-sectional design captures readiness at a single point in time and does not trace longitudinal transformation trajectories. Although robustness checks increase confidence in the findings, the analysis does not establish causality in an experimental or longitudinal sense.

Future research should address these limitations by extending the Triple-C framework beyond a single context and time horizon. Longitudinal transformation analysis would enable examination of how actors transition across cognitive, capability, and coordination readiness layers over time, providing stronger insight into process dynamics and temporal causation. Comparative cross-country investigations could further test the transferability of the configurational pathways across diverse institutional and ecological environments, clarifying how structural conditions shape alternative readiness architectures. Such extensions would strengthen causal inference and deepen understanding of how digital twin readiness supports regenerative supply chain intelligence across heterogeneous socio-technical systems.

ACKNOWLEDGMENTS

The authors acknowledge the funding received from the Indonesia Endowment Fund for Education, Ministry of Finance, Republic of Indonesia, with decision letter number KEP-2652/LPDP/LPDP.3/2022.

REFERENCES

Azizah, F. F. N., Ishihara, H., Zabala, A., Sakai, Y., Suantika, G., & Yagi, N. (2020). Diverse perceptions on eco-certification for shrimp aquaculture in Indonesia. *Sustainability, 12*, 9387, 1–19.

Bestianta, O. R. (2022). Optimisme ekspor udang Indonesia. *Buletin APBN, 7*(22), 3–6.

BPS-Statistics Indonesia. (2023). *Statistical yearbook of Indonesia*. BPS-Statistics Indonesia.

Braun, V., and Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology,* 3(2), 77–101.

Bryman, A., Clark, T., Foster, L. and Sloan, L. (2021) *Social Research Methods*. 6th edn. Oxford: Oxford University Press.

Creswell, J. W. and Creswell, J. D. (2023) *Research Design: Qualitative, Quantitative, and Mixed Methods Approaches*. 6th edn. Thousand Oaks, CA: Sage.

Creswell, J. W., & Poth, C. N. (2025). *Qualitative Inquiry and Research Design: Choosing Among Five Approaches* (5th ed.). Thousand Oaks, CA: Sage Publications.

Easton, G. (2010). Critical realism in case study research. *Industrial Marketing Management,* 39(1), 118–128.

FAO. (2024). *The State of World Fisheries and Aquaculture 2024: Blue Transformation in Action*. Food and Agriculture Organization of the United Nations.

Fiss, P. C. (2011). Building better causal theories: A fuzzy set approach to typologies in organisation research. *Academy of Management Journal,* 54(2), 393–420.

Fletcher, A. J. (2017) Applying critical realism in qualitative research: methodology meets method. *International Journal of Social Research Methodology*, 20(2), pp. 181–194.

Fuller, A., Fan, Z., Day, C., & Barlow, C. (2020). Digital twin: Enabling technologies, challenges and open research. *IEEE Access, 8*, 108952–108971.
Henriksson, P. J. G., Tran, N., Mohan, C. V., Chan, C. Y., Rodriguez, U. P., Suri, S., … Phillips, M. J. (2017). Indonesian aquaculture futures: Evaluating environmental and socioeconomic potentials and limitations. *Journal of Cleaner Production, 162*, 1482–1490.
Ivanov, D., & Dolgui, A. (2020). Viability of intertwined supply networks: Extending the supply chain resilience angles towards survivability. A position paper motivated by COVID-19 outbreak. *International Journal of Production Research, 58*(10), 2904–2915.
Ivanov, D., & Dolgui, A. (2021). A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *Production Planning & Control, 32*(9), 775–788.
Love, D. C., Nussbaumer, E. M., Harding, J., Gephart, J. A., Anderson, J. L., Asche, F., Stoll, J. S., Thorne-Lyman, A. L., & Bloem, M. W. (2021). Risks shift along seafood supply chains. *Global Food Security, 28*, Article 100476.
Mosallanezhad, B., Hajiaghaei-Keshteli, M., & Triki, C. (2021). Shrimp closed-loop supply chain network design. *Soft Computing, 25*, 7399–7422.
Pathumnakul, S., Piewthongngam, K., and Khamjan, S. (2009) Integrating a shrimp-growth function, farming skills information, and a supply allocation algorithm to manage the shrimp supply chain. *Computers and Electronics in Agriculture* 66, pp. 93–105.
Ragin, C. C. (2008). *Redesigning social inquiry: Fuzzy sets and beyond*. University of Chicago Press.
Stake, R. E. (1995). *The Art of Case Study Research*. Sage Publications.
Tao, F., Zhang, H., Liu, A., & Nee, A. Y. C. (2019). Digital twin in industry: State-of-the-art. *IEEE Transactions on Industrial Informatics, 15*(4), 2405–2415.
Tran, N., Rodriguez, U. P., Chan, C. Y., Phillips, M. J., Mohan, C. V., Henriksson, P. J. G., … Hall, S. J. (2017). Indonesian aquaculture futures: An analysis of fish supply and demand in Indonesia to 2030 and role of aquaculture using the AsiaFish model. *Marine Policy, 79*, 25–32.
Verdouw, C., Tekinerdogan, B., Beulens, A., & Wolfert, S. (2021). Digital twins in smart farming. *Agricultural Systems, 189*, 103046.
Wolfert, S., Ge, L., Verdouw, C., & Bogaardt, M.-J. (2017). Big Data in smart farming – A review. *Agricultural Systems, 153*, 69–80.
Yin, R. K. (2014). *Case Study Research: Design and Methods* (5th ed.). Thousand Oaks, CA: SAGE Publications.

Risk-Aware Capacity Contracting Under Carbon-Adjusted Transport Costs

Kannapha Amaruchkul

National Institute of Development Administration (NIDA), Thailand

ABSTRACT

Minimum-charge provisions are widely used in freight transport contracts to protect carriers against underutilization, but they expose shippers to asymmetric downside risk when demand is uncertain. This paper studies long-term capacity commitment under such contracts for risk-averse transport buyers, explicitly accounting for carbon and time disutilities through per-unit cost parameters. We model a shipper who reserves capacity under a minimum-charge contract and relies on a higher-cost fallback option to satisfy excess demand. Downside risk is captured using Conditional Value-at-Risk (CVaR), which protects against extreme cost realizations arising from both over-reservation in low-demand states and reliance on carbon-intensive fallback transport in high-demand states. We analytically characterize the structure of the optimal contract decision and identify conditions under which economically meaningful risk–capacity trade-offs arise. We show that minimum-charge provisions influence decisions only when they contribute to tail cost outcomes; otherwise, increased risk aversion drives capacity commitments to contractual bounds. A numerical sea–air sourcing case illustrates a clear trade-off between downside risk reduction and regenerative performance. Most environmental and service-related gains are achieved at moderate risk levels, while extreme conservatism yields diminishing returns under rigid contracts. The findings highlight the importance of jointly considering risk attitudes and contract structure when evaluating sustainable capacity commitments under demand uncertainty.

INTRODUCTION

Minimum-charge provisions are widely used in air cargo, maritime shipping, and multimodal transport contracts to protect carriers against underutilization. While such contracts stabilize expected transport costs, they shift downside risk to shippers when realized demand falls short of reserved capacity. This contractual exposure is amplified when environmental externalities and service-related disutility are internalized, as transport buyers face both volatile demand and growing pressure to account for carbon emissions and delivery-time performance. Capacity commitment decisions must therefore balance cost robustness against contractual rigidity and reliance on high-cost fallback modes, particularly when cleaner but slower services compete with faster, more carbon-intensive alternatives.

Prior research on quantity commitment and supply-chain contracting has largely examined reservation and pricing decisions under risk neutrality (e.g., Cachon, 2003). Related work in transport contracting similarly emphasizes pricing and capacity allocation mechanisms while abstracting from decision makers' risk preferences. Explicit modeling of shipper risk aversion has received comparatively limited attention. Existing contributions represent risk attitudes using alternative utility formulations, including mean–entropy objectives (Zhang et al., 2019) and piecewise-linear loss-aversion functions motivated by prospect theory (Wang et al., 2021). A notable exception is Wada et al. (2017), who apply Conditional Value-at-Risk (CVaR) to hedge downside demand risk in air-cargo operations. CVaR is a coherent and computationally tractable downside-risk measure widely used in operations research and finance (Rockafellar and Uryasev, 2000; Gotoh and Takano, 2007), with emerging applications in risk-averse transport network design and hazardous materials routing (Su and Kwon, 2020). Nevertheless, the use of CVaR to evaluate long-term capacity commitment under minimum-charge transport contracts, where contractual rigidity induces asymmetric exposure to low-demand realizations, remains limited.

Beyond demand uncertainty and contractual rigidity, environmental externalities and service-related disutility further complicate transport contracting decisions. Freight emissions vary substantially across modes, motivating carbon accounting and pricing frameworks that internalize environmental costs in operational models (McKinnon; 2010; Mostert and Limbourg;

2016, Arikan et al.; 2013). Related work studies how carbon responsibilities are allocated among supply-chain actors (Gallego and Lenzen; 2005, Rojon et al.; 2021). In parallel, recent studies quantify the value of time and delay costs in freight transport, particularly in air cargo, highlighting their operational relevance (Liu et al.; 2019, Binsuwadan et al.; 2022). However, most transport contract models abstract from carbon externalities and time-related disutility or treat them deterministically, and rarely examine how these cost components interact with downside risk and contractual rigidity.

This paper addresses these gaps by developing a risk-aware capacity contracting framework that explicitly links minimum-charge provisions, downside risk, and carbon- and time-adjusted transport costs. We model a transport buyer's long-term capacity commitment problem under demand uncertainty using CVaR, capturing asymmetric exposure arising from both minimum-charge billing in low-demand states and reliance on high-cost fallback transport in high-demand realizations. Carbon emissions and time-related service penalties are internalized through effective per-unit costs, allowing a unified comparison of cleaner but slower contracted services and faster, more carbon-intensive fallback options. The analysis provides closed-form structural results that characterize (i) when minimum-charge clauses meaningfully shape optimal commitments and (ii) when risk aversion instead drives boundary solutions. A calibrated sea–air case study illustrates how risk preferences and contractual rigidity jointly determine the trade-off between downside risk reduction and regenerative performance. Together, the results clarify the role of contract structure in shaping sustainable capacity commitments under uncertainty.

MODEL FORMULATION

We study a firm that must ship freight repeatedly on a fixed origin--destination lane but does not own transport capacity. The firm acts as a transport buyer, procuring capacity through a combination of long-term contracts and spot-market purchases. Shipment demand is uncertain when long-term decisions are made and is realized only after contracts are in place. The firm's central decision is the amount of capacity to commit under a long-term contract, given that excess demand can be satisfied through a more expensive fallback option. Shipment demand is modeled as a nonnegative random variable D with cumulative distribution function F. A realization of demand is denoted by d.

Two sourcing options are available. The first is a long-term *contracted* service arranged before demand realization, which specifies a unit transport rate, a maximum reservable quantity, and a minimum-charge provision governing billing when realized usage is low. Such provisions, commonly referred to as minimum freight charges or dead-freight clauses, are widely used in maritime, rail, air-freight, and intermodal transport to protect carriers against underutilization. The second option is a spot or *fallback* service procured after demand realization, which typically involves higher and more volatile costs and often corresponds to faster but more carbon-intensive transport modes, such as air freight.

Let $y \in [0, y_u]$ denote the quantity of capacity reserved under the contract, where y_u reflects contractual or operational limits. Actual usage of contracted capacity is $min\{d, y\}$, but billing follows a minimum-charge rule,

$$Q(y, d) = max\{\gamma y, min\{d, y\}\}$$

where $\gamma \in [0,1]$ is the minimum-charge fraction. Higher values of γ reduce the carrier's exposure to underutilization but amplify the buyer's downside cost risk in low-demand states. The reservation decision y is made before demand is realized, while spot sourcing decisions are made after observing d.

Let r_B and r_S denote the unit freight rates of the contracted and spot services, respectively, with $r_S \geq r_B$. Beyond freight charges, shipments incur carbon externalities and time-related disutility, which are increasingly internalized through sustainability targets, carbon pricing, and service-level requirements. Let τ_i denote the transit time of source $i \in \{B, S\}$ and let $\tilde{\eta}$ represent the buyer's value of time per unit shipped, yielding a time-related cost $\eta_i^T = \tilde{\eta}\, \tau_i$. Carbon emissions are monetized using an effective carbon price p^C, giving a per-unit carbon cost $\eta_i^C = p^C\, f_i^C$, where f_i^C is the emission factor associated with transport mode i. The total non-freight cost is the time-

related disutility and carbon externalities, $\eta_i = \eta_i^T + \eta_i^C$, and the effective unit transport cost is therefore

$$r_i^a = r_i + \eta_i.$$

The effective cost gap between spot and contracted services is

$$\Delta = r_S^a - r_B^a$$

which captures both monetary and non-freight cost-adjusted differences. The effective cost gap Δ summarizes all monetary, environmental, and service-related advantages of contracted transport relative to fallback sourcing.

Time- and carbon-related cost components are modeled as linear per-unit costs, reflecting standard valuation practices in freight transport. Given reservation level y and realized demand d, the buyer's total transport cost is

$$L(y,d) = r_B Q(y,d) + \eta_B \min(d,y) + r_S^a (d-y)^+$$

where the first term is the contracted freight cost determined by the minimum-charge billing rule, the second term is the contracted time cost incurred on actual usage of reserved capacity, and the last term is the fallback cost, including both freight and non-freight components. This piecewise structure partitions demand into three economically distinct regions:

$$L(y,d) = \begin{cases} \eta_B d + r_B \gamma y, & d \le \gamma y \\ (r_B + \eta_B) d, & \gamma y < d \le y \\ (r_S + \eta_S) d - \Delta y, & d > y. \end{cases}$$

When demand is very low (i), minimum-charge billing applies and the buyer pays for unused contracted capacity. For intermediate demand levels (ii), all shipments are served under the contract, and the contracted capacity is fully utilized. When demand exceeds the reserved capacity (iii), the excess must be sourced from the spot market, exposing the buyer to high freight, time, and carbon costs.

While long-term contracts stabilize expected transport costs, minimum-charge provisions can generate substantial losses in low-demand states, whereas insufficient commitments expose the buyer to costly fallback sourcing in high-demand realizations. To account for aversion to such downside outcomes, the buyer evaluates capacity commitments using CVaR.

Fix a confidence level $\beta \in [0,1)$, where $\beta = 0$ corresponds to the risk-neutral case. The β-Value-at-Risk (VaR) is defined as the β-quantile of the loss (cost) distribution. For continuous L, the associated CvaR admits the interpretation: $CVaR_\beta(L) = E[L \mid L \ge VaR_\beta(L)]$, that is, the expected cost shortfall in the worst $1-\beta$ fraction of realizations. The buyer's risk-aware reservation problem is

$$min\left\{ CVaR_\beta\big(L(y,D)\big) : 0 \le y \le y_u \right\}.$$

This formulation emphasizes protection against extreme cost realizations rather than average performance, penalizing large shortfalls arising from minimum-charge payments in low-demand states and from expensive fallback sourcing in high-demand states.

ANALYSIS

We analyze the buyer's CVaR minimization problem and characterize the structure of the optimal contracted quantity as a function of risk preferences and contract parameters. Analytical proofs rely standard arguments based on the Rockafellar-Uryasev reformulation and are omitted due to space limitations. Hereafter, we maintain the key assumption $\Delta > 0$, implying that fallback sourcing is strictly more expensive than contracted capacity in all realizations. This condition holds in many practical settings, including sea contracts with air freight fallback, rail contracts with road fallback, and air-freight BSA contracts using direct flights with ad-hoc fallback via longer-transit connections. (For rail–road sourcing, lower freight and emission costs may be offset by longer transit times on non–high-speed cargo rail; hence $\Delta > 0$ is an empirical condition.) The assumption ensures that long-term contracting provides a cost advantage in expectation while exposing the buyer to downside risk through minimum-charge provisions.

Proposition 1 (Interior vs. boundary structure under CVaR-based contracting).
Let $q_\beta := F^{-1}(\beta)$ denote the β-quantile of demand and assume $\Delta > 0$.

(Interior regime.) If, at the optimum, the VaR lies in the minimum-charge region, i.e., $q_\beta \leq \gamma\, y^*$*, then the problem admits an interior optimal contract level* $y^* > 0$ *satisfying the first-order condition*

$$r_B\gamma(F(\gamma y^*) - \beta) = \Delta\ (1 - F(y^*))$$

and the associated VaR is

$$\alpha_\beta(y^*) = r_B y^* + \eta_B q_\beta.$$

(Boundary regime.) If the VaR lies outside the minimum-charge region at the optimum, i.e., $q_\beta \geq \gamma\, y^*$*, then the CVaR objective is strictly decreasing in* y *and the optimal solution is attained at the upper bound:* $y^* = y_u$*.*

Proposition 1 shows that economically meaningful risk–capacity trade-offs arise only when minimum-charge exposure contributes to the upper tail of the cost distribution. In the interior regime, where the VaR lies within the minimum-charge region, the optimal contract level balances marginal downside exposure from minimum-charge billing against the reduction in tail losses from reliance on costly fallback transport. In contrast, when the VaR lies outside the minimum-charge region, minimum-charge payments no longer affect tail realizations. In this boundary regime, increasing contracted capacity strictly reduces CVaR by displacing high-cost fallback usage, and a risk-averse buyer optimally selects the maximum feasible commitment. Proposition 1 therefore implies that minimum-charge provisions influence capacity decisions only when they actively shape tail outcomes; otherwise, increased risk aversion masks contractual rigidity by pushing solutions to contractual bounds. This distinction clarifies when contractual rigidity creates genuine insurance trade-offs and when it merely induces conservative over-commitment.

Proposition 2 (Comparative statics of the optimal contract level). *Suppose that the optimal solution* y^* *is interior and that VaR lies in the minimum-charge region, i.e.,* $q_\beta \leq \gamma y^*$*. Then the optimal contracted quantity* y^* *is increasing in the buyer's risk level* β *and in the effective cost gap between spot and contracted services,* Δ*. Conversely,* y^* *is decreasing in the minimum-charge fraction* γ*.*

Proposition 2 characterizes how risk preferences and contract parameters jointly shape capacity commitments when downside risk from minimum-charge billing is binding in the tail. A higher risk level βincreases the weight placed on adverse demand realizations, inducing the buyer to reserve more capacity in advance in order to reduce exposure to costly fallback sourcing. Similarly, a larger effective cost gap Δ strengthens the incentive to hedge against high-cost spot usage, leading to higher contracted quantities. In contrast, a higher minimum-charge fraction γ amplifies the downside cost of over-reservation in low-demand states, weakening the insurance value of advance commitments and reducing the optimal contract level. Together, these comparative statics show that risk aversion and relative cost advantages promote capacity reservation, while contractual rigidity counteracts this effect by penalizing unused capacity. These monotonicity results hold only in the interior regime; once the boundary regime applies, further changes in risk preferences or cost parameters no longer affect the optimal reservation level.

AN ILLUSTRATIVE SEA–AIR SOURCING CASE UNDER RISK AVERSION

Case setting and experimental design

We consider a case study adapted from a lenses manufacturing firm shipping products from China to Malaysia. Each unit weighs 0.024 kg, with average monthly demand of 10,297 units (247.12 kg). Monthly demand follows a Gamma distribution with coefficient of variation approximately 0.6. This choice is motivated by three considerations: it provides a good fit to the firm's historical demand data, it offers sufficient flexibility to capture varying degrees of right skewness and dispersion, and it satisfies the analytical requirement that demand be supported on the nonnegative real line.

Two transport options are available. The contracted option uses deep-sea shipping with the upper bound $y_u = 963$ kg, while excess demand is served by ad-hoc air freight. Freight rates are $r_B =$ 1.50 USD/kg for sea and $r_S =$ 3.83 USD/kg for air. Following the OECD carbon-pricing benchmarks, we set the carbon price to 30 EUR per tonne of CO_2, representing a conservative low-end reference level for carbon costs (OECD, 2023). This implies per-unit carbon costs of approximately $\eta_B^C = 0.00133$USD/kg for sea transport and $\eta_S^C = 0.075$USD/kg for air transport, using a conversion rate of 1 EUR = 1.16 USD, sea- and air-freight emission factors of 8 and 602 g CO_2/tonne-km, respectively, as reported by Arikan et al (2013), and transport distances of 4,776 km (sea) and 3,580 km (air). Time-related disutility are incorporated using shipper's values of time and lead times of four weeks for sea transport and one week for air transport. This yields per-unit time costs of $\eta_B^T = 0.037$ USD/kg for sea and $\eta_S^T = 1.114$ USD/kg for air, based on values of time of 0.055 USD/tonne-hour for sea and 6.630 USD/tonne-hour for air (Binsuwadan, 2022), converted to per-kg costs using shipment weights and transit times. The total per-unit non-freight cost is given by $\eta_i = \eta_i^C + \eta_i^T$, resulting in $\eta_B = 0.038$ USD/kg for sea and $\eta_S = 1.189$ USD/kg for air. Accordingly, the effective cost gap between ad-hoc and contracted transport is

$$\Delta = (r_S + \eta_S) - (r_B + \eta_B) = 5.01884 - 1.53829 = 3.48055 > 0,$$

indicating that the fallback air option is substantially more expensive once carbon and time cost components are internalized. These values are intended to be illustrative rather than predictive, and are chosen to reflect conservative carbon-pricing benchmarks.

The buyer's risk preference varies over $\beta \in \{0.50, 0.51, \ldots 0.99\}$, and the minimum-charge fraction is set to $\gamma \in \{0.4, 0.5, 0.6\}$, the optimal contracted quantity $y^*(\beta, \gamma)$ is obtained analytically from Proposition 1; under rigid contracts, the boundary condition becomes active at moderate-to-high risk levels, leading to early saturation at y_u. Proposition 2 establishes that $y^*(\beta, \gamma)$ is non-decreasing in the buyer's risk level β, for a fixed γ, a monotonicity that is confirmed numerically in this case study.

To illustrate the trade-off between downside risk and environmental performance, we construct a risk–regeneration frontier analogous to an efficient frontier in portfolio analysis. Risk is measured by CVaR_β of total cost, while regenerative performance is defined as the expected avoided generalized non-freight cost relative to an all-air benchmark. For reservation level y and the realized demand d, the realized generalized non-freight cost equals $\tilde{E}(y, d) = \eta_B \min(d, y) + \eta_S (d - y)^+$. The corresponding regenerative performance, measured relative to an all-air benchmark, is $\tilde{G}(y, d) = \eta_S d - \tilde{E}(y, d) = (\eta_S - \eta_B)\min(d, y)$, which captures the avoid carbon and time-related burden from serving shipments under the contracted service rather than the fallback option. For comparability across risk preferences, regenerative performance is reported as a percentage of the maximum attainable expected gain, achieved when $y = y_u$.

$$\frac{E[\tilde{G}(y^*, D)]}{E[\tilde{G}(y_u, D)]} \times 100$$

Tracing this relationship yields the risk–regeneration frontier shown in Figure 1.

Discussion

The results reveal a clear trade-off between downside risk exposure and regenerative performance, and clarify the mechanisms through which risk aversion and contractual rigidity shape this relationship. Panel (a) shows that regenerative performances increase as the decision maker becomes more risk-averse, but at a diminishing rate. Most environmental and service-related benefits are realized at moderate levels of risk aversion, while further reductions in tail cost exposure generate only marginal additional regenerative gains. This concavity indicates that increasing risk aversion primarily reallocates cost exposure across extreme demand realizations rather than inducing proportionate changes in sourcing decisions.

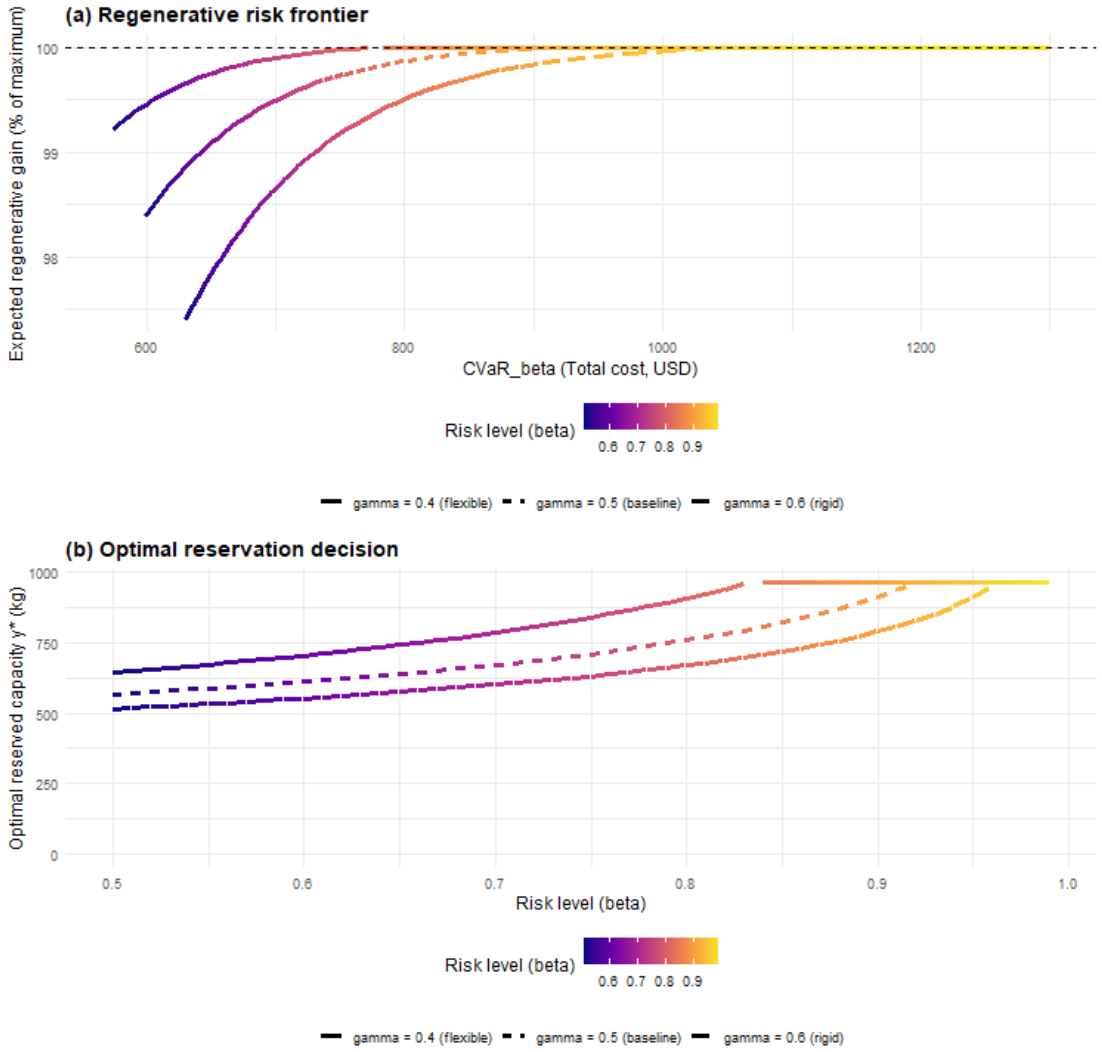


Figure 2: Risk aversion, downside risk, and regenerative performance

Panel (b) explains the mechanism underlying this frontier. Higher risk aversion induces larger capacity reservations under the contract, which reduces reliance on high-cost fallback option with higher generalized non-freight costs in high-demand states. However, as the reservation level approaches the contractual upper bound, the adjustment channel weakens. Under rigid minimum-charge provisions, sufficiently strong risk aversion pushes the optimal reservation to the contractual boundary, beyond which additional risk aversion no longer induces operational adjustment. In this regime, risk protection operates through over-commitment rather than through improved allocation efficiency. This boundary behavior is consistent with the structural result in Proposition 2 and clarifies why regenerative performances saturate at high confidence levels.

Contract rigidity, captured by the minimum-charge fraction γ, plays a decisive role in shaping the trade-off between downside risk exposure and regenerative performance. Flexible contracts allow reservation levels to respond smoothly to risk preferences and achieve comparable regenerative outcomes at substantially lower CVaR exposure. In contrast, rigid contracts require much higher risk tolerance to approach the same performance ceiling, pushing optimal reservations toward boundary solutions near contractual capacity limits. This behavior reflects the dominance of downside-risk penalties until feasibility constraints bind. From a system perspective, extreme conservatism under rigid contracts is therefore inefficient, increasing cost exposure without delivering commensurate environmental or service improvements. These results highlight the importance of jointly considering risk attitudes and contract structure when assessing the sustainability of long-term capacity commitments. These findings emphasize that

sustainability outcomes in capacity contracting depend not only on cost internalization, but also on how downside risk is contractually structured.

Managerial and policy implications

Interpreted within the scope of the modeled setting and numerical experiments, the results yield the following managerial and policy insights. Risk aversion and contract structure emerge as joint decision levers and should be evaluated together rather than through conservative risk settings alone. Moderate downside-risk aversion increases contracted capacity and reduces reliance on high-cost, carbon-intensive fallback transport, while further increases yield diminishing operational and environmental gains once reservation levels approach contractual bounds. Rigid minimum-charge provisions are particularly constraining, as they limit the responsiveness of capacity decisions and push solutions toward boundary outcomes while amplifying cost exposure. For shippers and freight forwarders, the analysis highlights the value of negotiating greater contractual flexibility—such as lower minimum-charge fractions or partial usage-based components—over relying exclusively on higher risk-protection parameters. Risk-aware decision tools are therefore most informative when used to identify balanced operating regions that capture robustness benefits without sacrificing contractual flexibility.

From a policy perspective, the findings indicate that sustainability outcomes in freight transport depend not only on the pricing of environmental externalities but also on the structure of long-term contracts and the allocation of downside risk. Contractual practices that favor rigid minimum-charge arrangements can interact with risk aversion in ways that encourage over-reservation and inefficient hedging, thereby diluting the effectiveness of cleaner transport options under demand uncertainty. Policy frameworks or industry guidelines that facilitate more flexible contracting—such as shared-risk mechanisms or adaptive capacity commitments—may therefore complement carbon pricing by improving firms' ability to internalize carbon and time-related externalities. More broadly, the results emphasize the importance of accounting for interactions between risk attitudes and contractual constraints when evaluating system-level cost, reliability, and environmental performance.

CONCLUSION

This paper studied long-term capacity commitment under minimum-charge transport contracts when shippers are risk-averse and carbon externalities and time-related disutility are internalized. Using a CVaR-based formulation, the analysis clarifies how downside risk from demand uncertainty interacts with contractual rigidity and reliance on high-cost fallback transport. The results show that risk aversion increases contracted capacity only when minimum-charge provisions contribute to tail outcomes; otherwise, greater risk aversion drives commitments to contractual bounds without improving operational performance.

The analytical characterization identifies an interior regime in which minimum-charge exposure shapes the upper tail of the cost distribution and economically meaningful risk–capacity trade-offs arise. Comparative statics show that higher risk aversion and larger effective cost gaps between contracted and fallback services promote advance reservation, while greater minimum-charge rigidity weakens this incentive by amplifying the downside cost of over-reservation. A numerical sea–air case illustrates that most regenerative and service-related gains are achieved at moderate risk levels, with diminishing returns under rigid contracts as reservation levels approach capacity limits.

Several extensions merit further study. These include strategic interactions among multiple carriers and shippers, dynamic settings with repeated contracting and learning, and asymmetric information regarding demand and risk attitudes. Such extensions would broaden the applicability of the framework to competitive and informationally constrained transport markets.

REFERENCES

Arıkan, E., Fichtinger, J. and Ries, J. M. (2013). Impact of transportation lead-time variability on the economic and environmental performance of inventory systems, International Journal of Production Economics 145: 596-603.

Binsuwadan, J., de Jong, G., Batley, R. and Wheat, P. (2022). The value of travel time savings in freight transport: A meta-analysis, Transportation 49(4): 1183-1209.

Cachon, G. P. (2003). Supply chain coordination with contracts. Handbooks in Operations Research and Management Science, 11, 227–339.

Gallego, B. and Lenzen, M. (2005). A consistent input-output formulation of shared producer and consumer responsibility, Economic Systems Research 17(4): 365-391.

Gotoh, J. and Takano, Y. (2007). Newsvendor solutions via conditional value-at-risk minimization, European Journal of Operational Research 179(1): 80-96.

Liu, Y., Yin, M. and Hansen, M. (2019). Economic costs of air cargo flight delays related to late package deliveries, Transportation Research Part E 125: 388-401.

McKinnon, A. (2010). Green Logistics: Improving the Environmental Sustainability of Logistics, Kogan Page.

Mostert, M. and Limbourg, S. (2016). External costs as competitiveness factors for freight transport – a state of the art, Transport Reviews 36(6): 692-712.

OECD (2023). Effective Carbon Rates 2023: Pricing Greenhouse Gas Emissions through Taxes and Emissions Trading, OECD Publishing, Paris.

Rockafellar, R. T. and Uryasev, S. (2000). Optimization of conditional value-at-risk, Journal of Risk 2(3): 21-41.

Rojon, I., Lazarou, N.-J., Rehmatulla, N. and Smith, T. (2021). The impacts of carbon pricing on maritime transport costs and their implications for developing economies, Marine Policy 132: 104653.

Su, L. and Kwon, C. (2020). Risk-averse network design with behavioral conditional value-at-risk for hazardous materials transportation, Transportation Science 54(1): 184-203.

Wada, M., Delgado, F. and Pagnoncelli, B. (2017). A risk averse approach to the capacity allocation problem in the airline cargo industry, Journal of the Operational Research Society 68(6): 643-651.

Wang, K. Y., Wen, Y., Yip, T. L. and Fan, Z. (2021). Carrier-shipper risk management and coordination in the presence of spot freight market, Transportation Research Part E: Logistics and Transportation Review 149: 102287.

Zhang, W., Wang, X. and Yang, K. (2019). Incentive contract design for the water-rail-road intermodal transportation with travel time uncertainty: A Stackelberg game approach, Entropy 21(2): 161.

LOGISTICS CONNECTIVITY

Socially Responsible Consumption as a Competing Logic for Last Mile Delivery: Case of Kerala

Mohita Gangwar Sharma

Indian Institute of Management Sirmaur, India

ABSTRACT

Purpose

The research illustrates how the Last mile logistics of various socially sensitive products can have distinctive impacts on different stakeholders. It gets impacted by the considerations of the context and an altered model is adopted. Stemming from the institutional theory, this delivery design get influenced by normative and mimetic pressures and social acceptance. The purpose of this paper is to develop a deeper insight into such deliveries and how they can be managed.

Design/methodology/approach

The research adopts the teleological perspective for the institutional competing logic theory and framework to elucidate the logical implementation of the model for distribution of liquor. This study adopts case methodology, which includes in-depth interviews with the stakeholders, which has been complemented with secondary data analysis of management reports, website and news items.

Findings

The Digitization of retail has got an impetus during and after Covid. Reflecting on the phenomenon from the institutional theory lens, the socially responsible consumption holistically has been analyzed. In this study the societal perspective towards liquor, effect on health and the taxation provides an umbrella of context to design the last mile delivery design. Regular door step delivery can negatively impact the social values and so altered design is adopted. The product and the social nature of the product can dictate the type of last mile delivery.

Originality/value

The original contribution lies in altering the traditional e-retail based on the context. It illustrates how retails chains respond to the institutional competing logic and influenced by legal, social and cultural aspects to define responsible consumption which have not been discussed in literature. It also highlights that a paradoxical situation arises between the normative and mimetic pressures, leading to performing and belonging paradox.

Research limitations

Covid transformed the last mile delivery for diverse products but this single context specific case study is exploratory in nature and has inherent biases.

Practical implications

Similar products need to be designed according to the normative forces of the institution.

Social implications

This study provides a different lens to the social sustainability angle of last mile delivery and consider the social context of the product for last mile delivery design..

Originality/value

This institutional embedded social sustainability has not been researched in the literature. Methodologically, the stakeholder, institutional and paradox theory has been combined for the analysis

INTRODUCTION

In the past decade, digitization, Omni-channel development, retail innovation has absolutely transformed the retail sector landscape leading to the growth and reorientation of the last mile delivery. This further got an impetus during and post-Covid (Olsson et.al, 2021) and has led to innovative delivery models. These include unattended home delivery, parcel delivery, out of home delivery (OOH), tokenized delivery etc.

But these deliveries are not stand alone but deeply embedded in the social context of the delivery and the product. This linkage is paramount. This study looks at last mile delivery for liquor retail embedded in territories to create an alternative discourse on the topic. Rooted in an exemplar case study based in Southern state of India this study stimulates discourse into the linkages between these research streams.

This study focusses on the liquor last mile distribution to elucidate the impact of territoriality and competing logic to configure last mile delivery for responsible consumption. It also explores a varied perspective to responsible consumption as well.

In this research, the competing logic of responsible consumption and social norms and practices provides an alternative perspective to digitization and last mile delivery through use of tokens. Through this study an inter-disciplinary conversation can start to create frameworks around last mile delivery, socially responsible consumption, and institutional theory.

This research addresses the following research question:

R1: Why token system is appropriate for liquor delivery in the given context?

R2: How do external pressure influence the last mile delivery of socially sensitive products to enhance credibility and social acceptance

R3: Which pressures are more dominant in the last mile delivery of socially sensitive products?

The broad objective is to use an illustrative case study within the context of the environment, to depict the importance of responsible consumption in Last Mile delivery.

The institutional theory lens has been adopted. Institutions matter and are paramount, unchallenging structures. These include the rules, conventions and codes of behavior. It also defines th preferences and power in the society (Powell and Di Maggio, 1991). Institutions impact the behavior and decisions of the actors and stakeholders. Institutional Theory is an established theory investigating the forces that exist for the success of an organization. It refers to the interplay between the external economic, poltical, cultural, social, legal, regulatory environment and the legitimate practices adopted for norms of the institutional environment for decision making (Bruntonetal.,2010; Hirsch,1975; Laietal., 2006; Roy,1997 Jennings and Zandbergen,1995; North,1990).

In the subsequent article, the relevant literature on Socially responsible consumption, Territorial, digitization, last mile delivery models have been reviewed. Next, the methodological considerations for the case study followed by the stakeholder analysis and mapping it to the institutional theory framework The findings based on institutional theory competing logic. The paper concludes with the major contribution and limitations.

SOCIALLY RESPONSIBLE CONSUMPTION:

The discussion on Socially Responsible Consumption draws from the Socially conscious consumer – 'the consumer-citizen concept'.individuals concerned not only with their personal satisfaction, but also with societal (environmental) wellbeing (Anderson and Cunningham, 1972) and Socially

responsible consumer 'is the one who purchases products and services perceived to have a positive (or less negative) influence on the environment or who uses his/her purchasing power to express current social concerns' (Roberts, 1999). Webster (1975) defined the socially conscious consumer as "a consumer who takes into account the public consequences of his or her private consumption or who attempts to use his or her purchasing power to bring about social change". Further, this is a combination of environmental and ethical consumption which include the dimensions related to consumers socio-demographic and characteristics of the values (Adams, Raisborough, 2010). The core of ethical consumption is "the conscious and deliberate decision to make certain consumption choices due to personal moral beliefs and values" (Crane and Matten (2004)). Interestingly there is an angle of Food Citizenship and talk about signaling socially responsible consumption amongst millennials (De Tavernier, 2012 ; Johnson & Chattaraman, 2020) . Dagilienė et. al 2022 observe a more passive and responsive role of retailing chains because of the inherent trade-off between revenue growth and sustainable consumption. In a comprehensive review study on the socially responsible consumption, the considerations have been economic, information, sense of effort, lack of feelings and the social factors and supply aspects (falcao and Roseira, 2022) This study focusses on social factors in last mile supply.

The Last Mile delivery:

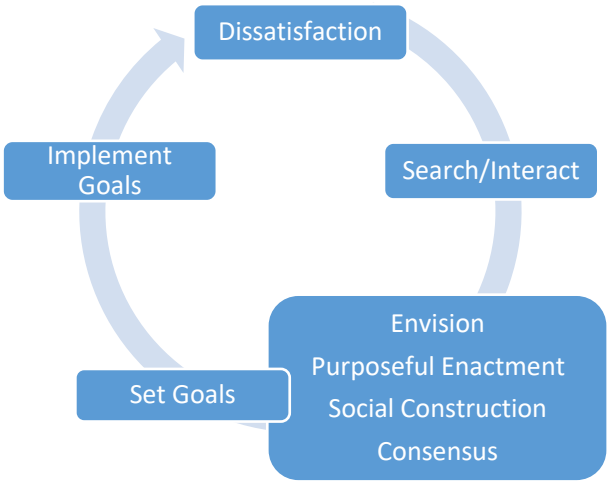
The Last mile delivery happens in time and space. Some previous studies have look at the problem from the reception box or delivery box (Punakivi et. al, 2001). Recent years there has been a huge focus on last mile delivery which has got impetus by massive digitization, more so driven by the pandemic (Puram et.al, 2022). Digitisation post Covid is the biggest transformation that has happened in the retail sector. Through a case study Hagberg and Jonson, 2022, has analysed the process of digitization for IKEA. Hanninen et. Al 2021 study looks at theorizing the process of digitization. Focussing on retail sector, studies have analysed for the retailers and the consumers perspective (Frasquet et. Al, 2021).

There has been a holistic study of literature by Lim et.al 2018, considering the process from multiple stakeholders and also proposes different frameworks (Risberg & Jafari, 2022). It is the most expensive activity in the delivery value chain almost contributing to 28% of the cost. It can be classified into two broad categories 'home delivery (HD)' and 'out of home delivery (OOH)' or 'delivery via collection points'. It is believed that OOH last mile delivery cost is almost 60% less than the HD (Punakavi et.al, 2001; Weltevreden, 2008; Boysen et. al, 2021). Click and Collect, pick up point, Parcel Lockers are some variations of OOH delivery. Further, innovative solutions are being used that draw on the logistics resources of the end consumers for parcel deliveries which include providing Last mile as aservice (LMaaS) (Correira et. Al, 2012) and also includes Self-Collection by Automated Parcel Station. This study proposes a token based pickup from the Shop or deliver partners. The Token system started during Covid to avoid rush and maintain social distancing but has continued because it also reduces the waiting time of the customer thereby making the system efficient.

There have been research on reconfiguring last mile delivery and options propounded as crowd sourced last mile delivery with parcel lockers (Lim et. al, 2019; Ghaderi et. al, 2022). Further the variables like customer preferences , costs have been considered for designing the last mile delivery (Merkert et. al,2022; Peppel & Spinler, 2022).

Linking Last mile delivery, Socially responsible consumption from the Social context:

No study has been done in this area and this research gap has been bridged by this study. It tries to provide a linkage between them.
The term theological comes from two words: 'telos' meaning 'goals' and 'logos' means 'science'. Thus it is a study wherein the actions are based on the goals and the consequences of the actions. This ensures that the actions are good and are based on a good purpose.



This study considers the teleological approach, wherein it is dictated by the philosophy of the ends. The choices are dictated by the moral consequences of a decision or choice. This approach becomes important in a multi stakeholder environment wherein the final decision and the business model are directed by the consequences of the action on the various stakeholders.

METHODOLOGY

The study adopts qualitative case method of analysis based on an exemplar case public sector organization. Given the exploratory nature of the research as the dominant and competing logic and the strategic choice of the action of the organization need to be studied it has been found appropriate. As has been explained by Yin (1989), to answer the "why" the observed phenomena occur, and the context is contemporary. The exemplar organization identified provides insights for theorizing and analyzing (Patton, 1990). There is an opposite school of thought which counter the method based on limited ability towards generisation but support the efficacy of the same. Digitization of the last mile delivery process of BEVCO in Kerala, India provided the context and the data was collected both primary and secondary and e and the interaction with different employees and customers.

The profile of the various stakeholders which participated in the semi structured interview are as follows:

Industry	Age	Experience	Gender	Perspective
Company IT 1	60	>30 years	Male	IT Manager
Expert 2	53	>25 years	Male	IT Manager.
Expert 3	38	>12 years	Female	Business development
Expert 4	42	>15 years	Male	Marketing Manager
Expert 5	49	> 20 years	Male	Company Secretary
Customers Expert 1	24	>Unemployed	Male	Young
Customers Expert 2	65	>30years	Male	Matured
Customers Expert 3	34	>12 years	Male	Family with young kids
Customers Expert 4	55	>10 years	Male	Family
Customers Expert 5	72	>40 years	Male	Grandfather

Delivery Partner Legal Expert Citizen Awareness Member	32 45 54	>8 years >20 years >30 years	Male Male Female	Partner incentives Legal angle Social angle
Coordinator	53	>25 years	Female	Academician

CONTEXT: THE LIQUOR DELIVERY IN KERELA

The state has almost 33.4 million populations 860 persons/sq.km population density and US $110 billion gross state domestic product (GSDP) at current prices. The state is unique with highest literacy and good sex ratio (Elias. 2019). This makes the state socially and societally conscious led by a Communist Government. Incorporated in 1984, BEVCO is a PSU (Public Sector Undertaking) owned by the State Government of Kerala, the most literate state in the Indian Union. Flagellation of arrack shops and presence of an informal supply chain for spurious liquor that caused serious health hazards in the state led to the formal institution of the Company. The government had by law, endowed the entire responsibility of the purchase, sale, and distribution of 5 variants of liquor-based beverages to the public, solely to the company. BEVCO also had a virtual monopoly over the retailing of liquor-based beverages in the state, with its control over 269 outlets, spread over the 14 districts in the state cementing a homogenous customer experience at the Point-of-Sale in the retail shops. Warehousing infrastructure spanned 26 facilities, with 6 regional offices that operated under the headquarters at Thiruvananthapuram. Kerala was the state with the reputation of having the highest alcohol consumption rate per person, at almost 8.3 litres per person in a year (Panickar, 2015) . Kerala is also the state that has the highest sales tax on liquor in the country- 254%. Even though the Government portrays this as a move to wean and discourage the consumption of liquor and inch closer towards Prohibition.

During Covid the organization started with a Technology enabled App called BEVQ which provided a token based delivery model. This was established because during Covid sale of liquor through brick and mortar shops was stalled.

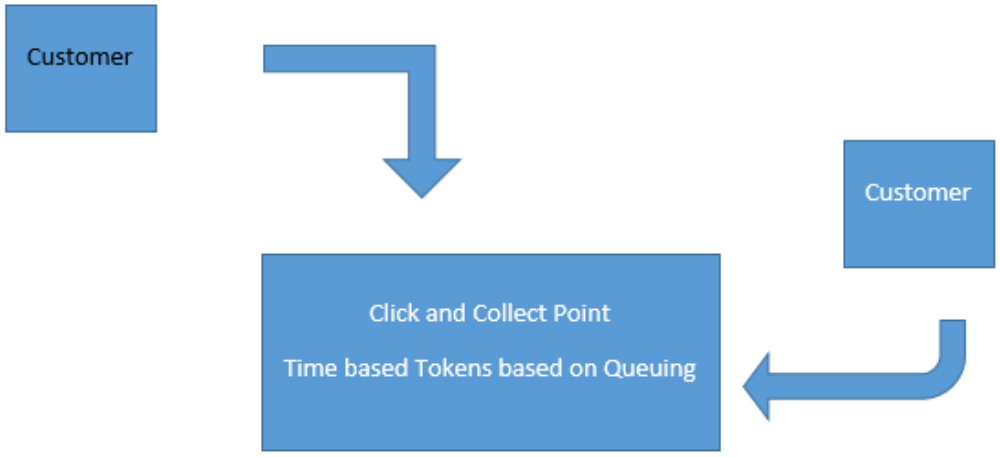


Fig. 1: Token based last mile delivery

In an attempt towards socially responsible consumption this model has been implemented for the liquor distribution. This was focused on restrained consumption (Fig.1). It also incorporates the restriction to the quantity that can be transported by an individual as per the law.

Frame of reference

This study adopts three theories for the analysis viz. Stakeholder analysis, Institutional theory and Paradox theory.

Stakeholder Theory

The Stakeholder theory has been propounded by Freeman (1984) wherein stakeholder has been defined as "an individual or group who can influence the achievement of the organizational goals by theat organization". Further studies mention that the stakeholders can be persons, groups, institutions, society and the environment.The classification based on the three properties is widely accepted (Mitchell. Agle &Wood, 1997).
Power is the influence that the stakeholder has on an organization to enforce his vision.
Legitimacy provides the approval for the requested actions as appropriate and necessary.
Urgency gives the temporal perspective wherein the organizations requirements are urgent and needs attention.

Institutional Theory

The theory underpinning the analysis is the Institutional Theory. Institutional theory has been selected to rigorously analyse the influence of external pressures on the organisational practice. Strategy and Operations get influenced by the institutional logic.

The definition of Institution as given by Scott (1995):

[..] social structures that have attained a high degree of resilience[..] [they] are composed of cultural-cognitive, normative and regulative elements that together with associated activities and resources, provide stability and meaning to social life.

Institutional logics 'represent frames of reference that condition actors' choices for sense-making and motivations (Thornton et al., 2012, p. 2). The institutional theory has been taken from the organisational sociology angle. It propounds that the business decisions are not always targeted for financial benefit maximization, but also consider norms, beliefs, regulations of the diverse stakeholders. They need legitimacy as socially appropriate.

As explained by North (1990), they constrain actor's behavior with an objective of channeling it in a direction, to create a stable structure. Pierson (2000) has mentioned about the increasing returns derived from the existence of an institution. There are three pillars of institutions: regulatory, normative and cognitive institutions. Regulatory looks at the legal and government directives, normative looks at the organizational norms and the cognitive looks at the values and traditions which relates to the culture..The drivers that have been established in the Institutional theory are Coercive, Normative and Mimetic (DiMaggioandPowell,1983; Scott, 2007). The Coercive drivers are due to the power of influence. The Normative drivers is embedded in what the organization and individual be doing, given the social fabric and social and obligation. It also ensures the perception of conformance to legal requirements. Mimetic drivers are essentially coming from mimicking the actions of the successful competitors to succeed (DiMaggioandPowell,1983,1991; Scott, 2007). The applicability of institutional theory in supply chain comprising of many organizations has provided explanations to questions regarding adoption of certain practices with different logics (Berrone et al., 2010; Meyer and Rowan, 1977;Williams et. al, 2009;; Glover et. al 2014).

While analyzing the case organization it is proposed that the focus should be on the role of regulation, conformance and social obligation and pressures.

Paradox theory

Paradox studies adopt an alternative approach to tensions, exploring how organizations
can attend to competing demands simultaneously (Smith and Lewis, 2011). Choosing among competing tensions might aid short-term performance. However, a paradox perspective argues

that long-term sustainability requires continuous efforts to meet multiple, divergent demands (Cameron, 1986; Lewis, 2000).

There are four types of paradox as classified in the Organization (Smith and Lewis, 2011):

Learning: This emanates from the fact of building upon the past and in some cases, destroying the past and moving to the future. This arises because of the efforts required to adjust, renew, change and innovate leads to tensions.

Belonging: The tension emanating from the individual and collective and between competing values, roles and individuals.

Performing: Plurality fosters multiple goals as stakeholders have divergent organizational goals.

Organizing: Structuring and leading fosters competition and collaboration. Fixation and distribution of organizational boundaries and authority.

ANALYSIS

Considering the intended teleological approach can explain the change process. As mentioned in the Stakeholder theory (Post, 2002), the main challenge is to convince the various stakeholders of their mutual interest.. In the previous studies, the responsible consumption has focused on energy efficiency, green and reduced social harm but in this study the societal perspective towards liquor, effect on health and the taxation provides an umbrella of context for responsible consumption.

The first step in the analysis has been to conduct a stakeholder analysis who have stakes in the organisation (Freeman and McVea, 2001). The identification of the stakeholders and their interest has been depicted in Table 1. Major stakeholders are the alcohol suppliers, state government, citizens, tax authorities, law makers, delivery logistics partners, hotels and Customers have been analysed in terms of the Power, Legitimacy and Urgency to better understand them (Delmas, 2002) as given in Table 2.

Table 1: Stakeholders interest

S. No.	Stakeholder	Stakeholders interest
1	State Government	Socially and Healthy people but also money through tax
2.	Management	Implement government mandate
3.	Alcohol suppliers	Higher sale
4.	Tax authorities	Higher tax collection means higher sales
5.	Citizens body	Socially responsible society
6.	Law makers	Regulation on liquor consumption
7.	logistics partners	Earn revenue through door step delivery
8.	Hotels	Enhanced consumption at hotels
9.	Customers	Availability and convenience
10.	Families	Prefer abstinence

Table 2: Stakeholder mapping

S. No.	Stakeholder	Power	Legitimacy	Urgency
1	State Government	H	H	M
2.	Management	M	H	H
3.	Alcohol suppliers	L	L	H
4.	Tax authorities	H	H	H
5.	Citizens body	M	H	M
6.	Law makers	H	H	M

7.	logistics partners	M	M	M
8.	Hotels	L	M	H
9.	Customers	M	M	H
10.	Families	L	M	M

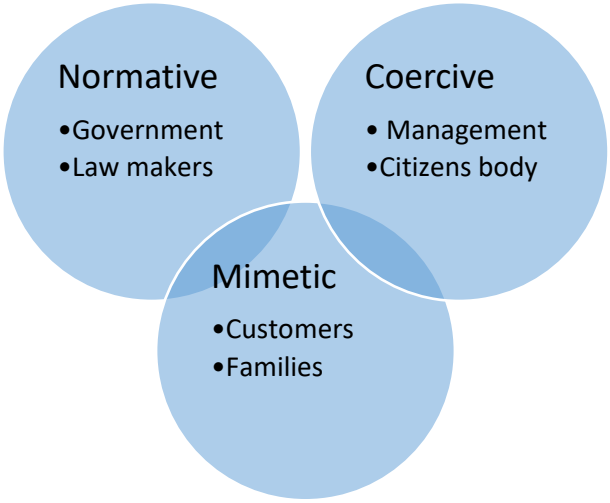


Fig. 2 Linking the Stakeholders to the Institutional drivers

Table 3: Institution theory analysis

Institution Logic	Illicit liquor is a major challenge. High drinking is a threat to health and also to the society. The mandate of the organization is to provide genuine liquor to the people. The Tax revenue is the highest for the state.
Normative Drivers	The Abkari law regulates that more than 3 litres of liquor cannot be held and transported by any citizen.
	The door step delivery in the hands of the kids is not acceptable. Kids are not allowed to handle alcohol.
Coercive Drivers	1 person 1 purchase per day
	Swiggy and Zomato are pushing the home delivery but top Management is not accepting the same.
Mimetic drivers	Abstinence and reduced consumption due to peer influence
	Nudge towards socially responsible consumption
Aligning Competing Logic	Given convenience to be paramount, although door step delivery is the established, but tokenised delivery from shops and pre- approved hotels only to operate within the regulatory framework." Employee interview

Discussion:

As the Covid-19 progressed and later, home delivery as the last mile delivery design became the established mode. This has been a change process involving multiple stakeholders and actors. The human convenience dictates but there can be diverse considerations interests and varied consequences as well for some commodity deliveries. The bottom-line in this discussion is that not always the customer's convenience is paramount. It is also in some cases the question of social construct, acceptance and embeddedness in the norms of the society. In this new paradigm, social sustainability and acceptance are imperative and external stakeholder's alignment. There has been studies which look at innovative business models by retail chains with a focus on sustainable development (Bilinska-Reformat et. al, 2019). Social sustainability is an important dimension of it which can be extended to social and responsible consumption (Adams and Raisborough, 2010).

Social acceptance is an important consideration and if not adhered to can face a lot of resistance (Simons et. al, 2016). Since this case is about a public service organization, the legal, and regulatory challenge become important. Further, Organizations are embedded in an environment, this study looks at institutional theory and logics (Thornton et. Al, 2012) for analysis. Previous studies have considered the customization versus conformity debate through institutional theory (Westphal et. al, 1997).

Stakeholder and Institutional logics

As has been cited in literature illicit liquor and adulteration is a major challenge and the mandate for government to operate in this area comes from this (Choksey and Shah, 2022). Amongst the stakeholders of the Value Chain, the State Government seems to be most powerful which is a Communist government driven by the Citizens which are educated and want to preserve the society and cultural fabric and thus upholds the territoriality of the place (Fig. 2).

This was clear from the remarks of all stakeholders:

"The state government is in our interest…" (customer 3)

"The directives are given by the government."

"Liquor is a state subject under the constitution" (Law maker)

The conclusion drawn based on the interviews that because of the powerful position held by the State Government and legal rules, they are using a coercive isomorphic driver to create an alternative narrative and distribution architecture for liquor. This contributes to socially responsible consumption.

Most discourse on socially responsible consumption focusses on minimization of consumption or greener consumption, but this includes corroboration with social acceptance.

Globally the last mile delivery dominant logic of product at the door step, convenience to the customer remains as the determinant of the distribution architecture.

"The basic reason of existence of the organization is the customer" (Customer 4)

"Customer is the boss" (Delivery partner)

The explanation given for this logic do not directly align with the dominant logic of convenience to the customer, Last mile delivery and product at the door step. The Convenience and last mile delivery remains the dominant logic because for FMCG retail which is an extremely competitive market, the customer remains the most powerful stakeholder.

Aligning competing logics: Although Token based last mile delivery is mostly not acceptable in last mile FMCG delivery, where product at the door step is paramount. However, in this case the Citizen awareness group, identified the negative impact on the teenagers and early adults as an equally convincing logic which found acceptance across all stakeholders.

"We can deliver the bottles to the customer but with the regulation of only 3 liters by one transporter the economies of scale do not work". delivery partner Swiggy Genie

"The delivery boys are of the age of 18-23 and the drinking age is 25. Easy access of liquor shall proliferate this which is not conducive to the society" – Citizens concern

Normative Isomorphic drivers.

Normative isomorphic drivers: Normative drivers refers to the adoption and integration of the new rules and legitimate practice to demonstrate to adherence to the social obligations. This normative driver focusses on the norms and values the structure choices. The focus is on 'how the things should be done legitimately'.

According to the Legal Position Abkari Law-

Any person cannot carry more than 3 litres of liquor. This can be considered as a deterrent for liquor drinking and also creating a monopoly in the market and having control over the distribution.

Liquor Sale is a state subject under the Indian government and different states with diverse cultural values can form policies accordingly

Challenge of underage drinking, which is a problem across the globe including India where, 88.8 percent of the youth drink alcohol before the legal age of 25

Coercive isomorphic driver: Coercive drivers comes from the word 'coercion' which means 'by force'. Coercive drivers involve use of forces to ensure that larger organizations or the big boys can dictate the smaller organizations to operate in a particular fashion.

This driver thus considers the entitlement and authority to dictate on the other stakeholders. This has been a legitimate people's power in their hands because of the mandate in a democracy and to be considered socially responsible.

Despite this the revenue that it will generate for the 3 PL partners, the 3 PL partners and taxation money are providing alternative ways to responding to the situation, because it can enhance the revenue for the,

Mimetic isomorphic driver:

Mimetic drivers occur when the stakeholders imitate the action. Given the chronological time when the project started, the Covid era and post covid era , the focus has shifted to responsible consumption. In continuation of this ideology, this offering has found acceptance amongst peers.

'In the pursuit of seen as socially responsible in the eyes of the citizens, the decision of not serving liquor at the doorstep holds on some customers due to unavailability which is good for the society.' Families of Customers.

It is clearly evident that there is a tradeoff as some customers and the delivery partners would prefer the delivery at the door step as this would enhance convenience and earnings respectively. But the dominant logic of the government and the citizens to consider the token system of delivery holds good. The data also indicated that the institutional body used demonstrative power to coerce or motivate the less powerful players to conform with the powerful players. Futuristic last mile delivery (Peppel et. al, 2022) need to incorporate this aspect as well.

The institution of the BEVCO is driven by the normative and coercive pressures drawn from the moral and ethical values of the society to create the last mile delivery. The coercive pressure of limiting the total no. of alcohol packs per customer provides a major barrier for delivery partners to supply alcohol. External pressures are a positive tool to decide the design of the last mile delivery , if the product can negatively harm the fabric of the society.

Paradox scholars analyses contradictory elements that are interrelated. The emerging conversations are looking at Both/And rather than either/or solutions. (Smith et. al, 2016; Cunha &Putnam, 2019;). Although Unattended, or wrongly attended delivery at home can have security implications but this study focusses on the social aspect of these culturally sensitive product delivery (McKinnon &Tallam, 2003). From the paradoxical lens, the deliberation is between Performing and Belonging Paradox (Lewis and Smith, 2022). More profoundly, the

organisation negotiates the paradoxical tension between the institutional forces and satisfying the customer on one hand vis a vis being embedded in a culture. Belonging Paradox and performing paradox are coexisting in the case and the last mile delivery has to straddle on both.

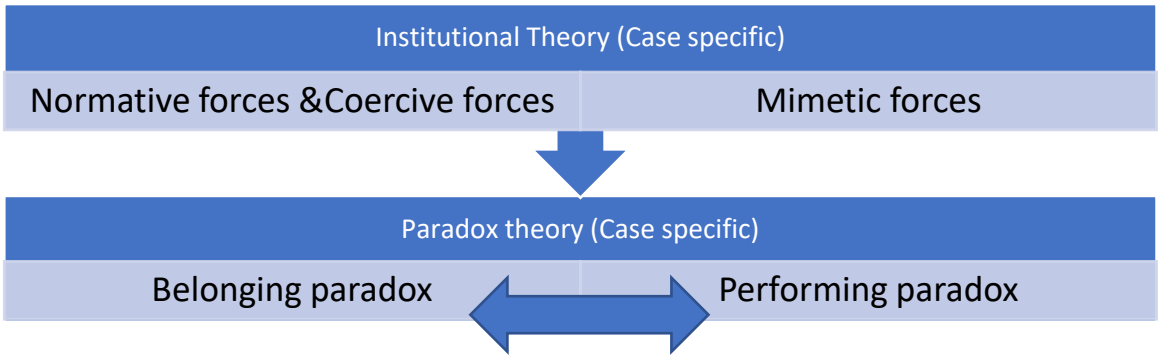


Fig. 3. Institutional and Paradox theory interpretation

Conceptually, this study introduces the social embeddedness context to the last mile delivery which can be explored across geographies, cultures and products. Methodologically, the theoretical contribution of this study includes bringing the stakeholder, institutional and paradox theory to explain a phenomenon. These three lens can provide valuable insights to the last mile delivery.

The practitioner's implication includes awareness of the social context of the product and designing the last mile delivery accordingly. Drawing on the instructive case, this study can be extended to other products like condom, sanitary napkins and other culturally sensitive products to devise the last mile considering the negative impact it can have on the social fabric.

From the social implication angle, the discussion on social sustainability has been limited to workers and drivers but this provides a different lens to the social sustainability angle of last mile delivery and consider the social context of the product for last mile delivery design..

CONCLUSION

By adopting the teleological compass to the combined stakeholder, institutional theory and paradox theory this study exemplifies that for certain products the last mile delivery has to encompass the social norms to gain legitimacy and acceptance. While designing the last mile business model the pressures from the institutional constituencies should be recognised by conforming with the values, beliefs and expectations of the society. The Digitization of retail has got an impetus during and after Covid. Although most commodities adopted the traditional approach of last mile delivery but this study creates a nuanced and contextual layer of Institution and provides an altered perspective. Based on an exemplar case study from India this study provides alternate insights. This study reiterates the concept of teleological approach for stakeholders and institutional theory in Last mile delivery. The use of stakeholder-institution theory provides the consolidation of the legal, regulatory, social, cultural which are important elements along with operational, customers intents and behaviors which have emanated from the three forces viz. coercive, normative and mimetic forces. Furthermore, paradox theory provides the inherent operational tradeoffs and dilemmas which coexist.

This study introduces the teleological lens to the last mile literature. As this study focusses on a single product and a particular geography, the future research can look at the competing logic for other products and geography as well. This can result in different architectures suited for these products given its embeddedness. Given the connect to the territorial discourse in responsible consumption, this study tries to kindle inter-disciplinary conversations and thereby create a socially responsible consumption and production framework. This shall bring scholars from diverse disciplines and perspectives. From the theoretical perspective this study contributes to last mile delivery, institutional theory, teleological approach, paradox theory. Recognizing this

study is qualitative research which is often criticized for its tendency to become biased as well as lacking scientific rigor this study can be corroborated by quantitative analysis in future.

REFERENCES

Adams, M., Raisborough, J. (2010). Making a difference: ethical consumption and the everyday. The British Journal of Sociology, 61 (2), 256 – 274. doi:10.1111/j.1468-4446.2010.01312.x

Anderson, W., & Cunningham, W. (1972). The socially conscious consumer.Journal of Marketing, 36(3), 23. https://doi.org/10.2307/1251036

Ashraf, M.H., Yalcin, M.G., Zhang, J. and Ozpolat, K. (2021), "Is the US 3PL industry overcoming paradoxes amid the pandemic?", The International Journal of Logistics Management, Vol. ahead-of-print No. ahead- of-print. https://doi.org/10.1108/IJLM-02-2021-0110

Bilińska-Reformat, K., Kucharska, B., Twardzik, M. and Dolega, L. (2019), "Sustainable development concept and creation of innovative business models by retail chains", International Journal of Retail and Distribution Management, Vol. 47 No. 1, pp. 2-18

Boysen, N., Fedtke, S. & Schwerdfeger, S. (2021). Last-mile delivery concepts: A survey from an operational research perspective, SpringerLink, OR Spectrum 43, 1–58. doi: https://doi.org/10.1007/s00291-020-00607-8

Brown, J. R., & Guiffrida, A. L. (2014). Carbon emissions comparison of last mile delivery versus customer pickup. International Journal of Logistics Research andApplications, 17(6), 503-521

Brunton, G.D.,Ahlstrom,D.,Li,H.-L.,2010.Institutionaltheoryandentrepreneur- ship: wherearewenowandwheredoweneedtomoveinthefuture?Entrep. Theory Pract.May,421–440.

Choksey, T., & Shah, A. A Study of the Two Alcohol Delivery Systems, the Online Aggregators Swiggy & Zomato, and the Individual Shop Deliveries, in India

Correia, D., Teixeira, L., & Marques, J. L. (2021). Last-mile-as-a-service (LMaaS): An innovative concept for the disruption of the supply chain. Sustainable Cities and Society, 75, 103310.

Crane, A., Matten, D. (2004). Business Ethics, Oxford: OUP.

Cunha, M. P. E., & Putnam, L. L. (2019). Paradox theory and the paradox of success. *Strategic organization*, *17*(1), 95-106.

Dagilienė, L., Varaniūtė, V. and Pütter, J.M. (2022), "Exploring institutional competing logic for sustainability implementation of retail chains", International Journal of Retail & Distribution Management, Vol. 50 No. 13, pp. 17-43.

Delmas, M.2002. "The diffusion of environmental management standards in Europe and the United States : An institutional perspective." Policy Sciences, 35: 91–119.

De Tavernier, J. (2012). Food citizenship: Is there a duty for responsible consumption?. Journal of Agricultural and Environmental Ethics, 25, 895-907.

DiMaggio, P.J.,Powell,W.W.,1991.Introduction.In:Powell,W.W.,DiMaggio,P.J. (Eds.), TheNewInstitutionalisminOrganizationalAnalysis.Universityof Chicago Press,Chicago,pp.1–38;.

Deutsch, Y., & Golany, B. (2018). A parcel locker network as a solution to the logistics last mile problem. International Journal of Production Research, 56(1-2), 251-261.

Elias, A. A. (2017). Systems thinking and modelling for stakeholder management. *IIM Kozhikode Society & Management Review*, *6*(2), 123-131.

Elias, A. A. (2021). Kerala's innovations and flexibility for Covid-19 recovery: Storytelling using systems thinking. Global Journal of Flexible Systems Management, 22(Suppl 1), 33-43.

Falcão, D., & Roseira, C. (2022). Mapping the socially responsible consumption gap research: Review and future research agenda. Int. J. Consum. Stud.

Fassin, Y. (2012). Stakeholder management, reciprocity and stakeholder responsibility. *Journal of business ethics*, *109*, 83-96.

Francois-Lecompte, A., Roberts, J.A. (2006). Developing a measure of socially responsible consumption in France. Marketing Management Journal, 16(2), 50-66.

Freeman, R. E., & Reed, D. L. (1983). Stockholders and stakeholders: A new perspective on corporate governance. *California management review*, *25*(3), 88-106.

Freeman, R. E. (2010). *Strategic management: A stakeholder approach*. Cambridge university press.

Ghaderi, H., Zhang, L., Tsai, P.-W. & Woo, J. (2022b), "Crowdsourced last-mile delivery with parcel lockers". *International Journal of Production Economics,* 251**,** 108549.

Glover L., Champion D., Daniels K.J., dainty A.J.D. (2014), An Institutional Theory perspective on sustainable practices across the dairy supply chain , International Journal of Production Economics Vol. 152, pp 102–111

Hing, N., Russell, A. M., & Hronis, A. (2018). A definition and set of principles for responsible consumption of gambling. International Gambling Studies, 18(3), 359-382.

Hirsch, P.M.,1975. Organizational effectiveness and the institutional environment. Administrative Science Quarterly Vol.20(3),327–344.

HW Stanger, S., Wilding, R., Hartmann, E., Yates, N., & Cotton, S. (2013). Lateral transshipments: an institutional theory perspective. *International Journal of Physical Distribution & Logistics Management*, *43*(9), 747-767.

Jennings, P.D., Zandbergen, P.A., 1995.Ecologically sustainable organizations: an institutional approach. Academy of Management Review 20(4),1015–1052.

Johnson, O., & Chattaraman, V. (2020). Signaling socially responsible consumption among millennials: an identity-based perspective. Social Responsibility Journal, 17(1), 87-105.

Kocabasoglu-Hillmer, C., Roden, S., Vanpoucke, E., Son, B.G. and Lewis, M.W., 2023. Radical innovations as supply chain disruptions? A paradox between change and stability. Journal of Supply Chain Management, 59(3), pp.3-19.

Lai, K.H., Wong, C.W.Y.,Cheng,T.C.E.,2006. Institutional isomorphism and the adoption of information technology for supply chain management. Computers and Industrial Engineering . 57(1),93–98.

Lewis, M. W., & Smith, W. K. (2022). Reflections on the 2021 AMR Decade Award: Navigating paradox is paradoxical. *Academy of Management review*, *47*(4), 528-548

Lim, S. F. W. T., Jin, X. & Srai, J. S. (2018), "Consumer-driven e-commerce". *International Journal of Physical Distribution & Logistics Management,* 48**,** 308-332.

Lim, S. F. W. T. & Winkenbach, M. (2019), "Configuring the Last-Mile in Business-to-Consumer E-Retailing". *California Management Review,* 61**,** 132-154.

Lim, S. F. W., Jin, X., & Srai, J. S. (2018). Consumer-driven e-commerce: A literature review, design framework, and research agenda on last-mile logistics models. International Journal of Physical Distribution & Logistics Management, 48(3), 308-332.

Maalouf, M. and Gammelgaard, B., 2016. Managing paradoxical tensions during the implementation of lean capabilities for improvement. *International Journal of Operations & Production Management*, *36*(6), pp.687-709.

Mangiaracina, R., Perego, A., Seghezzi, A. and Tumino, A. (2019), "Innovative solutions to increase lastmile delivery efficiency in B2C e-commerce: a literature review", International Journal of Physical Distribution & Logistics Management, Vol. 49 No. 9,pp. 901-920.

McKinnon, A.C. and Tallam, D. (2003), "Unattended delivery to the home: an assessment of the security implications", International Journal of Retail & Distribution Management, Vol. 31 No. 1,pp. 30-41.

Merkert, R., Bliemer, M. C. J. & Fayyaz, M. (2022), "Consumer preferences for innovative and traditional last-mile parcel delivery". *International Journal of Physical Distribution & Logistics Management,* 52**,** 261-284.

Mitchell, R. K., Agle, B. R., & Wood, D. J. (1997). Toward a theory of stakeholder identification and salience: Defining the principle of who and what really counts. Academy of management review, 22(4), 853-886.

Patton, M. (1990). *Qualitative evaluation and Research methods.* Beverly Hills,CA: SAGE .
Pålsson, H. & Sandberg, E. (2021), "Packaging paradoxes in food supply chains: exploring characteristics, underlying reasons and management strategies". *International Journal of Physical Distribution & Logistics Management,* ahead-of-print.

Pålsson, H. and Sandberg, E. (2020), "Paradoxes in supply chains: a conceptual framework for packed products", The International Journal of Logistics Management, Vol. 31 No. 3, pp. 423-442. https://doi.org/10.1108/IJLM-12-2019-0338

Punakivi, M., Yrjölä, H. & Holmström, J. (2001). Solving the last mile issue: reception box or delivery box? International Journal of Physical Distribution & Logistics Management, 31 (6), 427-439. doi: https://doi.org/10.1108/09600030110399423

Roberts, J. (1995). Profiling levels of socially responsible consumer behavior:A cluster analytic approach and its implications for marketing.Journal of Marketing Theory and Practice, 3(4), 97–117.

https://doi.org/10.1080/10696 679.1995.11501709

Roberts, J.A. (1996). Will the real socially responsible consumer please step forward? Business Horizons, 39(1), 79-83. doi:10.1016/S0007-6813(96)90087-7

Peppel, M., Ringbeck, J. & Spinler, S. (2022), "How will last-mile delivery be shaped in 2040? A Delphi-based scenario study". *Technological Forecasting and Social Change,* 177**,** 121493.

Peppel, M. & Spinler, S. (2022), "The impact of optimal parcel locker locations on costs and the environment". *International Journal of Physical Distribution & Logistics Management,* 52**,** 324-350.

Post, J.E., Preston, L.E. and Sachs, S. (2002), "Managing the extended enterprise. the new stakeholder view", California Management Review, Vol. 54 No. 1, pp. 6-28.

Puram, P., Gurumurthy, A., Narmetta, M., & Mor, R. S. (2022). Last-mile challenges in on-demand food delivery during COVID-19: understanding the riders' perspective using a grounded theory approach. The International Journal of Logistics Management, 33(3), 901-925.

Risberg, A. & Jafari, H. (2022), "Last mile practices in e-commerce: framework development and empirical analysis of Swedish firms". *International Journal of Retail & Distribution Management,* ahead-of-print.

Schad, J., Lewis, M. W., Raisch, S., & Smith, W. K. (2016). Paradox research in management science: Looking back to move forward.Academy of Management Annals, 10(1), 5–64.

Scott, W.R., 2007. Institutions and Organizations: Ideas and Interests. Sage Publications, Thousand Oaks, CA

Smith, W. K., & Lewis, M. W. (2022). Both/and thinking: embracing creative tensions to solve your toughest problems. Harvard Business Review Press.

Smith, W. K., & Lewis, M. W. (2011). Toward a theory of paradox: A dynamic equilibrium model of organizing. *Academy of management Review*, *36*(2), 381-403.

Smith, W. K., Lewis, M. W., & Tushman, M. L. (2016). Both/and" leadership. *Harvard Business Review*, *94*(5), 62-70.

Simons, T., Vermeulen, P.A., Knoben, J., 2016. There's no beer without a smoke: community cohesion and neighboring communities' effects on organizational resistance to antismoking regulations in the Dutch hospitality industry. Acad. Manag. J. 59 (2), 545–578

Tsai, Y. T., & Tiwasing, P. (2021). Customers' intention to adopt smart lockers in last-mile delivery service: A multi-theory perspective. *Journal of Retailing and Consumer Services*, *61*, 102514.

Thornton, P.H., Ocasio,W., Lounsbury, M., 2012. The Institutional Logics Perspective: a New Approach to Culture, Structure and Process. Oxford University Press,Oxford.

Wang, X., Yuen, K. F., Wong, Y. D. & Teo, C.-C. (2019), "Consumer participation in last-mile logistics service: an investigation on cognitions and affects". *International Journal of Physical Distribution & Logistics Management,* 49**,** 217-238.

Webster, F. E. Jr. (1975). Determining the characteristics of the socially conscious consumer. Journal of Consumer Research, 2(3), 188-196. doi:10.1086/208631

Weltevreden, J.W.J. (2008). "B2C e-commerce logistics: the rise of collection-and-delivery points in The Netherlands", International Journal of Retail & Distribution Management, 36 (8), 638-660. doi: http://dx.doi.org/10.1108/09590550810883487

Westphal, J.D.,Gulati,R.,Shortell,S.M.,1997.Customization or Conformity ? An institutional and network perspective on the content and consequences of TQM adoption. Administrative Science Quarterly 42(2), 366–394

Williams, Z., Lueg, J. E., Taylor, R. D., & Cook, R. L. (2009). Why all the changes? An institutional theory approach to exploring the drivers of supply chain security (SCS). *International Journal of Physical Distribution & Logistics Management*, *39*(7), 595-618.

Yin, R. (1993). *Applications of Case Study Research. .* Newbury Park, CA.: Sage.
Zhou, M., Zhao, L., Kong, N., Campy, K. S., Xu, G., Zhu, G., ... & Wang, S. (2020).Understanding consumers' behavior to adopt self-service parcel services for last-mile delivery. Journal of Retailing and Consumer Services, 52, 101911.

Conceptualisation of Dry Port Logistics Service Quality

Khun Aye Han Kyu, Thananya Wasusri

Mahidol University, Bangkok, Thailand

INTRODUCTION

Maritime transportation is considered an essential foundation for the extensive and intricate operations underpinning the global movement of products and information, in line with the expansion of international and intraregional trade. In response to escalating consumer demands, maritime transport providers including shipping firms, terminal operators, and freight forwarders have increasingly shifted toward offering integrated door-to-door logistics and multimodal services as an effective option to minimize overall transaction costs. Furthermore, the role of ports has evolved from simple transit points to hubs for value-added logistics services such as warehousing, packaging, and labelling.

However, despite these advancements, the current conceptualisation of Logistics Service Quality (LSQ) in the maritime sector faces significant research gaps. First, there is a notable lack of literature regarding Dry Ports (inland intermodal terminals) as distinct nodes of service quality, with most studies focusing exclusively on seaports. Second, traditional LSQ frameworks often fail to incorporate new trends such as ICT and Sustainability. Specifically, there is a deficiency in research addressing how Information and Communication Technology (ICT) must now comply with Artificial Intelligence (AI) to provide predictive and autonomous service solutions. Additionally, while environmental concerns grow, sustainable logistics practices are rarely integrated into the measurement of maritime service quality, leaving a gap in understanding how "green" services drive customer satisfaction.

This study to develop a modern framework for Dry Port Logistics Service Quality by defining its building blocks and associated measurement indicators. By incorporating AI-driven ICT systems, intermodal accessibility, and environmental sustainability, this research provides a comprehensive tool for evaluating the services provided by logistics service providers in the contemporary era.

RESEARCH METHODOLOGY

The initial stage involved an extensive search for relevant literature to establish a robust data foundation for the study. The process began by identifying 500 records across prominent international academic databases, including Elsevier and EBSCOhost. The investigation covered a longitudinal period from 1980 to 2025, allowing for a comprehensive analysis of the transition from traditional port-centric logistics to the modern integrated dry port concept. To ensure a thorough capture of concepts, a tiered keyword strategy was applied, utilizing primary terms such as "dry port logistics service quality," "inland container depot," and "seaport-dry port". Following an initial screening for relevance based on titles and abstracts, the sample was refined to 250 highly relevant papers.

During the second phase, a deep investigation of the selected abstracts and full texts was conducted to extract critical data points. This stage involved a systematic coding process where definitions, methodologies, and geographical contexts were documented to identify recurring factors and existing research gaps. A specific emphasis was placed on identifying the technological shift from basic Information and Communication Technology (ICT) to AI-compliant systems, as contemporary maritime logistics increasingly rely on Artificial Intelligence for predictive analytics, real-time visibility, and automated operations. Furthermore, the extraction process highlighted the escalating importance of sustainable practices, such as carbon footprint transparency and green innovation, which were historically excluded from traditional service quality frameworks.

The final phase involved the synthesis of the coded data to develop the integrated conceptual model. Findings were grouped by comparing similar concepts and theories to determine the most significant measurement indicators for modern dry port operations.

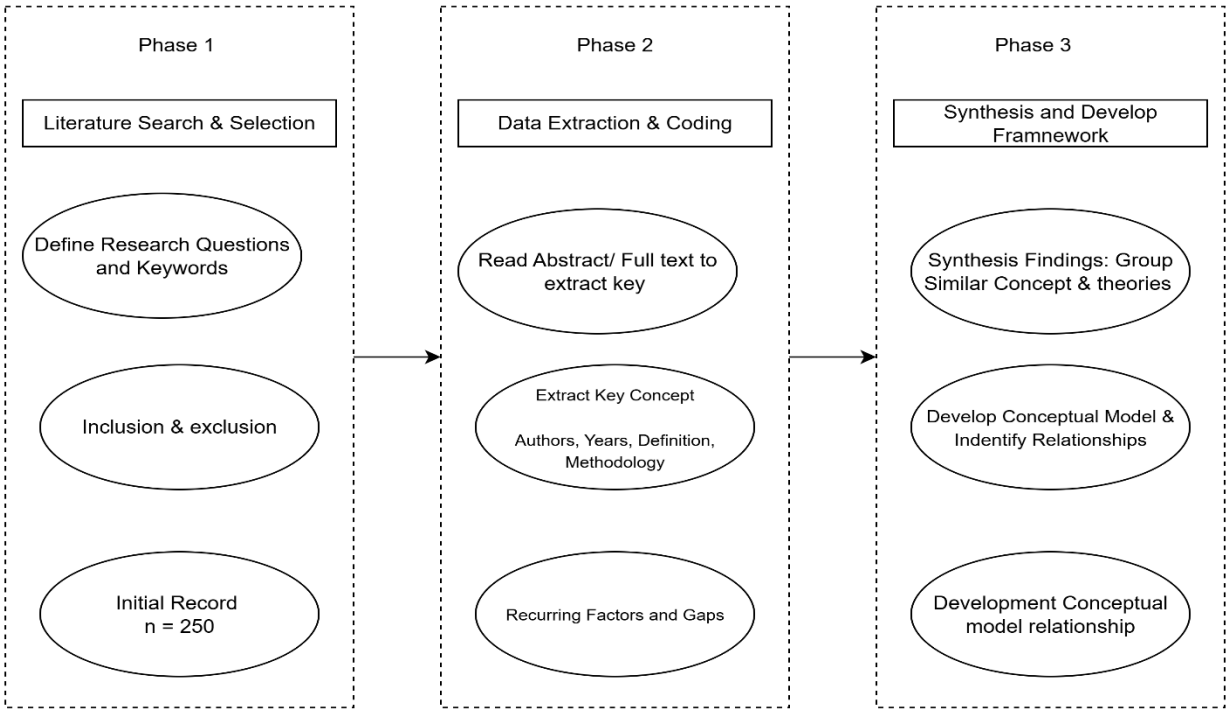


Fig 1 Flow Diagram for Literature Identification and Selection.

This synthesis identified the specific relationships between service quality dimensions categorised into the Traditional SERVQUAL cluster and the Extended Context-Specific cluster and their collective impact on customer satisfaction. By grouping these theoretical insights, the study establishes a comprehensive foundation for the final questionnaire design, ensuring it effectively accommodates the latest trends in digital intelligence and environmental accountability.

RESULTS AND DISCUSSION

Concept of Service Quality

Service quality denotes a comprehensive assessment of a firm's service delivery system and may also be characterised as the consumer's overall perception of the firm's performance in terms of relative inadequacy or superiority [3]. Moreover, service quality is frequently defined as the assessment of the gap between customer expectations and actual service performance [4]. Furthermore, they asserted that service quality precedes customer satisfaction, and customers' perceptions of service performance are the paramount indicator of service quality. Moreover, service quality can be conceptualised as a multidimensional entity comprising service-related aspects evaluated by the customer [5,6]. To evaluate service quality, numerous studies have examined the quality dimensions that serve as the foundation for the development of a conceptual construct operationalised by quantitative indicators [7]. Numerous prior studies have investigated the various dimensions of service quality and their corresponding measurable items to assess the performance of different service industries [8,9,10].

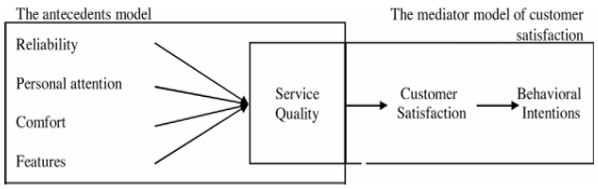


Fig.2 The antecedents and mediator model

Sources: (Dabholkar et al., 2000)

Concept of logistics service quality

Providing high-quality logistics services to consumers is essential for effective supply chain management (SCM) to maintain a strategic competitive advantage by enhancing customer satisfaction [11]. The quality of logistics services serves as a critical criterion for a firm to distinguish itself from competitors by providing superior logistics services in competitive scenarios where logistics are more significant than product attributes and pricing. This internal differentiation of a firm may emphasise the quantity and quality of various logistics services provided, while concurrently, value-added logistics service alternatives are regarded as the primary external factor for logistics differentiation [12]. To evaluate logistics service quality, some authors have established a quality construct comprising various dimensions along with their associated measurement criteria [12,13,14].

Quality dimensions and associated measurement indicators for the assessment of Dry port

Dry port logistics service quality denotes the customers' comprehensive assessment of logistics services provided by principal logistics service providers in the maritime sector for the transportation of products and services, together with information, globally by sea. Previous literature in the maritime domain has concentrated on the resource and logistics service capabilities of shipping companies [15] the logistics service attributes offered by maritime firms [16], environmental issues associated with shipping [17,18,19,20], the service quality of ocean freight logistics services [21,22,23,24]. Nevertheless, a deficiency exists in the characterization and assessment of logistics service quality within the maritime sector.
This work seeks to develop a conceptual model of dry port logistics service quality This study develops a conceptual model of Dry Port Logistics Service Quality (LSQ) by integrating traditional service quality dimensions with dry port–specific extensions. LSQ is conceptualized as a multidimensional construct comprising the five SERVQUAL dimension's reliability, responsiveness, assurance, empathy, and tangibles which capture customers' fundamental perceptions of service performance. To reflect the operational and strategic characteristics of dry ports, the model is extended by incorporating three additional dimensions, namely transport accessibility, information and communication technology (ICT), and sustainability practices. Transport accessibility evaluates the efficiency and reliability of intermodal connections and hinterland accessibility, ICT reflects the adoption of digital systems that enhance service transparency and coordination, and sustainability practices emphasize environmentally responsible logistics operations. Collectively, these dimensions form an integrated LSQ framework that directly influences customer satisfaction as the primary outcome of dry port logistics service performance. To evaluate dry port logistics service quality, all recognized logistics service attributes pertaining to maritime transportation referenced in the literature are considered.

Table 1. Dimensions and associated measurement indicators for the assessment of Dry Port Logistics Services

Construct	Dimension Code	Measurement Indicators	Key References
Logistics Service Quality (LSQ)	Reliability	Punctuality, service consistency, transit time reliability, error-free operations, service accuracy	[25], [26], [27]
	Responsiveness	Handling speed, waiting time, complaint resolution speed, service recovery effectiveness	[28], [31]
	Assurance	Staff competence, customs support reliability, professional knowledge, security compliance	[31], [36]
	Empathy	Customer support availability, individualized service, responsiveness to customer needs	[33], [34]

	Tangibles	Infrastructure adequacy, handling equipment availability, storage facilities, technological infrastructure	[29], [30]
Extended LSQ Dimensions	Transport Accessibility	Transport frequency, intermodal connectivity, route optimization, utilization rate, proximity to gateways	[25], [26], [29]
	Information & Communication Technology	Automation level, tracking & tracing availability, ICT usage, system reliability, digitalization level	[32], [22], [35]
	Sustainability	Renewable energy use, emissions reduction, waste recycling, green initiatives, environmental compliance	[35], [28]
Outcome Variable	Customer Satisfaction	Overall service reliability perception, customer feedback, complaint resolution satisfaction	[34]

Dry port logistics service quality construct will comprise several pertinent measurement indicators derived from prior literature, as outlined in Table 1.
Each dimension is paired with measurable indicators derived from prior literature, offering a holistic approach to evaluating service quality. This framework not only integrates operational metrics but also emphasizes modern priorities such as technological adoption, sustainability, and security, providing actionable insights for improving dry port performance and competitiveness in global supply chains. Future validation of this model in diverse contexts will strengthen its applicability and contribute to advancing the efficiency and quality of dry port logistics services worldwide.

The outcome of Dry Port Logistics Services Quality in Customer Satisfaction

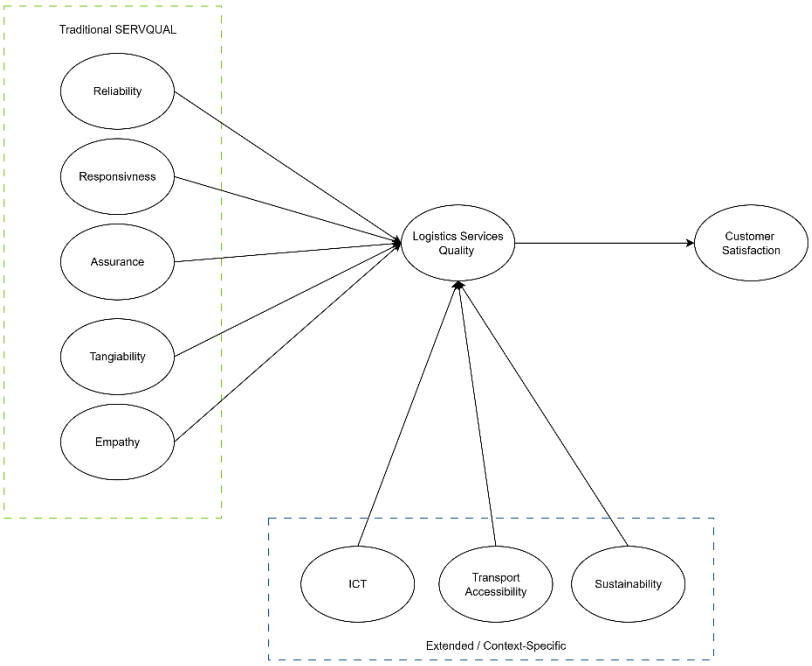
Satisfaction denotes an evaluative outcome on the degree to which customers are content and possess a favorable emotional appraisal of suppliers [36]. Customer satisfaction frequently hinges on the perceived quality of service delivery, with the primary argument being that a satisfied customer is more inclined to exhibit loyalty and maintain a long-term relationship with the service provider [7,10]. Loyalty is typically defined as the intention to repurchase items and services or to maintain a long-term professional relationship [23]. In this context, establishing robust long-term relationships with consumers or fostering customer loyalty is a crucial element in acquiring market share and maintaining competitive advantage for service providers [11]. Consequently, dry port logistics services can be viewed as a framework for enhancing the performance of logistics service providers, fostering long-term commitment through improved customer satisfaction.

Conceptual model and Proposition

A conceptual model of dry port logistics service quality is presented in Figure 2 which portrays the association between the perceived dry port logistics service quality and the outcome in terms of customer satisfaction. In this conceptual model, dry port logistics service quality is viewed as an antecedent of customer satisfaction and repurchasing intention. Therefore, it is reasonable to anticipate that there is an interaction between these components and consequently, several proposition on the conceptual model will be constructed as follows.

Proposition 1: Dry port logistics service quality is a multidimensional construct composed of the traditional SERVQUAL dimensions reliability, responsiveness, assurance, empathy, and tangibles together with three extended dimensions specific to dry port operations, namely transport accessibility, information and communication technology (ICT), and sustainability practices, and is measured using empirically observable indicators derived from prior literature.

Proposition 2: Dry port logistics service quality has a positive and significant impact on customer satisfaction with logistics services.



Proposition 3: Higher levels of transport accessibility, ICT adoption, and sustainability practices enhance overall dry port logistics service quality, which in turn leads to increased customer satisfaction.

Fig3 Conceptual Framework of Dry Port Logistics Service Quality (DP-LSQ) Dimensions and Outcome.

CONCLUSIONS

Only a few studies have examined the influence of dry port logistics service quality on customer satisfaction. Therefore, this study conceptualised the quality of dry port logistics service using an eight-dimensional construct. These dimensional constructs of dry port logistics service quality, along with related measurement indicators, are expected to provide direction for improving logistics service providers' performance and enhancing customer satisfaction.

Prior literature presents that numerous factors can have either direct or indirect impact on customer satisfaction. Previous studies have linked customer satisfaction with transport and operational efficiency, connectivity of dry port, customs service, technology and security. In future research, the hypotheses developed in this study could be empirically tested using qualitative and quantitative methods. As a conceptual study, this research does not involve empirical analysis; future studies may validate the proposed framework using quantitative or mixed methods approaches.

REFERENCES

[1] Anderson, E. W., Fornell, C., & Lehmann, D. R. (1998). Customer satisfaction, market share, and profitability: Findings from Sweden. Journal of Marketing, 58(3), 53–66.
[2] Banomyong, R., & Supatn, N. (2011). Developing a logistics service quality index for maritime transport in Thailand. International Journal of Shipping and Transport Logistics, 3(2), 189–206.
[3] Bienstock, C. C., Mentzer, J. T., & Bird, M. M. (2008). Measuring physical distribution service quality. Journal of the Academy of Marketing Science, 25(1), 31–44.
[4] Berle, Ø., Asbjørnslett, B. E., & Rice, J. B. (2011). Formal vulnerability assessment of a maritime transportation system. Reliability Engineering & System Safety, 96(6), 696–705.
[5] Bottani, E., & Rizzi, A. (2006). A fuzzy TOPSIS methodology to support outsourcing of logistics services. Supply Chain Management: An International Journal, 11(4), 294–308.
[6] Caro, L. M., & Garcia, J. A. M. (2007). Measuring perceived service quality in urgent transport service. Journal of Retailing and Consumer Services, 14(1), 60–72.

[7] Caruana, A., Money, A. H., & Berthon, P. R. (1999). Service quality and satisfaction—the moderating role of value. European Journal of Marketing, 34(11/12), 1338–1353.
[8] Chen, H., Tian, Y., & Dagger, T. S. (2009). Building a model of quality evaluation for airfreight logistics service. Supply Chain Management: An International Journal, 14(5), 349–359.
[9] Chowdhary, N., & Prakash, M. (2007). Prioritizing service quality dimensions. Managing Service Quality: An International Journal, 17(5), 493–509.
[10] Dabholkar, P. A., Shepherd, C. D., & Thorpe, D. I. (2000). A comprehensive framework for service quality: An investigation of critical conceptual and measurement issues through a longitudinal study. Journal of Retailing, 76(2), 139–173.
[11] Deng, Z., Lu, Y., Wei, K. K., & Zhang, J. (2010). Understanding customer satisfaction and loyalty: An empirical study of mobile instant messages in China. International Journal of Information Management, 30(4), 289–300.
[12] Durvasula, S., Lysonski, S., & Mehta, S. C. (1999). Testing the SERVQUAL scale in the business-to-business sector: The case of ocean freight shipping service. Journal of Services Marketing, 13(2), 132–150.
[13] Ekinci, Y. (2001). The validity of the SERVQUAL and SERVPERF scales: A study in a British holiday context. Service Industries Journal, 21(1), 1–23.
[14] Flint, D. J., Blocker, C. P., & Boutin, P. J. (2011). Customer value anticipation, customer satisfaction and loyalty: An empirical examination. Industrial Marketing Management, 40(2), 219–230.
[15] Kersten, W., & Koch, J. (2010). The effect of quality management on the service quality and business success of logistics service providers. International Journal of Quality & Reliability Management, 27(2), 185–200.
[16] Kang, G. D., & James, J. (2004). Service quality dimensions: An examination of Grönroos's service quality model. Managing Service Quality: An International Journal, 14(4), 266–277.
[17] Lai, K.-H., Wong, C. W. Y., & Cheng, T. C. E. (2011). Ecological modernisation of Chinese export manufacturing via green logistics management and its regional implications. Technological and Economic Development of Economy, 17(1), 59–73.
[18] Lu, C. S. (2000). Logistics services in Taiwanese maritime firms. Transportation Research Part E: Logistics and Transportation Review, 36(2), 79–96.
[19] Martinez, J. A., & Martinez, L. (2010). Some insights on conceptualizing and measuring service quality. Journal of Retailing and Consumer Services, 17(1), 29–42.
[20] Psaraftis, H. N., & Kontovas, C. A. (2010). Balancing the economic and environmental performance of maritime transportation. Transportation Research Part D: Transport and Environment, 15(8), 458–462.
[21] Ruyter, K. D., Wetzels, M., & Bloemer, J. (1997). On the relationship between perceived service quality, service loyalty, and switching costs. International Journal of Service Industry Management, 9(5), 436–453.
[22] Thai, V. V. (2008). Service quality in maritime transport: Conceptual model and empirical evidence. Asia Pacific Journal of Marketing and Logistics, 20(4), 493–518.
[23] Wong, C. Y., & Karia, N. (2010). Explaining the competitive advantage of logistics service providers: A resource-based view approach. International Journal of Production Economics, 128(1), 51–67.
[24] Yang, C. C., Marlow, P. B., & Lu, C. S. (2009). Assessing resources, logistics service capabilities, innovation capabilities and the performance of container shipping services in Taiwan. International Journal of Production Economics, 122(1), 4–20.
[25] Banomyong, R., & Supatn, N. (2011). Developing a regional logistics network in ASEAN: The role of dry ports and logistics hubs. Transport and Communications Bulletin for Asia and the Pacific, (80), 61-72.
[26] Brady, M. K., & Cronin, J. J. (2001). Some new thoughts on conceptualizing perceived service quality: A hierarchical approach. Journal of Marketing, 65(3), 34-49.
[27] Ng, A. K. Y., & Cetin, I. B. (2012). Locational characteristics of dry ports in developing economies: Some lessons from Northern India. Regional Studies, 46(6), 791-807.
[28] Notteboom, T. E., & Rodrigue, J. P. (2005). Port regionalization: Towards a new phase in port development. Maritime Policy & Management, 32(3), 297-313.
[29] Parasuraman, A., Zeithaml, V. A., & Berry, L. L. (1988). SERVQUAL: A multiple-item scale for measuring consumer perceptions of service quality. Journal of Retailing, 64(1), 12-40.

[30] Roso, V. (2007). Evaluation of the dry port concept from an environmental perspective: A note. Transportation Research Part D: Transport and Environment, 12(7), 523-527.
[31] UNCTAD. (2003). Challenges in Implementing Trade Facilitation Reforms. United Nations Conference on Trade and Development (UNCTAD).
[32] UNCTAD. (2009). Review of Maritime Transport 2009. United Nations Conference on Trade and Development (UNCTAD).
[33] Veenstra, A. W., Zuidwijk, R. A., & Van Asperen, E. (2012). The extended gate concept for container terminals: Expanding the notion of dry ports. Maritime Economics & Logistics, 14(1), 14-32.
[34] World Bank. (2010). Connecting to Compete: Trade Logistics in the Global Economy. World Bank.
[35] Yuen, K. F., & Thai, V. V. (2017). Service quality and customer satisfaction in liner shipping: The moderating role of customer co-creation. Transportation Research Part E: Logistics and Transportation Review, 97, 9-22.

Greenhouse Gas Emissions and Financial Performance in Shipping Decarbonisation

Huong Le[1,2], Petri Helo[1], Khuram Shahzad[1], Vinh Thai[2], Aswini Yadlapalli[2]

1: School of Technology and Innovations, Production, University of Vaasa, Finland; 2: School of Accounting, Information Systems and Supply Chain, RMIT University, Australia

INTRODUCTION

The shipping industry is a critical backbone of international trade, but also a major source of greenhouse gas (GHG) emissions. The sector accounts for over 80% of world merchandise trade by volume and causes 5% of GHG emissions (UNCTAD, 2025). These gases, with carbon dioxide (CO2) being a dominant component, contribute to global warming. In response to this issue, IMO introduced its GHG reduction strategy in 2018 and accelerated its decarbonisation ambitions in 2023 through stricter targets. As part of this strategy, measures and solutions have been analysed and adopted, including the Carbon Intensity Indicator, cleaner fuels, and fuel technology (Ma, Zhe and Xiao, 2025). However, shipping is predicted to reduce GHG emissions only by 40-75% in 2050, falling short of the IMO 2050 net-zero GHG target (Laskar, Dowlatabadi and Giang, 2025).

Compliance with the IMO 2023 strategy requires substantial investments in technology, operations, and fleet improvements, affecting shipping lines' ability to generate profits from operations. Given the high costs and economic uncertainty of decarbonisation initiatives, concerns have been raised regarding these firms' ability to meet emission targets while maintaining viable operations (Govindan *et al.*, 2024; Karahalios, 2024). Therefore, it is crucial to examine the relationship between firms' GHG emissions and financial performance, an area that remains underexplored in the shipping industry.

Within the shipping industry, the evidence linking firms' emission intensity to their financial performance, particularly in relation to decarbonisation initiatives, remains scarce (Wang, Cheng and Zhen, 2023; Govindan *et al.*, 2024). Emission intensity, measured as emissions relative to firm revenue, can be used as a proxy for GHG emissions because absolute emissions largely reflect firm size and therefore limit meaningful comparisons across firms (Busch and Lewandowski, 2018) Existing studies have often examined the relationship between financial performance and sustainability-related indicators (Tsatsaronis *et al.*, 2024; Jia and Azevedo, 2025), yet none have examined GHG emission intensity directly, particularly after IMO agreed on new mandatory measures in 2020. Addressing this gap is important for two reasons. Firstly, by examining GHG emissions and financial performance, we gain a direct assessment of the impact of decarbonisation on firms. Secondly, we can uncover patterns in how different decarbonisation initiatives are associated with emission–financial performance profiles, offering practical insights for industry transition. Therefore, this study aims to fill this gap by tracking the shipping industry's progress towards decarbonisation. Adopting an exploratory approach, the study is guided by the following research questions:

RQ1: How have the GHG emission intensity and financial performance among shipping companies evolved since 2021?

RQ2: What decarbonisation initiatives are adopted by firms, and how do these initiatives relate to differences in GHG emissions and financial performance?

To address these questions, this paper analyses the evolution of shipping companies' GHG emission intensity and financial performance and explores how their decarbonisation initiatives are associated with emission-financial performance patterns, using the publicly available data (i.e., Bloomberg and company reports) between 2021 and 2024.

LITERATURE REVIEW

Shipping business and GHG emission scope

It is important to understand the different GHG emission scopes and business types that exist in the shipping industry, as they determine operational and emission responsibility. According to the GHG Protocol, GHG emissions can be classified into three scopes (WRI, 2004). Scope 1 emissions refer to the direct emissions from sources owned or controlled directly by a firm, while scope 2 and 3 emissions refer to the indirect emissions from upstream or downstream sources that are still the result of the firm's operation. In the industry, the emission scopes depend on the operational control of the ships by firms.

Shipping services are generally categorised into liner shipping and tramp shipping (Kendall, 1986). Liner shipping operates on fixed routes and schedules with a fixed price. In contrast, tramp shipping operates based on customer demand and is subdivided into two common charter types: voyage charter and time charter (Kendall, 1986). Under a voyage charter, the charterer hires the ship for a single voyage or consecutive voyages while the shipowner retains control over vessel operations. Under a time charter, the vessel is hired for a specific period, during which the charterers are responsible for fuel and other cargo-related costs, and voyage directions (Stopford, 2008). Overall, liner shipping companies and shipowners under voyage charter directly own or control the ship operations, thereby being responsible for scope 1 GHG emissions from ship emissions. This study focuses on scope 1 emissions, as they directly represent emissions from the primary activities of these shipping businesses.

Financial performance and GHG emissions in the shipping industry

The relationship between firms' GHG emissions and their financial performance has been a focal point of many researchers, who have found positive, negative and even non-linear correlations. Studies show a negative link, especially between emission intensity and return on assets and return on equity (Le and Nguyen-Phung, 2024). On the other hand, others reported a decline in financial performance with emission reduction, attributed to the cost burden of decarbonisation initiatives (Busch *et al.*, 2022). Other studies also identified a non-linear, U-shaped relationship (Trumpp and Guenther, 2017).

Research focusing on the shipping industry, however, remains scarce (Wang, Cheng and Zhen, 2023; Govindan *et al.*, 2024). Firstly, some studies imply that there is a link between financial performance and sustainability. For example, Tartarinis *et al.,* (2024) found a positive correlation between Corporate Social Responsibility (CSR) disclosures and financial performance. Koutsos, Panayides and Tsouknidis, (2023) also reported that innovation in ship design, particularly eco-type vessels that improve fuel efficiency and reduce emissions, leads to financial gains. These innovations, however, lead to increased spending. Lastly, Jia and Azevedo (2025) found no significant relationship between Environmental, Social and Governance (ESG) scores and financial performance, leading to concerns about whether decarbonisation initiatives will lead to any return on investment. Secondly, it is shown that regulations affect firms' sustainability performance. According to Jia and Azevedo (2025), the 2020 IMO regulations have increased firms' ESG scores. Furthermore, Lu and Theocharis (2025) found that ships that score better on IMO's energy-efficiency and carbon indicators have higher second-hand prices.

This study thus analyses the relationship between shipping companies' GHG emissions and their financial performance. Subsequently, the paper discusses what decarbonisation initiatives firms can adopt to reduce their emissions while not risking their financial gains.

RESEARCH DATA AND METHODOLOGY

Research approach

This study adopts an exploratory research design through a multi-method approach. Exploratory research develops a deeper understanding of under-researched phenomena by describing current conditions and emerging patterns (Yin, 2018). This approach is appropriate given the evolving nature of shipping decarbonisation. The quantitative method in the first phase examines the extent of the phenomenon, whereas the qualitative approach in the second phase explores how it is understood (Choi, Cheng and Zhao, 2016).

Data collection and analysis

In this study, return on assets (ROA) is used as a proxy for firms' financial performance, consistent with prior studies of shipping firms (Drobetz, Janzen and Requejo, 2019; Kouspos, Panayides and Tsouknidis, 2023). ROA is calculated as the ratio of net income to total assets,

indicating a company's operating efficiency in utilising its total assets. Given the asset-intensive nature of the shipping industry, where ships account for a large share of firms' total assets, ROA is a suitable ratio for capturing firms' financial performance.

Direct GHG emission performance is measured using scope 1 GHG emission intensity. As larger companies naturally exhibit higher absolute emissions, it is more appropriate to normalise emissions by firm size when comparing across companies (Ferrat, 2021; Busch *et al.*, 2022). Absolute emission levels provide limited insight without business context, and most studies examining the relationship between emissions and financial performance thus rely on emission intensity measures (Delmas, Nairn-Birch and Lim, 2015; Busch and Lewandowski, 2018) Therefore, this study measures the GHG emission intensity scope 1 as direct GHG emissions (in CO2 equivalent) divided by the firm's revenue. We focus on scope 1 since it reflects the emissions that are most directly from companies' main shipping activities and hence most influenced by their decarbonisation initiatives.

This paper analyses shipping sector data from the Bloomberg database based on the Bloomberg Industry Classification Standard, collected from 2021 to 2024 (Bloomberg, 2025). The initial population comprises over 300 companies in the shipping classification standard. From this sample, firms are selected according to two criteria: 1) they follow the liner shipping or voyage charter business model, and 2) more than 60% of their revenue comes from shipping activities. The revenue criterion ensures that financial performance measures mainly reflect firms' core shipping operations rather than diversified activities, consistent with prior research (Kouspos, Panayides and Tsouknidis, 2023). Firms belonging to these two business models are chosen as they directly own or control their vessels. Therefore, their scope 1 emissions more directly reflect the emissions coming from their main business activities. In contrast, other business models that primarily lease their vessels to customers report shipping emissions under scope 3, specifically category 13 - downstream leased assets and are therefore excluded. Scope 2 emissions, which are from purchased electricity for onshore facilities, are not considered, as they are not directly related to firms' main business activities. Subject to data availability, the sample consists of 46 publicly listed shipping companies, all of which satisfy that they operate primarily under liner shipping or voyage charter models and derive over 60% of their revenue from shipping activities. Although the Bloomberg database limits the sample of publicly listed companies, this sample size is reasonable given the study's exploratory purpose.

In the first quantitative phase, the sample of 46 firms is divided into two datasets to maximise the study's exploratory scope. Among these, 40 companies with complete data across four years are included in the first dataset for the trend analysis. The second dataset includes the full sample of 46 firms and focuses on the recent snapshot (2024). First, given the small sample size and non-normally distributed dataset, non-parametric statistical tests are applied. Specifically, this paper applies the Friedman and Wilcoxon signed-rank tests to analyse the changes in firms' financial performance and GHG emission intensity across four years. Second, firms are positioned in a two-by-two quadrant matrix based on their ROA and direct GHG emission intensity, capturing firms' performance patterns.

In the second qualitative phase, decarbonisation initiatives from 46 companies' sustainability reports from their websites are analysed to provide insights into their performance patterns and current decarbonisation strategies in 2024. This paper uses 5 groups of technological and operational solutions from Bouman *et al.,* (2017) as a benchmark to categorise firms' decarbonisation initiatives: 1) hull design, 2) power and propulsion system, 3) alternative fuels, 4) alternative energy sources, and 5) operation.

FINDINGS

Between 2021 and 2024, firms' ROA fluctuated while direct GHG emission intensity showed a declining trend (Figure 1). The Friedman test results show that the changes in ROA and direct GHG emission intensity across four years are statistically significant (p-value < 0.05). Specifically, according to the Wilcoxon test, ROA changed significantly, with a decline between 2022 and 2023, while emission intensity declined significantly year over year (p-value < 0.05) (Table 1 and 2).

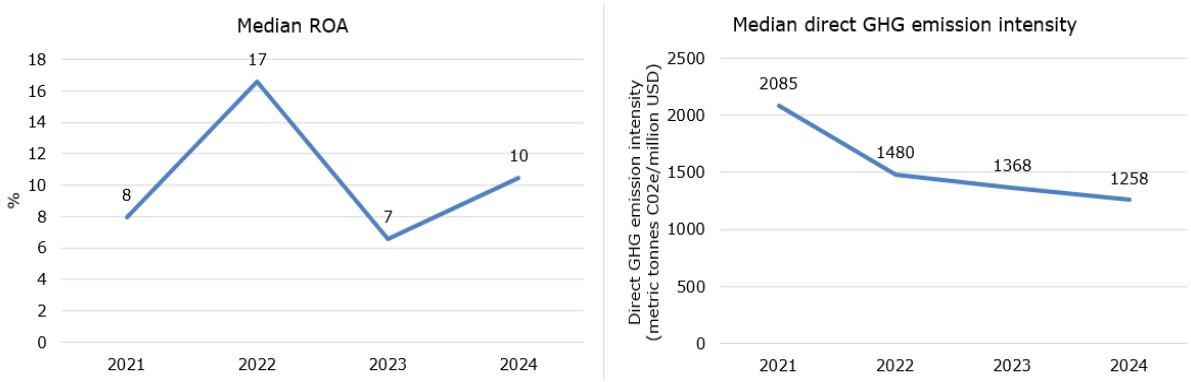


Figure 1: Median ROA and direct GHG emission intensity from 2021 to 2024
Source: Authors' own work

2021–2024	Friedman χ^2	df	p-value
ROA	12.3	3	0.006423
Direct GHG emission intensity	25.433	3	1.25E-05

Table 1: Friedman test from 2021 to 2024
Source: Authors' own work

	21–22	22–23	23-24
ROA	0.209	9.19E-05	0.56
Direct GHG emission intensity	6.91E-08	0.03627	0.00248

Table 2: Wilcoxon test from 2021 to 2024
Source: Authors' own work

To further detect the emission-financial performance patterns among firms, our quadrant analysis categorises companies into four quadrants based on their median value of ROA and direct GHG emission intensity. Firms are grouped according to whether their performance lies above or below the sample medians. Quadrant 4, the ideal quadrant, represents 'leading firms' which have high ROA and generate low levels of emissions. These firms can balance both their environmental and financial performance. Quadrant 3 includes 'emerging firms' with low emission intensity but below-median ROA. While these firms can maintain low emissions, their operation may be inefficient. Quadrant 2 comprises the 'passive firms', characterised by low ROA and high levels of emissions. These firms are likely engaged in inefficient and carbon-intensive operations. Quadrant 1 includes 'indifferent firms' that achieve high ROA while exhibiting high emission intensity. Their main challenge lies in moving away from carbon-intensive operations rather than overcoming financial constraints.

Table 3 shows the trends in company quadrant analysis across four years. 70% of firms maintained a strong relative performance across 4 years. Among these firms, five maintained the same quadrant position over the period. For example, Matson, ranked 29th by TEU in container shipping (Alphaliner, 2026), was consistently positioned in Quadrant 4. Only three companies managed to improve their position on the performance quadrant from Quadrant 2 to Quadrant 3 or 4 (from passive firms to emerging or leading firms): Chinese Maritime Transport, Ardmore, and CMB.TECH.

Meanwhile, several firms struggled to improve their performance. Six firms (15%) remained constrained by low ROA (Quadrant 2 and 3 – emerging and passive firms), while 14 firms (35%) continued to exhibit high emission intensity (Quadrant 1 and 2 – leading and passive firms). One firm, Stolt-Nielsen, consistently remained in the passive firm position, having low ROA and high emission intensity (Quadrant 2). Interestingly, AP Moller-Maersk, ranked 2nd by TEU (Alphaliner, 2026), had high GHG emission intensity and low ROA compared to their peers.

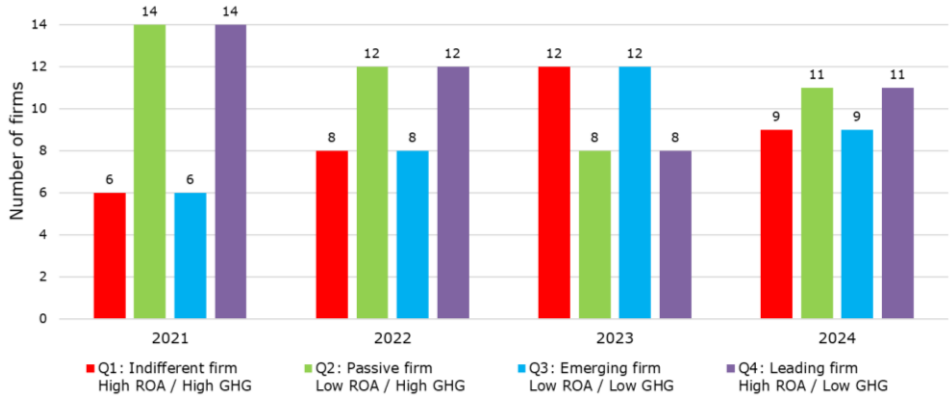


Table 3: 40 firms' quadrant position from 2021 to 2024
Source: Authors' own work

Figure 2 shows the company quadrant analysis in 2024. Firms that achieved strong performance in both financial dimension and direct GHG emission intensity are primarily container shipping companies.

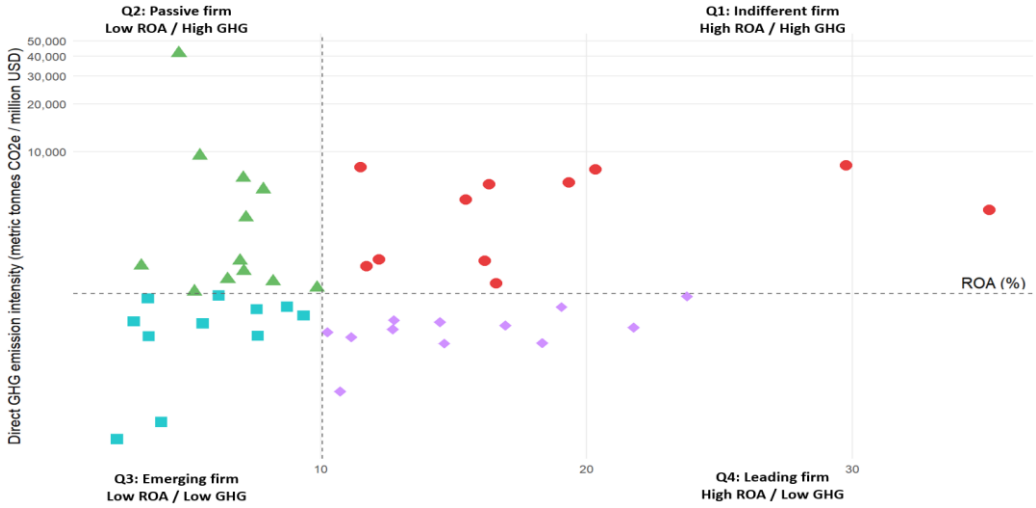


Figure 2: 46 firms' quadrant position in 2024
Source: Authors' own work

We compare companies' position against their decarbonisation initiatives in 2024 to understand whether their financial performance and GHG emissions are associated with the initiatives they adopted (Table 4). All companies adopt a range of measures, rather than a single measure. Widely adopted measures are operational solutions (96%), hull design (93%), and power and propulsion systems (89%). In contrast, alternative fuels (50%) and energy sources (15%) are not commonly implemented. Firms that perform strongly in GHG emissions and ROA (Quadrant 4 – leading firms) act as forefront adopters, implementing more decarbonisation initiatives and prioritising investments in alternative fuels (66.7%) and energy sources (25%). In contrast, despite high ROA, indifferent firms (Quadrant 1) have a low adoption rate of alternative fuels (36.4%) and energy sources (9.1%). On the other hand, despite low ROA, emerging firms (Quadrant 3) have the second-highest adoption rates in alternative fuels (54.5%) and energy sources (18.2%). Finally, passive firms (Quadrant 2) lag behind in commonly adopted measures (83.3% in operational solutions) and less common measures (8.3% in alternative energy sources).

Measure / Quadrant	Hull design	Power & propulsion system	Alternative fuels	Alternative energy sources	Operation
Q1 Indifferent firm	90.9%	90.9%	36.4%	9.1%	100%
Q2 Passive firm	100%	91.7%	41.7%	8.3%	83.3%
Q3 Emerging firm	81.8%	81.8%	54.5%	18.2%	100%
Q4 Leading firm	100%	91.7%	66.7%	25%	100%
Average adoption rate	93%	89%	50%	15%	96%

Table 4: The adoption rate of the decarbonisation measures by quadrant in 2024
Source: Authors' own work

DISCUSSIONS

Financial performance and direct GHG emission intensity

Our findings are consistent with previous studies that most container shipping companies have good performance in ROA and emission intensity because of the high earnings of this container sector compared to other sectors. Container ships usually have a higher freight rate and utilisation rate, creating higher revenue despite high fuel consumption (Gong, Wu and Luo, 2019; Salman, 2025).

The longitudinal data confirms the efficacy of regulations on reducing firms' GHG output, as discussed in Jia and Azevedo (2025). After the introduction of mandatory measures in 2021, the median GHG emission of firms declined substantially and statistically according to the Wilcoxon test, a trend that persisted for the next four years, which also includes the 2023 GHG strategy. Meanwhile, firms' financial performance fluctuated, probably because of volatile freight rates and the unstable market rather than the regulations.

Decarbonisation measures

Measures, such as hull design, power and propulsion system, and operational solutions, are widely adopted because of their low cost and smooth integration into existing vessels. However, their potential to reduce emissions is relatively low (Bouman *et al.*, 2017), often below 10% (Khan *et al.*, 2022). In contrast, alternative fuels and energy sources are not widely adopted due to their implementation constraints. For example, although LNG offers lower CO2 emissions during combustion than fossil fuels, it faces challenges such as methane leakage or the limited availability of bunkering facilities (Luo, Yan and Wang, 2024). Moreover, empirical studies on the use of alternative energy sources remain scarce, making it difficult to assess their impact (Bouman *et al.*, 2017).

The findings reveal that decarbonisation strategies focus on easy-to-implement measures with low emission-reduction impact rather than transitions to alternative fuels and energy sources. Notably, firms with stronger financial performance and lower emission intensity are more willing to invest in alternative fuels and energy sources, as larger firms have more resources for investment, which in turn deliver greater economic benefits (Salman, 2025). In contrast, despite a strong financial background, indifferent firms show limited investment in high-impact measures, suggesting that financial capacity does not guarantee strong decarbonisation ambition. Emerging firms prioritise decarbonisation goals through their high adoption of alternative fuels despite their low ROA, implying their considerations for the decarbonisation transition. Finally, passive firms illustrate how weak financial performance restricts even the commonly adopted decarbonisation initiatives.

Our study has also uncovered how decarbonisation initiatives are adopted in practice. These initiatives have previously been synthesised from the literature by Bouman *et al.,* (2017), yet it is our study that has examined their adoption rate by firms in practice. Therefore, the study highlights the gap between solutions proposed in the literature and those that are currently feasible and adopted by firms.

CONCLUSION

This study provides empirical analyses of the relationship between direct GHG emission intensity and the financial performance of shipping firms in the context of the recent IMO decarbonisation strategies. It shows that, after the mandatory IMO GHG strategy, shipping firms have reduced their GHG emission intensity, while financial performance remains heterogeneous and path dependent. Moreover, financial strength enables the adoption of higher-impact initiatives, highlighting its key role in shaping firms' decarbonisation efforts. These insights suggest that while regulation has been effective in reducing emissions, the level of firms' decarbonisation investment depends on their financial capacity.

The findings contribute to the shipping industry literature by demonstrating four groups of firms based on their emissions and financial performance. Moreover, the study enriches the literature

by examining how decarbonisation investments are linked with firms' emission-financial performance profiles, highlighting the role of financial capacity in reducing emissions. This research also identifies the gap between theoretical decarbonisation solutions (Bouman *et al.*, 2017) and their actual implementation in practice, emphasising the difference between technically feasible measures and those that are economically and realistically viable solutions.

According to the findings, regulation is a key driver of emission reduction and should be maintained to ensure the continued progress towards decarbonisation. Moreover, subsidies could promote the adoption of high-impact decarbonisation measures (i.e. alternative fuels and energy sources). Specifically, policies that are tailored to different performance patterns across firms could support a more balanced and effective industry transition.

To transition towards leading firms, achieving high ROA and low direct GHG emission intensity, firms need different strategies depending on their current performance. Indifferent firms, which achieve high ROA but exhibit high emission intensity, can leverage their strong financial background to invest in higher-impact decarbonisation measures and adopt a broader combination of measures. For firms that lag behind their peers in both financial performance and direct GHG emissions, they should initially prioritise and improve the effectiveness of the low-cost measures. After having a stronger financial condition, firms should consider other high-impact decarbonisation measures.

This work, however, still has some limitations that can be considered in future studies. First, the sample excludes some companies because of their private ownership and thus a lack of publicly available data. Second, our research focuses on the disclosure of decarbonisation initiatives and not on the extent to which they implement these initiatives. Therefore, future research could expand the sample and investigate the implementation level of decarbonisation strategies to provide more comprehensive findings.

REFERENCES

Alphaliner (2026) 'Alphaliner TOP 100'. Available at: https://alphaliner.axsmarine.com/PublicTop100/.

Bloomberg (2025) 'Bloomberg'. Available at: https://www.bloomberg.com/professional/.

Bouman, E.A., Lindstad, E., Rialland, A.I. and Strømman, A.H. (2017) 'State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review', *Transportation Research Part D: Transport and Environment*, 52, pp. 408–421.

Busch, T., Bassen, A., Lewandowski, S. and Sump, F. (2022) 'Corporate Carbon and Financial Performance Revisited', *Organization & Environment*, 35(1), pp. 154–171.

Busch, T. and Lewandowski, S. (2018) 'Corporate Carbon and Financial Performance: A Meta-analysis', *Journal of Industrial Ecology*, 22(4), pp. 745–759.

Choi, T., Cheng, T.C.E. and Zhao, X. (2016) 'Multi-Methodological Research in Operations Management', *Production and Operations Management*, 25(3), pp. 379–389.

Delmas, M.A., Nairn-Birch, N. and Lim, J. (2015) 'Dynamics of Environmental and Financial Performance: The Case of Greenhouse Gas Emissions', *Organization & Environment*, 28(4), pp. 374–393.

Drobetz, W., Janzen, M. and Requejo, I. (2019) 'Capital allocation and ownership concentration in the shipping industry', *Transportation Research Part E: Logistics and Transportation Review*, 122, pp. 78–99.

Ferrat, Y. (2021) 'Carbon emissions and firm performance: A matter of horizon, materiality and regional specificities', *Journal of Cleaner Production*, 329, p. 129743.

Gong, X., Wu, X. and Luo, M. (2019) 'Company performance and environmental efficiency: A case study for shipping enterprises', *Transport Policy*, 82, pp. 96–106.

Govindan, K., Dua, R., Mehbub Anwar, A. and Bansal, P. (2024) 'Enabling net-zero shipping: An expert review-based agenda for emerging techno-economic and policy research', *Transportation Research Part E: Logistics and Transportation Review*, 192, p. 103753.

Jia, H. and Azevedo, P. (2025) 'Sustainable investing and ownership structure in international shipping companies', *Maritime Policy & Management*, 52(5), pp. 691–708.

Karahalios, H. (2024) 'Evaluation of constraints for investment in NOx emission technologies: case study on Greek bulk carrier owners', *Maritime Business Review*, 9(2), pp. 160–176.

Kendall, L.C. (1986) *The Business of Shipping*. Dordrecht: Springer Netherlands.

Khan, S., Grudniewski, P., Muhammad, Y.S. and Sobey, A.J. (2022) 'The benefits of co-evolutionary Genetic Algorithms in voyage optimisation', *Ocean Engineering*, 245, p. 110261.

Kouspos, A., Panayides, P. and Tsouknidis, D. (2023) 'The relationship between technical innovation and financial performance in shipping firms', *Maritime Economics & Logistics*, 25(4), pp. 698–727.

Laskar, I.I., Dowlatabadi, H. and Giang, A. (2025) 'Expert Assessments of Maritime Shipping Decarbonization Pathways by 2030 and 2050', *Earth's Future*, 13(4), p. e2024EF005255.

Le, H. and Nguyen-Phung, H.T. (2024) 'Assessing the impact of environmental performance on corporate financial performance: A firm-level study of GHG emissions in Africa', *Sustainable Production and Consumption*, 47, pp. 644–654.

Lu, P.-H. and Theocharis, D. (2025) 'The influence of energy efficiency and carbon indicators on ship prices: early evidence from the tanker and bulk carrier sectors', *Maritime Economics & Logistics*, 27(3), pp. 549–566.

Luo, X., Yan, R. and Wang, S. (2024) 'After five years' application of the European Union monitoring, reporting, and verification (MRV) mechanism: Review and prospectives', *Journal of Cleaner Production*, 434, p. 140006.

Ma, T., Zhe, T. and Xiao, R. (2025) 'Topics and trends in maritime decarbonization: A structural topic model approach', *Maritime Economics & Logistics* [Preprint].

Salman, M. (2025) 'Exploring economic and cargo efficiencies in the global shipping sector: A convergence analysis', *Journal of Cleaner Production*, 501, p. 145298.

Stopford, M. (2008) *Maritime Economics 3e*. Routledge.

Trumpp, C. and Guenther, T. (2017) 'Too Little or too much? Exploring U-shaped Relationships between Corporate Environmental Performance and Corporate Financial Performance', *Business Strategy and the Environment*, 26(1), pp. 49–68.

Tsatsaronis, M., Syriopoulos, T., Gavalas, D., Boura, G., Trakadas, P. and Gkorila, M. (2024) 'The impact of Corporate Social Responsibility on corporate financial performance: an empirical study on shipping', *Maritime Policy & Management*, 51(2), pp. 226–239.

UNCTAD (2025) 'Maritime trade under pressure – growth set to stall in 2025'. Available at: https://unctad.org/news/shipping-data-unctad-releases-new-seaborne-trade-statistics.

Wang, T., Cheng, P. and Zhen, L. (2023) 'Green development of the maritime industry: Overview, perspectives, and future research opportunities', *Transportation Research Part E: Logistics and Transportation Review*, 179, p. 103322.

WRI (2004) *A Corporate Accounting and Reporting Standard*. Available at: https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf.

Yin, R.K. (2018) *Case study research and applications: design and methods*. Sixth edition. Los Angeles London New Delhi Singapore Washington DC Melbourne: SAGE.

Integrating Connectivity Design and Coordination for Sustainable Logistics: Insights from Japanese Supply Chain Innovation Award-Winners

Sara Abdalla, Siti Mariam Man, Arbaiah Abdul Razak, Wan Rohaida Wan Husain

International Islamic University Malaysia, Malaysia

INTRODUCTION

Achieving a balance between logistics efficiency and sustainability objectives poses a major challenge. Firms across various industries are pressured to cut costs and improve speed while simultaneously reducing emissions, labour burdens, and waste. In this context, logistics connectivity is critical for optimising supply chain (SC) performance, as it integrates dispersed actors, assets, and information flows into coherent end-to-end systems that can support both efficiency and sustainability. Despite large investments in developing logistics connectivity strategies, companies often encounter difficulties in achieving seamless integration across network components. This issue is exacerbated by the limited sharing of detailed strategies and operational optimisation efforts among organisations, which restricts opportunities for learning from effective practices. The resource-based view (RBV) perspective (Barney, 1991), which continues to shape SC research (e.g., Kou & Chiang, 2026; Rahman et al., 2025; Van et al., 2024), posits that integrating logistics network components enables organisations to collaborate, share, and synergise resources essential for success in dynamic environments (e.g., Abdalla, 2021; Khirfan et al., 2025; Rahman et al., 2025).

Recognising that strategies emphasising information sharing and collaboration enhance performance (Kou & Chiang, 2026), research in SCM has increasingly examined best practices and strategies of top-performing or award-winning companies. Recent work examined sustainability and green practices (Al-Kaabi, 2024; Liu, 2024), digitalisation and artificial intelligence adoption (Cannas et al., 2024; Li, 2025), and operational excellence and resilience (Botchie et al., 2021). While these and other contributions offer valuable insights, few studies provide a granular examination of *how* connectivity is actually built and managed. This could be attributed to the fact that companies rarely disclose detailed connectivity and optimisation strategies, instead sharing only high-level descriptions of achievements, lacking the detail level required for corporate benchmarking.

In this regard, award-winning cases offer particularly valuable insights because recognition programs require documented evidence of successful practices. Japanese firms, recognised for resilient and sustainable SCs (World Economic Forum, 2024), provide an exemplary context. The Japanese government has promoted SC transformation through coordinated national initiatives, including the "White Logistics" movement, launched in 2019 to improve logistics productivity and working conditions (White Logistics Movement Official Website, 2019), and the Supply Chain Innovation (SCI) Award, administered by the Ministry of Economy, Trade and Industry (METI) since 2011 to recognise remarkable efforts in optimising entire SCs through cross-sectoral cooperation, aiming to eliminate inefficient operations and establish systems that create new value (*METI*, 2025). Nevertheless, language barriers have limited access to this accumulated knowledge for the global research community.

This research addresses these gaps by examining how award-winning Japanese companies build and manage logistics connectivity to achieve White Logistics objectives. The study analyses Gold Prize-winning cases from METI's SCI Award (2020-2025) to reveal the strategies, mechanisms, and practices enabling successful connectivity implementation. By systematically documenting these previously inaccessible practices, the study contributes empirical insights into how leading firms configure network architectures, coordinate operational flows, and integrate connectivity with sustainability goals. The remainder of this study details the research methodology, presents and discusses the analysis results, and concludes with practical implications, limitations, and trajectories for future research.

METHODOLOGY

This study utilises qualitative document analysis to examine presentation materials from Japan's SCI Gold Award-winners between 2020 and 2025. This prestigious award recognises excellence in collaborative SC optimisation among manufacturers, wholesalers, and retailers (*METI*, 2025). The sample comprises six gold award-winners (see Table 1), representing the highest tier of domestic achievement. Data sources include original competition submissions retrieved from METI archives. These documents offer granular insights into organisational challenges, strategic responses, and quantified outcomes. Document analysis was selected for its capacity to examine rich descriptions of specific phenomena and its efficiency compared to interview-based approaches, which are often prone to subjective bias (Bowen, 2009; Morgan, 2022). For the analysis process, Japanese source texts were translated into English using Sider AI's GPT translator (*Sider*, 2025) to preserve structural context, supplemented by specialised image translation for graphical elements. All translations underwent verification by a native speaker to ensure linguistic and technical precision. The interpretation phase employed reflexive thematic analysis (Braun & Clarke, 2021; Byrne, 2022) through a dual-team coding structure. The first team generated initial codes, while the second team performed reviews and finalisation. Final results were established through iterative reviews and collaborative discussion, ensuring full consensus on final themes.

Table 2. Summary of the Gold award-winning initiatives (2020-2025)

ID	Description
I20	Standardised wheeled carriers from the production line to the retail shelf.
I21	Collaboration for early information sharing and point of sale (POS)-linked planning.
I22	Lead time extension from the next day to N+2 with delivery order cutoff time adjustments.
I23	"Menu Pricing" system to incentivise efficient ordering behaviours.
I24	Industry-wide standardised digital logistics information exchange.
I25	Full-line integrated logistics for food and non-food with aligned layouts.

RESULTS AND DISCUSSION

The analysis revealed three interrelated themes addressing logistics connectivity strategies. Connectivity design emphasises proactive planning and strategic configuration of logistics network architectures that enable materials, information, and financial flows to move in connected, end-to-end patterns. Connectivity coordination focuses on the dynamic management and synchronisation of operational flows within these frameworks through mechanisms such as contracts, standards, information sharing, and joint decision-making. For instance, designing a shared EDI platform represents connectivity design, while establishing protocols for how partners exchange data through that platform constitutes connectivity coordination. The White Logistics theme examines the performance and sustainability outcomes achieved by integrating design and coordination, demonstrating how companies balance economic growth with social responsibility and sustainability. These themes represent sequential and interdependent dimensions: design establishes the structural foundation, coordination operationalises it through aligned behaviours and processes, and together they enable the sustainability and performance outcomes captured in the White Logistics theme. The resulting thematic map is presented in Figure 1.

Connectivity Design

This main theme included six subthemes: data-flow digitalisation, unit-load standardisation, lead-time extension, logistics vertical integration, milk-run logistics, and facilities integration. The initiatives recognised information sharing as crucial for the effective achievement of efficiency and sustainability goals, as stated by one company:

"The realisation of a sustainable and low-cost system and social contribution means that, in this sense, 'logistics' and 'information flow' are areas of cooperation across the three layers" (I22)

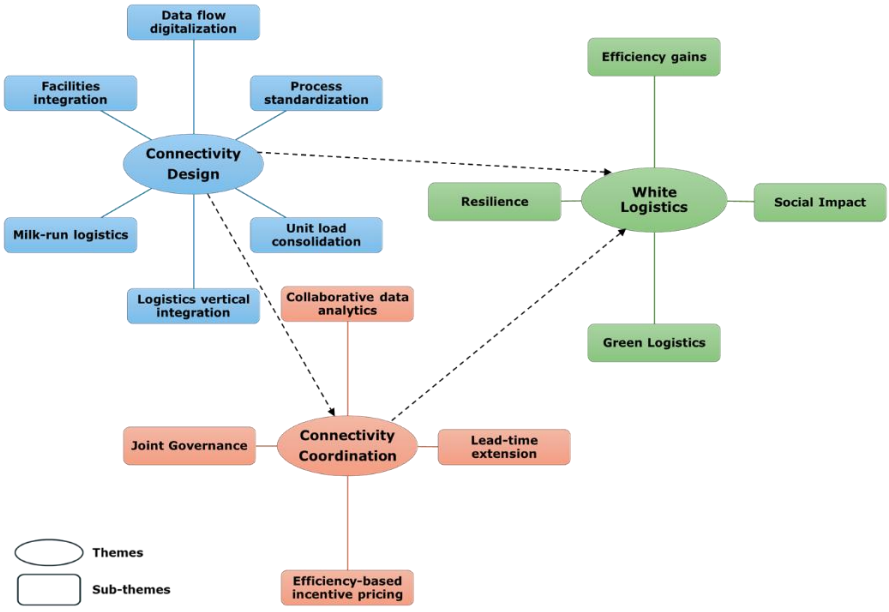


Figure 1. Thematic Analysis Map

Digital connectivity is recognised as a key driver of sustainability (e.g., Dey et al., 2025; Neri et al., 2023; Van et al., 2024). To enhance data flow among stakeholders, a primary improvement target was to digitise information by creating an industry-wide, standardised Electronic Data Interchange (EDI) infrastructure to enable the digital exchange of Advanced Shipping Notices (ASN) between manufacturers and wholesalers. The central achievement was the operational launch of ASN, digitally replacing paper-based documentation and individual information sharing with structured data exchanged via the standardised Logistics EDI. This goal was stated as follows:

"Instead of each manufacturer and wholesaler exchanging data in their own individual ways, the industry will establish a standard logistics information infrastructure and conduct data exchange through that system" (I24)

Logistics operations such as handling and loading consume most of the workers' time. Sequential stages involving inconsistent packaging and container formats increase both operational duration and physical strain, creating inefficiencies. Optimising unit loads through standardisation, pallet redesign, and size adjustments can significantly improve operational efficiency and environmental sustainability (Al-Hourani, 2023; Kim et al., 2023). Following this approach, one initiative utilised standardised wheeled carriers within existing infrastructure, yielding significant results as described by the company:

> *"By introducing unit load systems, a substantial reduction in workload and a significant reduction in working hours (was achieved) without major investment required" (I20)*

Furthermore, refining service standards and optimising them for greater efficiency emerged as primary institutional concerns. While the established benchmark of next-day delivery signalled high responsiveness and service quality, it fostered significant systemic inefficiencies, characterised by "chasing logistics" through small-scale, high-frequency shipments. One initiative proposed adjusting the delivery lead-time to an N+2 framework, coupled with a 2-hour extension of the order confirmation deadline. Although this modification required only a single additional day of processing, it facilitated substantial operational advantages, as documented by a participating firm:

> *"If we deliver on the second day after order receipt, (this will lead to) improvement of the working environment for logistics workers, 'forward-looking' planned logistics, and building flexible logistics from daily operations in preparation for emergencies" (I22)*

Physical integration complements the digital operations by consolidating processes and facilities. One initiative merged previously separate deliveries across different product categories, resulting in a "consolidate to a full-line hybrid centre" (I25). Milk-Run logistics, a delivery method used to transport mixed loads from various suppliers to a single customer, was widely adopted by companies to reduce inbound/outbound and waiting times and increase efficiency. These results were reported across multiple initiatives:

> *"Milk-run collection and delivery system [enabled] consolidated operations [to] ensure efficient mixed-load utilisation" (I25)*

> *"Before the initiative, the round-trip loaded rate was approximately 50%. After the initiative, the round-trip loaded rate increased to approximately 87%" (I23)*

A further step was taken through an initiative to consolidate the facilities. As described by the initiative:

> *"[We achieved] consolidation of [our] shipping base and [our partner's] delivery base into a single location through collaboration" (I23)*

Connectivity Coordination

This theme included process standardisation, collaborative data analytics, efficiency-based incentive pricing, and joint governance. Recognising that the environmental and operational challenges they faced could not be solved in isolation, companies emphasised coordination as the foundation for meaningful change. This belief was shared across multiple firms:

> *"We believe that manufacturing, distribution, and sales are connected as one chain. We are working on optimising and improving the efficiency of the entire distribution process through the cooperation of manufacturing, distribution, and sales" (I20)*

> *"In order to build sustainable logistics, collaboration among the three layers of manufacturing, distribution, and sales is essential" (I22)*

> *"Collaboration among production, distribution, and sales is essential to build supply chains that transcend industry and business model boundaries" (I25)*

The optimisation of data sharing via digitalisation necessitated a comprehensive evaluation and standardisation of current operational procedures, followed by the systematic dissemination of these protocols to all relevant stakeholders. This approach was articulated as follows:

> "We will identify business practices in logistics and information *domains that are recognised as common by manufacturers, distributors, and retailers, from the perspective of overall optimisation, and consider reviewing them and formulating new rules" (I22)*

> *"In order to effectively improve operational efficiency using ASN, it is necessary for manufacturers, wholesalers, and logistics providers to clearly define logistics service standards and promote the standardisation of operations, including 'inspection-free' procedures at the time of receiving goods" (I24)*

Data-flow digitalisation enabled paperless, inspection-free logistics operations, reducing drivers' long wait times while procedures finished. This relief was stated by one initiative:

> *"Once the ASN is sent, the delivery driver leaves the warehouse after unloading is complete, without waiting for the wholesaler to scan the products" (I23)*

Furthermore, the shared EDI systems generated data that companies leveraged for collaborative data analytics via improved demand forecasting and inventory planning by applying predictive sales models to shared POS data, as described by one initiative:

> *"To create a detailed sales plan, a predictive model was developed from the formula derived by graphing the forecasted sales volume by selling price for discontinued products based on daily POS data" (I21)*

Another coordination mechanism aligning private incentives with system-wide connected flows was the implementation of a "menu pricing" framework to decouple product pricing from logistics service costs. Maintaining fixed product prices while adjusting logistics fees incentivises stakeholders to streamline procurement processes. This strategy facilitates logistical optimisation without affecting base consumer prices. The specific parameters of these new terms are articulated by a participating firm as follows:

> *"For deliveries that improve efficiency beyond the standard shipping unit, we provide incentives, while deliveries or returns below the standard shipping unit incur a handling fee. Shipments below the minimum shipping unit are not accepted" (I23)*

This approach facilitated enhanced logistical planning and the consolidation of shipments, resulting in improved operational resilience, as stated by the initiative representatives:

> *"With an increase in early order confirmation, work efficiency improved, making warehouse operations more favourable. In addition, it became possible to respond to logistics fluctuations in advance" (I23)*

Beyond operational integration, coordination evolved into a framework of joint governance characterised by shared accountability. Rather than adopting an adversarial approach to problem-solving or assigning blame for systemic failures, partners established formal mechanisms for collective oversight and mutual commitment to continuous improvement. This was evident in the following statement:

"Regardless of where the responsibility lies for delivery defects, both the manufacturer and logistics provider shall evaluate and analyse the frequency and causes of such occurrences, striving to maintain and improve logistics quality" (I24)

White Logistics

The implementation of strategic connectivity design and coordination, alongside the adoption of industry best practices, has generated significant empirical outcomes. A synthesis of these strategies and practices, along with their reported impacts, is provided in Table 2. Japanese companies, particularly gold award winners of the SCI Award, were driven to achieve sustainable operational excellence through the Sustainable Development Goals (SDGs) alongside several national initiatives, such as the White Logistics movement (Hirata & Matsuda, 2023), the 2024 Work Style Reforms, and the Physical Internet Roadmap. The SDGs provided a framework that connects logistics optimisation to broader environmental and social goals, particularly by reducing carbon emissions and improving working conditions (World Economic Forum, 2024). This is evident in several statements across the initiatives:

> *"We believe this initiative contributes to solving issues tackled by society as a whole, [including] achievement of SDGs, "White Logistics" movement, optimisation and efficiency of the entire supply chain, and work style reform" (I20)*

> *"Due to the '2024 Problem' and logistics crisis, the transition to sustainable logistics is an urgent task" (I23)*

> *"[We aim to] simultaneously achieve overall improvement of productivity in distribution and contribute to sustainability" (I25)*

The White Logistics movement proved most relevant and was frequently mentioned by award winners. Launched by the Ministry of Land, Infrastructure, Transport and Tourism, the Ministry of Economy, Trade and Industry, and the Ministry of Agriculture, Forestry and Fisheries, the initiative addressed severe labour shortages and deteriorating working conditions in the logistics sector. The movement pursued two critical objectives: improving truck transportation productivity and logistics efficiency, and creating a more accessible work environment for women and older workers (White Logistics Movement Official Website, 2019). Major Japanese companies are committed to these improvements through voluntary participation. As stated by one company:

> *"Participation in the "White Logistics" promotion movement was also announced [to] reduce the workload and working hours for truck operators, and address the worsening shortage of truck drivers" (I20)*

Table 3. Reported impacts of strategies and best practices

Themes	**Sub-themes**	**Examples of reported impacts**
Connectivity Design	Data flow digitalisation, Unit load consolidation, Lead-time extension, Logistics vertical integration, Milk-run logistics, and Facilities integration	- Work time: -60% (I20), -10% (I21), -30% (I24), -20% (I25) - Workload: -75% (I20) - Loading rate: +20-30% (I20), +50% (I25) - Delivery frequency: -15% trucks (I23), -50% (I25) - CO2 emissions: -20-30% (I23, I25) - Addressed SDGs: SDGs 3 and 8 (I20), SDGs 12, 13, 14, and 15 (I25)
Connectivity Coordination	Process standardisation, Collaborative data analytics, Efficiency-based incentive pricing, and Joint Governance	- Guidelines disseminated industry-wide (I24) - Store replenishment labour: -20% (I25) - Return rate: 1.3% → 0.8% (I21) - Inspection-less/paperless operations: (I23, I24) - Inventory: -10% (I21), -20% (I25) - Sales increase despite reduced labour (I25) - Stable supply maintained (I22, I25)

The gold-winning companies demonstrated a sense of responsibility and commitment to disseminating the best practices they developed throughout their SCs and across industries. This was evident in several statements, such as:

> *"In the future, we would like to expand this initiative throughout the entire supply chain" (I20)*

> *"This guideline is considered to be useful not only for daily necessities but also for consumer goods in general, including food" (I24)*

The combination of the SDGs and the White Logistics movement created a shared commitment to logistics transformation, positioning sustainability not as an individual corporate choice but as a collective industry responsibility. This alignment proved instrumental in achieving both efficiency and resilience goals that companies had long pursued. The sustainability framework provided companies with a structured approach to address multiple objectives simultaneously, demonstrating that environmental responsibility and operational excellence were mutually reinforcing rather than competing priorities. One company reported these outcomes:

> *"Additional impacts of sustainable and White logistics included a reduction of vehicle count and improved round-trip loaded rate, work efficiency, and environmental impact" (I23)*

The resilience dimension emerged as a particularly significant outcome of sustainability efforts. By optimising logistics networks, standardising processes, and fostering collaboration across SC partners, companies built systems capable of withstanding disruptions. This resilience proved essential in Japan's context, where natural disasters and infrastructure vulnerabilities pose recurring threats to SC continuity. As one initiative described:

> *"Even during disasters or data communication failures, a stable product supply (and an) uninterrupted logistics is realised" (I25)*

The sustainability orientation shifted focus toward resilience and shared value creation. Collaborative frameworks emphasised maintaining essential SC functions, with shared benefits among participants. This principle was particularly evident in the food sector, as one company stated:

> *"Priority will be given to building a strong and resilient food supply chain to maintain and develop the overall mission of the food supply chain, which is the uninterrupted supply of food to consumers, and the benefits generated from this will be shared" (I22)*

CONCLUSION

This study examined how Japanese SCI Gold award-winning companies leverage logistics connectivity to satisfy efficiency and sustainability objectives. The analysis identified three interrelated themes: connectivity design, connectivity coordination, and White Logistics. Connectivity design involves the proactive strategic configuration of network architectures to enable end-to-end material, information, and financial flows. Connectivity coordination manages these flows dynamically through contracts, standards, information sharing, and joint decision-making. The White Logistics theme represents the resulting performance and sustainability outcomes derived from integrating design and coordination. By centring on Japanese SCI Gold award winners, this study provides SC managers with a structured roadmap and concrete implementation examples, even as its specific institutional focus invites further validation in diverse contexts.

ACKNOWLEDGMENTS

This research was funded by the Centre for Islamic Economics (CIE) under Grant Number CIE25-027-0027.

REFERENCES

Abdalla, S. S. A. (2021). Logistics innovation and integration: Impact on supply chain adaptability. *Adapting to the Future: How Digitalization Shapes Sustainable Logistics and Resilient Supply Chain Management. Proceedings of the Hamburg International Conference of Logistics (HICL), Vol. 31*, 639–661. https://www.econstor.eu/handle/10419/249632

Al-Hourani, S. (2023). 'Unit load' evolution: A literature review from 1950–2020. *Journal of Engineering Research*, *11*(2), 192–206. https://doi.org/10.36909/jer.12011

Al-Kaabi, H. (2024). Sustainable Supply Chain Management: A Comparative Analysis of Green Practices in Various Industries. *World Research of Business Administration Journal*, *4*(2). https://doi.org/10.56830/WRBA07202406

Barney, J. (1991). Firm Resources and Sustained Competitive Advantage. *Journal of Management*, *17*(1), 99–120. https://doi.org/10.1177/014920639101700108

Botchie, D., Damoah, I. S., & Tingbani, I. (2021). From preparedness to coordination: Operational excellence in post-disaster supply chain management in Africa. *Production Planning & Control*, *32*(1), 1–18. https://doi.org/10.1080/09537287.2019.1680862

Bowen, G. A. (2009). Document Analysis as a Qualitative Research Method. *Qualitative Research Journal*, *9*(2), 27–40. https://doi.org/10.3316/QRJ0902027

Braun, V., & Clarke, V. (2021). *Thematic analysis: A practical guide*. Sage.

Byrne, D. (2022). A worked example of Braun and Clarke's approach to reflexive thematic analysis. *Quality & Quantity*, *56*(3), 1391–1412. https://doi.org/10.1007/s11135-021-01182-y

Cannas, V. G., Ciano, M. P., Saltalamacchia, M., & Secchi, R. (2024). Artificial intelligence in supply chain and operations management: A multiple case study research. *International Journal of Production Research*, *62*(9), 3333–3360. https://doi.org/10.1080/00207543.2023.2232050

Dey, S., Mishra, R., & Mukherjee, S. (2025). Supply Chain Resilience and Sustainable Digital Transformation with Next-Generation Connectivity in a Smart Port. *Communications of the Association for Information Systems*, *57*. Scopus. https://www.scopus.com/inward/record.uri?eid=2-s2.0-105016363436&partnerID=40&md5=1f67baa1d6155a213aecfc09f3fd5269

Hirata, E., & Matsuda, T. (2023). Examining logistics developments in post-pandemic Japan through sentiment analysis of Twitter data. *Asian Transport Studies*, *9*, 100110. https://doi.org/10.1016/j.eastsj.2023.100110

Khirfan, R., AlHasan, N., Atiyeh, H., Khalifeh, A. H., Holmes, S., & Kotb, H. (2025). Optimising Resources Management in Crises: Strategies, Challenges, Benefits and Conceptual Framework Development. *Research Journal of Pharmacy and Technology*, 2249–2255. https://doi.org/10.52711/0974-360X.2025.00322

Kim, S., Horvath, L., Russell, J. D., & Park, J. (2023). Sustainable and Secure Transport: Achieving Environmental Impact Reductions by Optimising Pallet-Package Strength Interactions during Transport. *Sustainability*, *15*(17), 12687. https://doi.org/10.3390/su151712687

Kou, T.-C., & Chiang, C.-T. (2026). Effects of supply chain strategies on performance and key account management. *Journal of Manufacturing Technology Management*, *37*(1), 23–42. https://doi.org/10.1108/JMTM-11-2024-0613

Li, Y. (2025). Digitalisation and green supply chain activities in manufacturing: A case study of Huawei. *Asia Pacific Journal of Marketing and Logistics*, *37*(8), 2351–2366. https://doi.org/10.1108/APJML-04-2024-0442

Liu, G. (2024). Supply Chain Enhancement Strategies in the Era of Green Development: A Case Study on SF Express. *Highlights in Business, Economics and Management*, *28*, 104–109. https://doi.org/10.54097/ct1dw879

METI. (2025). サプライチェーン　イノベーション大賞（METI/経済産業省）. https://www.meti.go.jp/policy/economy/distribution/shh_scitaisyou.html

Morgan, H. (2022). Conducting a Qualitative Document Analysis. *The Qualitative Report*. https://doi.org/10.46743/2160-3715/2022.5044

Neri, A., Negri, M., Cagno, E., Kumar, V., & Garza-Reyes, J. A. (2023). What digital-enabled dynamic capabilities support the circular economy? A multiple case study approach. *Business Strategy and the Environment*, *32*(7), 5083–5101. https://doi.org/10.1002/bse.3409

Rahman, F., Anwar, D., & Faizanuddin, Md. (2025). Interconnected Supply Chain Management and Logistics: Key to Driving Business Success. *Management (Montevideo)*, *3*, 142. https://doi.org/10.62486/agma2025142

Sider. (2025). [Computer software].

Van, N. T. A., Hieu, N. K., & Hanh, N. T. M. (2024). Logistics 4.0 capabilities and performance: The moderating role of digital transformation. *J. for Global Business Advancement*, *17*(1), 121–142. https://doi.org/10.1504/JGBA.2024.149488

White Logistics Movement Official Website. (2019, October 8). 「ホワイト物流」推進運動について. *「ホワイト物流」推進運動ポータルサイト*. https://white-logistics-movement.jp

World Economic Forum. (2024, February 20). *How Japan is creating a sustainable and resilient future for the logistics industry*. World Economic Forum. https://www.weforum.org/stories/2024/02/japan-sustainable-and-resilient-future-for-logistics/

Transit-Net: Mastering the Traffic-Aware Vehicle Routing Problem With Time Windows Using Multi-Stream Attention

Dhawal Thakkar, Balamurugan Palaniappan

Indian Institute of Technology (IIT), Bombay, India

INTRODUCTION

Efficient logistics are foundational to the global economy, yet real-world urban distribution faces complexities far exceeding the classic Vehicle Routing Problem (VRP). Modern operations require fleets with varying capacities [1, 2], customer delivery time windows [3], and resilience against time-varying traffic congestion [4]. The Traffic-Aware Heterogeneous Capacitated VRP with Time Windows (TA-HCVRPTW) encapsulates these challenges, seeking minimal-cost routes while adhering to operational constraints under traffic conditions. Classical solvers like Google OR-Tools and heuristic libraries (e.g., PyVROOM) solve static instances efficiently but are inherently rigid [5]. They rely on expert tuning, struggle to adapt to traffic conditions, and cannot learn from data [6]. While neural approaches have advanced rapidly from early RNNs [7] to Transformers [6] and decoders [8], most still assume static travel times and require retraining for new locations, creating a major scalability bottleneck. We introduce TRANSIT-Net, a Multi-Stream Transformer designed to solve the TA-HCVRPTW. TRANSIT-Net utilizes three parallel streams (Site, Vehicle, Time) to jointly predict routing triplets (Site, Vehicle, Time Bucket). Trained via a supervised self-improvement fashion, TRANSIT-Net generates high-quality, traffic-aware routes in 0.1 seconds, an order of magnitude faster than traditional solvers.

LITERATURE REVIEW

The VRP landscape is defined by the trade-off between optimality and speed. Exact methods guarantee optimality but struggle to scale. Heuristics like Genetic Algorithms (GA) and Ant Colony Optimization (ACO) offer industrial scalability but depend heavily on problem-specific tuning and lack adaptivity [11, 12]. Neural networks have emerged to bridge this gap. Attention-based models [6,13] have approached heuristic performance on static VRPs. Recent works have targeted specific constraints: Lietal. [8] introduced heterogeneous fleet decoding, while Mozhdehi et al. [14] utilised edge encoding for time windows. However, these models typically treat routing based constraints (heterogenous vehicles, time windows) in isolation. The closest predecessor, SED2AM [15], models time-dependent travel for multi-trip scenarios but lacks fleet heterogeneity and granular time-window prediction. To the best of our knowledge, most of the existing learning-based solvers simultaneously struggle to unify dynamic traffic, heterogeneous fleets, and hard time windows while offering zero-shot generalization. Table 1 illustrates how TRANSIT-Net addresses this fragmentation. By integrating a traffic-aware Graph Attention Network (GAT) with a grid-based abstraction, TRANSIT-Net learns the complexities of urban congestion rather than overfitting to specific coordinates, enabling it to solve complex, unseen scenarios in real-time.

Table 1: Comparison of TRANSIT-Net with state-of-the-art learning-based VRP solvers

Method	Problem Variant	Traffic Aware	Depot Depart.	Time Window	Scale	Zero-Shot Generaliz.
AM [6]	CVRP	×	×	×	×	×
HeteroVRP [8]	HCVRP	×	×	×	✓	×
Edge-DIRECT [14]	E-VRP	×	×	×	✓	×
SED2AM [15]	MTTDVRP	✓	✓	×	×	×
TRANSIT-Net (Ours)	TA-HCVRPTW	✓	✓	✓	✓	✓

PROBLEM DEFINITION & TRAFFIC-AWARE MODELING MOTIVATION

We formally define the Traffic-Aware Heterogeneous Capacitated Vehicle Routing Problem with Time Windows (TA-HCVRPTW) on a directed graph $G = (\mathrm{V}, \mathrm{E})$. The node set $V = \{0, 1, \ldots, N\}$ comprises a central depot (node 0) and N customer nodes. Each customer $i \in V \setminus \{0\}$ is associated with a demand $m_i > 0$, a strict service time window $[e_i, l_i]$, and a service duration $\sigma_i \geq 0$. The fleet K consists of heterogeneous vehicles located at the depot. Each vehicle $k \in K$ is defined by a specific capacity Q_k, a fixed dispatch cost c_k^f, and a variable travel cost rate c_k^v. Incorporating time-dependent travel times is crucial for generating realistic urban route plans, as traditional static models based on average speeds fail to account for significant congestion fluctuations. A route optimized for average conditions may become infeasible during peak hours, potentially causing missed delivery windows. By utilizing a time-dependent travel function $\tau_{ij}(\theta)$, where travel time depends on the departure time θ from node i, our traffic-aware model proactively adjusts routes and departure times to ensure robust schedules and on-time deliveries. This transforms the problem from a static combinatorial task into a dynamic decision-making process, allowing the TRANSIT-Net framework to balance travel costs and time-window feasibility by adapting to traffic based transit times throughout the day. We define the travel time function $\tau_{ij}(\theta)$ as the duration to travel from node i to j departing at time θ, capturing time-varying congestion. A feasible solution consists of routes $\{(v_0^k, \ldots, v_{p+1}^k)\}$ for vehicle k, starting and ending at the depot ($v_0^k = v_{p+1}^k = 0$), subject to specific constraints. First, the total demand $\sum_{j=1}^{p} m_{v_j^k}$ must not exceed capacity Q_k. Second, the service start time $u_{v_j^k} = \max\left(A_{v_j^k}, e_{v_j^k}\right)$ must satisfy $u_{v_j^k} \leq l_{v_j^k}$, where $A_{v_j^k}$ is the arrival time of vehicle k at site v_j^k. Third, arrival times propagate according to $A_{v_{j+1}^k} = u_{v_j^k} + \sigma_{v_j^k} + \tau_{v_j^k, v_{j+1}^k}\left(u_{v_j^k} + \sigma_{v_j^k}\right)$. The objective is to minimize total operational cost $C = \sum_k \left(c_k^f + c_k^v \sum_j \tau_{v_j^k, v_{j+1}^k}\right)$. To rigorously evaluate predictions, we employ a generalized cost including penalties for wait times $\lambda_{wt} \sum \max\left(0, e_{v_j^k} - A_{v_j^k}\right)$ and late arrivals $\gamma_{lt} \sum \max\left(0, u_{v_j^k} - l_{v_j^k}\right)$, where λ_{wt} and γ_{lt} are constants. The problem reduces to the classical HCVRPTW when $\tau_{ij}(\theta)$ is constant.

SOLUTION METHODOLOGY

We propose TRANSIT-Net, a deep learning framework designed to solve both the Static HCVRPTW (S-HCVRPTW) and its traffic-aware extension, TA-HCVRPTW. Our methodology centersontraininganovelmulti-streamTransformeronhigh-qualitysupervisedd ata. Lever-aging the ability of Transformers to model complex dependencies, we reformulate the rout-ing problem as a sequence prediction task. The objective is to generate a master sequence

of triplets S = ⟨(g1,k1,b1),(g2,k2,b2),...,(gN,kN,bN)⟩, where gi represents the grid label of a customer node, ki is the assigned vehicle ID, and bi is the discrete time bucket for the service start time. Crucially, this sequence is arranged chronologically such that bi ≤ bi+1. This sorting transforms the problem from optimizing isolated vehicle routes into learning a global fleet schedule, allowing the model to perceive simultaneous activities across the entire fleet rather than processing one vehicle at a time. For S-HCVRPTW, we generate baseline solutions using Google OR-Tools. For the traffic-aware variant, where standard solvers are not useful, we employ a custom heuristic (K-Means + ACO + Local Search). To overcome the sub-optimality of the heuristic baselines for TA-HCVRPTW, TRANSIT-Net utilizes a self improvement mechanism (to be discussed later).

Data Preparation and Triplet Construction: To illustrate the transformation from raw problem instance to training targets, consider a synthetic example with N = 10 customers (v1 ...v10) served by a heterogeneous fleet.

Step 1: Spatial Discretization. Customer coordinates (x,y) are mapped to discrete cells in a 20 × 20 grid. For instance, v1 maps to grid label 42, v2 to 86, etc.

Step 2: Baseline Solution Generation. The solver produces routes with specific start times. For example:

• Route A (Vehicle 1): Depot → v1 (08:10) → v5 (09:00) → v2 (10:30) → Depot.

• Route B (Vehicle 6): Depot → v3 (08:15) → v8 (09:45) → v4 (11:00) → Depot. •

Route C (Vehicle 2): Depot → v9 (08:05) → v6 (08:45) → v10 (09:30) → …

Step 3: Label Transformation & Sequencing. Continuous times are discretized into 15-minute buckets (e.g., 08:10 → bucket 32). All stops are then merged into a single master sequence sorted by time bucket as follows:

S = ⟨ (101,2,32), // v9 (Veh 2, 08:05)

(42,1,32), // v1 (Veh 1, 08:10)

(150,6,33), // v3 (Veh 6, 08:15)

(15,2,35), // v6 (Veh 2, 08:45)...and so on. ⟩

This chronological ordering teaches the model the natural progression of the day.

Step 4: Inference and Reconstruction. At inference, the model autoregressively predicts triplets (gˆt,kt,bt),ˆ cônstrained by feasibility masks. The final route plan is reconstructed by grouping the predicted triplets by Vehicle ID (k) and ôrdering them by Time Bucket (b), ensûring a physically realizable schedule.

SYNTHETIC DATA GENERATION FRAMEWORK

To rigorously evaluate our model, we developed a synthetic data generation framework capable of producing diverse and challenging problem instances for both S-HCVRPTW and TA-HCVRPTW variants.

The spatial environment is a unit square S = [0,1]2 partitioned into a 20×20 grid G of 400 cells, where coordinates map to the top-left corner (Figure 1). This discretization generalizes to continuous coordinates via g = ⌊x · G dim⌋ × G dim + ⌊y · G dim⌋, eliminating the need for retraining on new locations. An instance graph G = (V,E) consists of a central depot at (0.5,0.5) and n customer nodes sampled uniformly from G \ {0}. As shown in Table 2, each customer i is assigned a demand mi ∼ U(12,15), a fixed service duration σi = 15 min, and a time window [ei,ℓi] in either the [08:00,14:00] slot or [14:00,20:00] slot, where baseline travel costs are derived from the Euclidean distance matrix D = [dij].

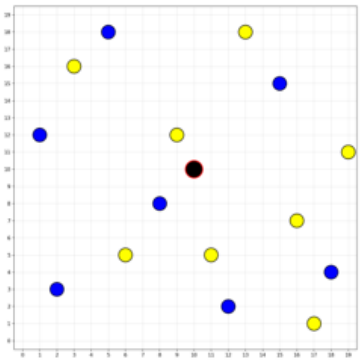


Figure 1: Example grid layout (N = 15). Active sites are shown in colors indicating time windows (blue: 8am-2pm, yellow: 2pm-8pm). The depot is marked in black.

Table 2: Site Node Attributes

Attribute	Specification
Node ID	Unique identifier $i \in \{0, 1, \ldots, n\}$
Coordinates (x_i, y_i)	Top left corner of grid cell in $[0, 1]^2$
Demand m_i	Integer sampled from $U(12, 15)$
Time Window $[e_i, \ell_i]$	Randomly assigned to $[08:00, 14:00]$ or $[14:00, 20:00]$
Service Time σ_i	Constant duration of 15 minutes

Heterogeneous Fleet Composition: Each instance is serviced by an unlimited heterogeneous fleet of five vehicle types (k ∈ K). As detailed in Table 3, each type is characterized by capacity Qk, variable travel cost ¢k, and fixed dispatch cost ₹k.

Table 3: Heterogeneous Vehicle Fleet Characteristics.

Type	**Capacity (Q_k)**	**Var. Cost (c_k)**	**Fixed Cost (c_k)**
1	50	10	10,000
2	100	15	12,000
3	150	20	13,000
4	200	25	13,500
5	250	30	13,800

Time-Dependent Travel Model: To simulate urban congestion, we introduce a multiplier δ(θ) that scales the baseline distancedij. This multiplier follows a piecewise-constant function of the departure time θ, sampled from uniform distributions for typical and extreme conditions:

$$\delta(\theta) \sim \begin{cases} \mathcal{U}(3,6) \text{ "typical conditions" / } \mathcal{U}(4,10) \text{"extreme conditions} & \theta \in [8,10) \\ \mathcal{U}(2.5,4) \text{ "typical conditions" / } \mathcal{U}(3,6) \text{"extreme conditions} & \theta \in [10,13) \\ \mathcal{U}(2,5) \text{ "typical conditions" /} \mathcal{U}(3,6) \text{"extreme conditions"} & \theta \in [13,16) \\ \mathcal{U}(4,7) \text{ /"typical conditions" / } \mathcal{U}(5,11) \text{"extreme conditions} & \theta \in [16,20] \end{cases}.$$

The effective travel time is computed as τij(θ) = dij · δ(θ).

HYBRID HEURISTIC FOR TA-HCVRPTW SOLUTION GENERATION

To generate robust baseline solutions for TA-HCVRPTW, where standard solvers struggle with dynamic travel times, we developed a custom multi-stage hybrid metaheuristic. This algorithm employs a cluster-first, route-second methodology to decompose the complex problem into tractable sub-problems, as visualized in Figure 2.

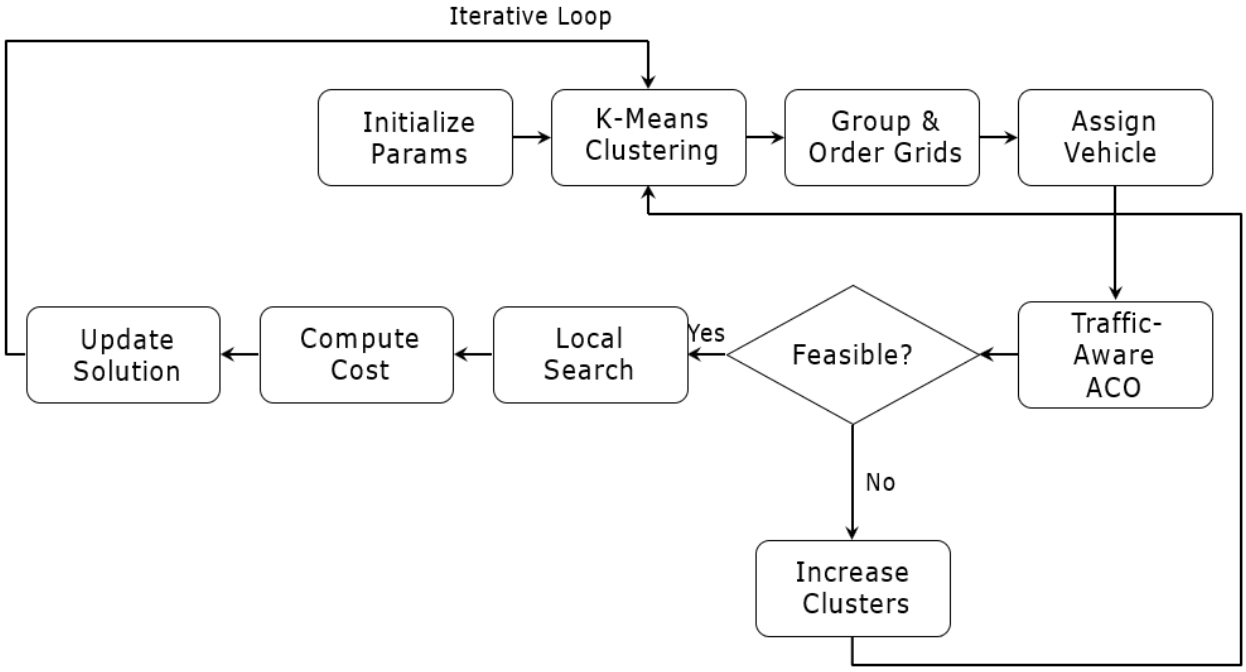


Figure 2: Workflow of the Hybrid Heuristic. The process runs iteratively within a time limit to refine clusters and routes.

The workflow begins by initializing the minimum number of clusters required based on total demand. The core logic is enclosed in an iterative loop that continues until a maximum solve time is reached, allowing the algorithm to explore different configurations for a better solution cost. In the first phase, K-Means-clustering spatially partitions the customers, and grids within each cluster are ordered by time-windows. The smallest feasible vehicle is assigned to each group. The second phase involves routing and feasibility checks. A Traffic-Aware Ant Colony Optimization (ACO) algorithm constructs initial routes. Each candidate route undergoes a feasibility check where a subroutine searches for a valid depot departure time that satisfies all constraints under dynamic traffic. If no such time exists, the algorithm increments the number of clusters and restarts the grouping process. If a feasible time is found, the route is refined using Local Search operators to minimize cost. This entire cycle repeats to continuously improve the solution quality.

PROPOSED MODEL: TRANSIT-NET

We introduce TRANSIT-Net, a multi-stream Transformer architecture designed to solve the TA-HCVRPTW by unifying it into a sequence prediction task. The model operates on three parallel streams: Sites, Vehicles, and Time.

Feature Engineering and Encoder Architecture: The efficacy of TRANSIT-Net relies on rich, multi-stream feature representations. We engineer distinct feature sets for each stream. Site Features encode normalized coordinates, demands, time windows, and critical demand-to-capacity ratios for every vehicle type to explicitly signal fleet compatibility. Vehicle Features encode normalized capacity, costs, and unique identifiers to distinguish heterogeneous capabilities. Time Features provide a simplified spatio-temporal view combining coordinates with discrete time bucket indices. These raw features are projected into a d-dimensional space and processed by three parallel Transformer Encoders. To

capture the specific topology of the problem, we augment these streams with a Graph Attention Network (GAT) [14]. The GAT processes a k-NN graph where edges represent accessibility. For the traffic-aware variant, edge features are 4-dimensional vectors containing inverse travel times for different traffic slots allowing the model to perceive time-dependent congestion. This graph context is fused into the Site and Vehicle embeddings via element-wise addition, ensuring the encoder outputs are topologically-aware and traffic-aware.

Decoder and Training with Self-Improvement: The decoding module consists of three parallel Transformer stacks that jointly predict the next Grid label, Vehicle ID, and Time Bucket. As illustrated in Figure 3, the decoders interact with all encoder memories via a shared Multi-Head Cross-Attention bus. To enforce strict constraint adherence, we inject dynamic feasibility masks directly into this attention mechanism. A Vehicle Capacity Matrix masks vehicles with insufficient remaining load, and a Time Window Matrix masks time buckets that violate customer service windows.

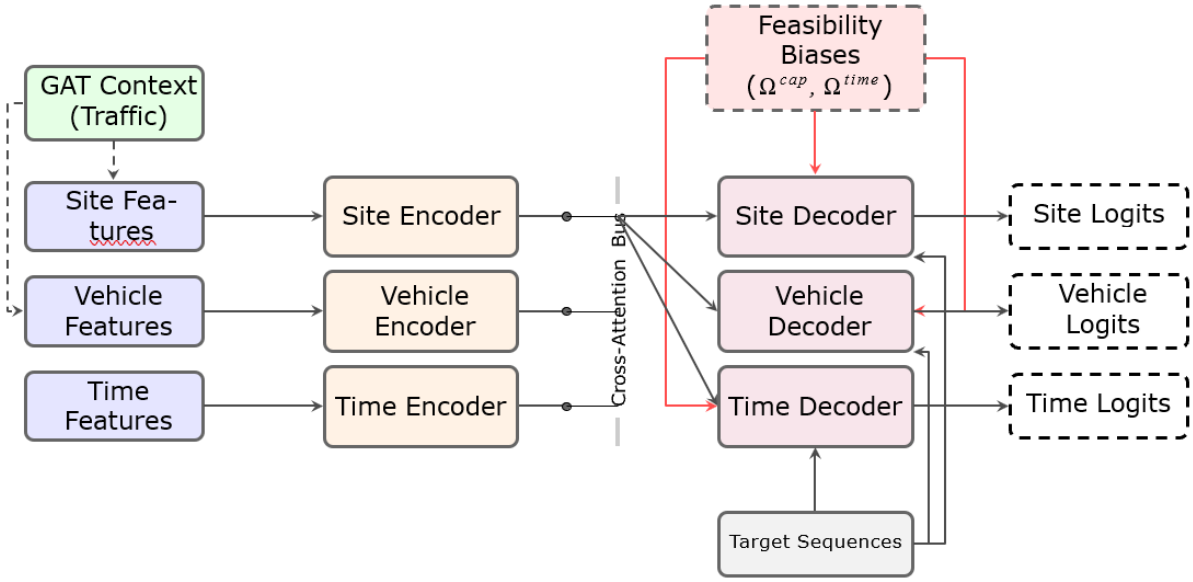


Figure 3: TRANSIT-Net Architecture Overview. Parallel Site, Vehicle, and Time streams are enriched by a traffic-aware GAT. Multi-stream attention across three decoders is implemented where dynamic feasibility biases are introduced.

Training is supervised using a weighted cross-entropy loss against ground-truth sequences derived from baselines. We employ a Self-Improvement Loop where the model periodically runs inference on training samples. If it generates a solution with a lower cost than the current baseline, the training target is overwritten, allowing the model to iteratively surpass its initial heuristic baseline solutions.

INFERENCE: FEASIBLE SOLUTION GENERATION

Generating solutions for unseen instances involves a masked greedy decoding strategy that autoregressively constructs the route step-by-step. Inference relies on the TRANSIT-Net's own predictions from previous step to update the routes and enforce validity.

The inference workflow is visualized in Figure 4. At step zero, the process initializes with an empty set of served customers and full vehicle capacities. For each subsequent step, TRANSIT-Net computes feasibility biases based on the current state of the solution. The Vehicle Capacity Bias prevents assignment to vehicles lacking sufficient capacity for specific nodes, while the Time Window Bias invalidates time buckets that fall outside a customer's service window. These biases are applied to the raw logits produced by the decoder. We then perform a masked greedy selection to identify the most probable valid triplet. This selection triggers a state update where the customer is marked as served, and the vehicle capacity is reduced. This cycle repeats until the End-of-Sequence token is predicted, guaranteeing that the final constructed route is physically realisable and strictly compliant with all constraints.

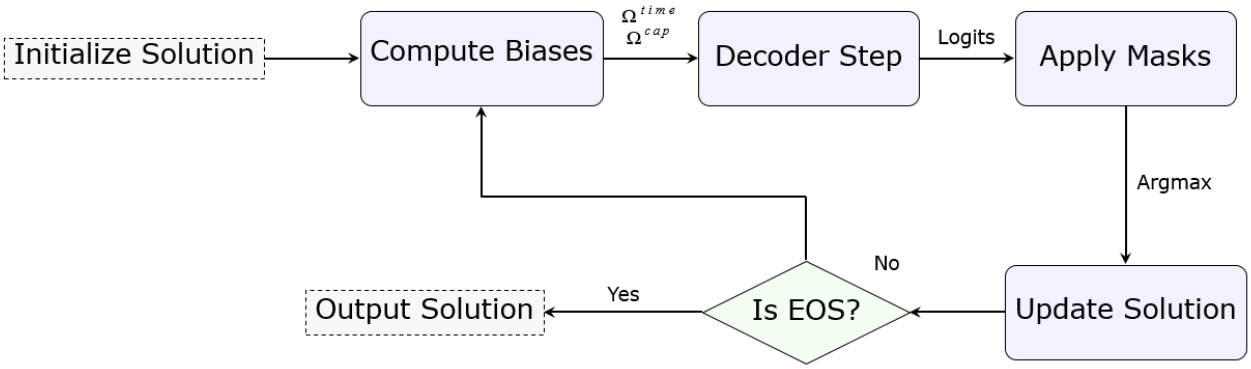


Figure 4: Cyclic Inference Workflow. Dynamic feasibility biases computed from the current state, mask output logits to ensure valid triplet selection. The process iterates with state updates until the End-of-Sequence token is generated.

EXPERIMENTAL EVALUATION

In this section,we present a comprehensive evaluation of TRANSIT-NetonbothS-HCVRPTW and TA-HCVRPTW. Experiments are conducted on synthetically generated instances reflecting the characteristics defined in Section 5. Our evaluation follows a two-stage validation process. First, we assess foundational performance on S-HCVRPTW by benchmarking against state-of-the-art solvers to establish competence in core combinatorial optimization. Second, we evaluate TRANSIT-Net's primary strength in handling traffic-dependent travel times by benchmarking on TA-HCVRPTW against high-quality heuristic solutions.

This highlights TRANSIT-Net'scapacity to navigate traffic-induced complexity where conventional solvers struggle and TRANSIT-Net'sability to surpass heuristic solutions.

To train TRANSIT-Net, we generated two synthetic datasets. For S-HCVRPTW, we created 50,000 instances solved using Google OR-Tools (3-minute limit) to provide baseline labels. For Traffic-Aware TA-HCVRPTW, we generated 92,000 instances, where each static layout is paired with 5 distinct traffic scenarios (re-sampled delay curves), creating a rich dataset of congestion patterns solved by our hybrid heuristic. The number of customer sites N is sampled uniformly from [10,15]. We utilize held-out test sets totally unseen during training: 3,000 distinct static instances and around 7,300 traffic-aware instances.

Results and Analysis

We benchmark TRANSIT-Net against industry-standard open-source solvers: Google OR-Tools, PyVRP (Hybrid Genetic Search), and PyVROOM. We exclude specific neural architectures from literature as most do not support the combined constraints of heterogeneous fleets, hard time windows, and lack reproducible code. Our results demonstrate that TRANSIT-Net is competitive and often superior to these gold standards on completely unseen test cases, proving robust zero-shot generalization.

Performance on S-HCVRPTW

We compare TRANSIT-Net against Google OR-Tools (Training Baseline solved for 180s and Fast Solution solved for 1s), PyVRP (1s solve time limit), and PyVROOM (1s solve time limit). Table 4 reports key metrics, while Table 5 details generalization capability. The most impactful observation is inference speed. TRANSIT-Net generates routes in 0.1 seconds, a 10x speed-up over 1-second benchmarks and 1800x over the 3-minute baseline. This validates it as a true real-time solver. In terms of solution quality, TRANSIT-Net frequently outperforms PyVRP and PyVROOM. For N = 10, it achieves a97%exactmatchratewiththeoptimal-tierbaselineandsurpassesPyVRPin98%ofcases. As complexity increases to N = 15, exact matches decrease to 74.8%, but the model still beats PyVRP in 77% of cases and PyVROOM in 25%. Feasibility rates remain robust, with

over 93% of instances having zero wait times across all sizes. While late penalties cause some cost inflation in larger instances, the routing efficiency (distance) remains consistently superior to PyVRP. These results are presented in Table 5.

Performance on TA-HCVRPTW

For traffic-aware evaluation, we compare against three baselines: Traffic-Aware Ant Colony Optimization (ACO) (our training heuristic), Traffic-aware Genetic Algorithm (GA). Both traffic-aware ACO and traffic-aware GA methodsrunfor180 seconds, while TRANSIT-Net operates at 0.1s. TRANSIT-Net demonstrates remarkable dominance in the traffic-aware setting. For N = 11, it out-performs the GA in 87.5% of cases and the ACO in 79.7%, as seen in Table 6. The 0.1s inference speed offers an 1800x speed-up over the 180s heuristic baselines. While feasibility rates drop slightly to 61.5% for N = 15 due to late arrivals in complex scenarios, the model consistently finds shorter paths (avg distance 155.1 vs 152.4 for ACO), as seen in Table 7. This confirms that TRANSIT-Net effectively learns the spatio-temporal structure of the problem, offering a viable real-time solution for dynamic logistics.

CONCLUSION

We introduce TRANSIT-Net, a deep learning framework for the Heterogeneous Capacitated Vehicle Routing Problem with Time Windows in static and dynamic traffic conditions. Experiments confirm that it matches established solvers like Google OR-Tools in solution quality while enabling real-time inference for unseen S-HCVRPTW instances. In complex traffic scenarios for TA-HCVRPTW instances, the model demonstrates self-improvement, frequently outperforming the heuristics solutions on completely unseen test instances by effectively learning congestion dynamics. Although limited data causes occasional feasibility gaps, the results validate our multi-stream Transformer architecture TRANSIT-Net as a robust, scalable foundation for next-generation autonomous logistics systems.

REFERENCES

1 Kool,W.,vanHoof,H.,&Welling,M.(2018). Attention, learnt to solve routing problems!

ICLR.

2 Ichoua, S., Gendreau, M., & Potvin, J. Y. (2003). Vehicle dispatching with time-dependent travel times. European Journal of Operational Research.

3 Tilk, C., et al. (2021). The last-mile vehicle routing problem with time windows.

4 Anderluh, A., Hemmelmayr, V. C., & Nolz, P. C. (2020). Synchronizing vans and cargo bikes in a city distribution network.

5 Wouda, N. A., et al. (2024). PyVRP: a high-performance VRP solver.

6 Kool, W., van Hoof, H., & Welling, M. (2019). Attention, Learn to Solve Routing Prob-lems! ICLR.

7 Bello, I., et al. (2016). Neural combinatorial optimization with reinforcement learning. arXiv preprint.

8 Li, J., et al. (2022). Heterogeneous Fleet Vehicle Routing Problem with Deep Rein-forcement Learning.

9 Gasse, M., et al. (2021). Combinatorial Generalization.

10 Laporte, G. (2009). Fifty years of vehicle routing. Transportation Science.

11 Wang, Y., et al. (2018). An effective ACO for the rich vehicle routing problem. 12 Vidal, T. (2022). Hybrid genetic search for the vehicle routing problem.

13 Zhang, K., et al. (2020). Multi-agent reinforcement learning for VRPTW. 14 Mozhdehi, et al. (2024). Edge-DIRECT: Edge-encoding for VRPTW.

15 Mozhdehi, et al. (2025). SED2AM: Learning to solve time-dependent VRP.

Table 4: Performance benchmarking on small Static HCVRPTW instances ($N = 10$ to 15).

Size (N)	Method	Avg. Cost (Obj.)	Avg. Wait (min)	Avg. Late (min)	Avg. Dist.	Veh. Used
10	OR-Tools (180s)	20509.2	0.00	0.00	358.3	1–2
	OR-Tools (1s)	20523.8	0.00	0.00	359.7	1–2
	PyVRP (1s)	29894.9	0.00	0.00	427.1	1–3
	PyVROOM (1s)	26872.1	0.00	0.00	365.3	1–3
	TRANSIT-Net (0.1s)	20643.1	0.2	0.4	365.9	1–2
11	Baseline OR-Tools (180s)	21767.4	0.00	0.00	378.3	1-2
	Google OR-Tools (1s)	21815.7	0.00	0.00	379.6	1-2
	PyVRP (HGS) (1s)	31128.17	0.00	0.00	449.3	2-3
	PyVROOM (1s)	27864.4	0.00	0.00	385.9	1-3
	TRANSIT-Net (0.1s)	22455.4	1.4	0.3	389.1	1-3
12	Baseline OR-Tools (180s)	24012.7	0.00	0.00	393.3	1-2
	Google OR-Tools (1s)	24128.5	0.00	0.00	395.3	1-2
	PyVRP (HGS) (1s)	32296.3	0.00	0.00	468.5	2-3
	PyVROOM (1s)	28983.0	0.00	0.00	400.8	1-3
	TRANSIT-Net (0.1s)	24578.1	0.98	2	405.8	1-2
13	Baseline OR-Tools (180s)	24924.70	0.00	0.00	411.5	1-2
	Google OR-Tools (1s)	25069.6	0.00	0.00	414.7	1-2
	PyVRP (HGS) (1s)	33993.7	0.00	0.00	491.3	2-3
	PyVROOM (1s)	30318.3	0.00	0.00	422.7	1-3
	TRANSIT-Net (0.1s)	26005.1	1.6	4.6	434.3	1-2
14	Baseline OR-Tools (180s)	25811.6	0.00	0.00	425.5	1-2
	Google OR-Tools (1s)	26110.5	0.00	0.00	428.1	1-2
	PyVRP (HGS) (1s)	35760.3	0.00	0.00	512.7	2-3
	PyVROOM (1s)	32246.4	0.00	0.00	442.9	1-3
	TRANSIT-Net (0.1s)	27676.7	1.6	8.0	458.0	1-3
15	Baseline OR-Tools (180s)	28830.4	0.00	0.00	441.3	1-2
	Google OR-Tools (1s)	29329.0	0.00	0.00	445.4	1-2
	PyVRP (HGS) (1s)	37789.3	0.00	0.00	540.3	2-3
	PyVROOM (1s)	34920.4	0.00	0.00	465.7	1-3
	TRANSIT-Net (0.1s)	31751.4	1.7	16.1	494.8	1-3

Table 5: Granular Analysis of TRANSIT-Net Generalization (Static).

Size (N)	Total Inst.	Exact Match vs Baseline (%)	Superiority vs. Fast Solvers (%) > OR-Tools (1s)	> PyVROOM	> PyVRP	Feasibility Rates (%) 0 Wait	0 Late	0 Violations
10	500	97.0%	3.8%	7.4%	98.4%	99.6%	99.6%	98.4%
11	514	85.4%	2.5%	4.5%	96.1%	95.7%	95.7%	94.6%
12	472	90.9%	4.0%	7.4%	97.2%	96.6%	95.3%	93.6%
13	510	81.8%	4.1%	13.1%	92.7%	94.9%	90.8%	89.0%
14	468	76.5%	4.5%	17.7%	87.4%	94.7%	86.3%	83.8%
15	536	74.8%	4.3%	25.0%	77.4%	93.5%	78.4%	76.7%

Table 6: Performance comparison on TA-HCVRPTW instances ($N = 11$ to 15).

Size (N)	Method	Avg. Cost	Avg. Wait (min)	Avg. Late (min)	Avg. Dist.	Veh. Used	Solve Time
11	Genetic Algorithm	32,141.3	0.0	0.0	140.5	2-3	180s
	Traffic-Aware ACO	30,474.3	0.0	0.0	140.0	2-3	180s
	TRANSIT-Net	29,825.4	0.4	9.3	124.6	2-3	0.1s
12	Genetic Algorithm	33,421.0	0.0	0.0	148.8	2-3	180s
	Traffic-Aware ACO	31,721.5	0.0	0.0	145.5	2-3	180s
	TRANSIT-Net	30,948.3	0.6	11.0	133.0	2-3	0.1s
13	Genetic Algorithm	34,838.0	0.0	0.0	149.6	2-3	180s
	Traffic-Aware ACO	32,995.9	0.0	0.0	147.4	2-3	180s
	TRANSIT-Net	31,923.0	0.4	12.8	140.8	2-3	0.1s
14	Genetic Algorithm	36,180.5	0.0	0.0	154.5	2-3	180s
	Traffic-Aware ACO	34,218.1	0.0	0.0	150.7	2-3	180s
	TRANSIT-Net	32,511.6	0.4	11.3	145.1	2-3	0.1s
15	Genetic Algorithm	37,550.7	0.0	0.0	158.8	2-3	180s
	Traffic-Aware ACO	35,548.1	0.0	0.0	152.4	2-3	180s
	TRANSIT-Net	34,075.6	0.5	19.2	155.1	2-3	0.1s

Table 7: Analysis of TRANSIT-Net Superiority and Feasibility on TA-HCVRPTW.

Size (N)	Total Inst.	Superiority Rates (%)		Feasibility Rates (%)		
		$\leq$ GA	$<$ ACO	0 Wait	0 Late	0 Violations
11	1428	87.5%	79.7%	98.8%	78.6%	78.0%
12	1439	86.8%	76.7%	98.1%	76.4%	76.0%
13	1457	86.8%	74.5%	98.0%	74.5%	74.3%
14	1416	89.7%	75.4%	98.1%	75.4%	74.9%
15	1355	83.6%	75.2%	97.4%	61.9%	61.5%

From Cost Minimization to Environmental Stewardship: Transportation Trade-Offs in Supply Chains

Youssef Sayed Morsy[1], Esraa Zayed[2]

1: German International University, Egypt; 2: American University in the Emirates, United Arab Emirates

INTRODUCTION

Transportation decisions in general represent one of the most critical and important supply chain management components, as they have a direct influence on both the economic performance and the organizations environmental footprint (Denant-Boemont et al., 2025). Transportation activities account for a substantial share of the total logistics costs as well as being a major contributor to emissions of the greenhouse gas, fuel consumption, and air pollution (Banihashemi and Khalilzadeh, 2020). As supply chains nowadays became much more globalized and complex, decision-makers are required to evaluate transportation alternatives that balance efficiency, reliability, and sustainability (Khorsandi Karimi et al., 2021).

Historically, transportation decision-making in general has been dominated by cost-oriented objectives. As the managers minimizing direct costs such as fuel expenses, vehicle maintenance and labor costs all was on the top of the list of priorities, moreover, the delivery times in order to maintain the competitiveness level and meet requirements of service-level (Stankov et al., 2024). Cost efficiency has been treated as the primary and the main indicator of transportation performance, especially in emerging markets and economies as Egypt, where margins are tight and operational constraints are significant (Tavasszy et al., 2020). However, the growing urgency of climate change, stricter environmental regulations, and rising stakeholder expectations have placed increasing pressure on organizations to reduce the environmental impacts associated with transportation activities (BaniHashemi and Khalilzadeh, 2020).

Environmental considerations in the transportation process includes carbon emissions, energy efficiency and noise pollution (Halsnaes et al., 2023). While technological advancements as the software systems for the route optimization processes and digital tracking tools have a significant position in order to reduce the level of emissions and improve the level of efficiency (Hauschild et al., 2022). In real life, environmental moves often require significant financial investment and organizational commitment as well as a long-term strategic plan, which may conflict with short-term cost reduction goals (Bai et al., 2020).

The conflict between minimizing transportation costs and reducing environmental impact has created a solid and clear trade-off that managers must navigate and deal with. In many organizations and industries, usually environmental considerations remains secondary especially in operational decision-making (Banihashemi and Khalilzadeh, 2020). This gap between the two main variables highlights the importance and needs for a much deeper understanding of how transportation managers perceive and manage competing objectives in real-world contexts (Khorsandi Karimi et al., 2021). Existing research has largely focused on quantitative optimization models or technological solutions, offering limited insight into how mangers could deal with this kind of trade-off (Slattery et al., 2021).

This study mainly responds to this gap by examining transportation decision-making through a qualitative data lens, focusing on how managers evaluate cost drivers, recognize the environmental impacts as well as how to balance the trade-off between these two variables. By exploring managerial perspectives, the research contributes to a more understanding of sustainable transportation decision-making, particularly within cost-sensitive and developing market contexts.

LITERATURE REVIEW

Transportation costs have a significant portion of total logistics expenses and are highly influenced by factors such as fuel prices, labor and maintenance costs (Tavasszy et al., 2020). Past research emphasizes that cost minimization remains the first dominant objective in transportation planning, especially in a competitive and resource-constrained environments and economies (Bani Hashemi and Khalilzadeh, 2020). Organizations and institutions frequently adopt digital tools and automation technologies to enhance efficiency and reduce the total operational costs (Bai et al., 2020).

Furthermore, transportation activities and process are widely recognized as one of the major and main sources of environmental impact, that mainly contributing to carbon emissions and subscribe in energy consumption and air pollution (Hauschild et al., 2022). Studies highlight the role of the vehicle type and model and the total traveled distance as well in determining environmental performance (Halsnaes et al., 2023). While technological advancements offer many opportunities in order to mitigate environmental impacts, their effectiveness depends on managerial willingness to integrate environmental criteria into decision-making processes (Stankov et al., 2024).

The literature identifies the existence of a trade-off between both the cost efficiency and the environmental responsibility when taking a transportation process (Banihashemi and Khalilzadeh, 2020). Moreover, transportation options that are environmentally friendly usually requires a significant initial investment or operational costs, which may deter organizations from adopting them, especially in the absence of strong regulatory incentives (Khorsandi Karimi et al., 2021). As a result, environmental considerations are usually treated as constraints rather than to be treated as a strategic objective (Stankov et al., 2024).

Although past studies provide valuable insights into transportation efficiency and sustainability, there is a large limited qualitative research examining how managers perceive and manage this trade-off in practice (Slattery et al., 2021). This study builds on existing literature by shifting the focus from technical solutions to managerial decision-making, which is more of a real experience decisions, thereby addressing a critical gap in understanding the human and organizational dimensions of transportation sustainability (Tavasszy et al., 2020; Halsnaes et al., 2023).

Having the target of growing body of literature review showing how transportation decisions are actually made especially when conflicts between cost efficiency and environmental impact (Tavasszy et al., 2020). Many studies have examined transportation cost optimization techniques and environmental assessment tools independently, without sufficiently and accurately addressing how decision-makers prioritize or integrate these objectives in real life practices (Slattery et al., 2021; Bai et al., 2020).

The core research problem addressed in this study mainly in the part of disconnection between the increasing recognition of the responsibility regarding the environment and the continued dominance of cost-driven especially decisions related to the transportation process (Banihashemi and Khalilzadeh, 2020). While organizations may express commitment to the sustainability process and activities on the other hand that the managers managing the transportation process usually operate under strict cost constraints, performance targets, and operational pressures that limit the extent to which environmental considerations can be applied (Khorsandi Karimi et al., 2021). This issue is particularly evident in emerging economies, where infrastructure limitations, fuel price volatility, and limited regulatory enforcement further reinforce cost-focused decision-making (Stankov et al., 2024).

Moreover, existing research stated that in order to achieve a sustainable transportation, the primary pathway is to emphasize technological solutions (Halsnaes et al., 2023). Although digital technologies can enhance efficiency as well as cutting emissions, but they do not entirely address the underlying managerial and organizational variables (Hauschild et al., 2022). The importance of managerial, experience and organizational culture in affecting the cost–environment trade-off remains underexplored, especially from a qualitative viewpoint (Slattery et al., 2021).

Simply, this research aims and seeks to investigate transportation decision-making by focusing on the managers perspectives involved in transportation and logistics activities. The main aim

for the study is to explore how cost and environmental considerations are evaluated and prioritized and how managers navigate the inherent trade-off between these competing objectives. And accordingly, the following research questions are developed.

RQ1: How can transportation managers balance between the financial efficiency with sustainability objectives when taking a transporting decision?

RQ2: What are the main environmental impacts and cost factors influencing in transportation decisions?

RQ3: What decision-making approach can help in balancing the cost efficiency with environmental sustainability in transportation?

METHODOLOGY

Showing the exploratory nature of the research problem, this study adopts a qualitative research methodology, this enables a richer and more nuanced analysis (Rahman, 2016). This qualitative research is particularly suitable when the objective is to gain an in-depth understanding of experiences and especially decision-making processes rather than to test already pre-defined hypotheses (Oliver, 2015; Pham, 2018).

The study mainly uses an exploratory research design, as the trade-off between the two variables remains underexplored from a managerial perspective, for the exploratory research design, simply allows flexibility in both data collection and data analysis process (Atmowardoyo, 2018).

To collect our primary data to be collected, a semi-structured interviews were used and chosen as the data collection method (Farooq et al., 2017). For the semi-structured interviews are extremely effective in capturing detailed insights and data particularly when examining complex trade-offs involving both economic and environmental considerations (Gray et al., 2020). The semi-structured interviews format allowed the researcher to follow a predefined set of guiding questions while retaining the flexibility to probe deeper into relevant issues raised by participants (Bowden & Galindo-Gonzalez, 2015). The questions of the interviews were developed and extracted based on the literature review and the research objectives (Farooq et al., 2017). Questions focused on transportation cost drivers, environmental awareness, the role of technology in transportation decisions and how managers balance between the two variables (Gray et al., 2020).

The targeted interviewed cadres consisted of 8 professionals working in transportation, logistics and supply chain management roles who are always directly involved in transportation related decision-making processes, table 1 provides sample profile. Confirming that our sample included cadres from different managerial hierarchy levels, as well as the different years of experience and functional responsibilities to capture diverse perspectives. Data collection process continued until reaching the theoretical saturation level. Next data was analyzed using qualitative thematic analysis in which interview transcripts were manually coded to identify the main concepts, patterns and relationships related to the trade-off. The analysis process involved iterative comparison between interview data and existing literature (Neuendorf, 2017).

Table 4: Sample Profile

Interviews	Current Position	Industry	Years Of Experience
Interviewee 1	CEO (Chief Executive Officer)	Automotive industry	40 Years
Interviewee 2	General Manager of the Factory	Production of the industrial machines industry	25 Years
Interviewee 3	CEO (Chief Executive Officer)	Seating and Medical Solution Manufacturing Industry	30 Years

Interviewee 4	Supply Chain Manager	Construction and Heavy Equipment Industry	15 Years
Interviewee 5	Head of Procurement and Logistics Department	Textile Industry	17 Years
Interviewee 6	Fleet Manager	Logistics and Transportation Services Industry	12 Years
Interviewee 7	Transportation Junior Manger	Transportation Industry	5 Years
Interviewee 8	Supply Chain Manger	Retail and E-commerce Industry	10 Years

FINDINGS AND DISCUSSION

The findings simple indicates that transportation decision-making is largely driven by cost considerations as it is on the top of the prioritize list for the entities and mangers, while on the other hand environmental aspects are increasingly acknowledged but remains as a secondary in practice. Through the qualitative analysis, trying to reflect to how managers perceive and manage the trade-off between cost efficiency and environmental impact which counts as the two main variables.

After the analysis processes some findings have been revealed that cost efficiency remains the primary determinant in the transportation decisions processes. The interviewed cadres consistently identified fuel costs, vehicle and labor expenses and delivery reliability as one of the most influential factors shaping their decisions. The total transportation costs found that having a direct impact on supply chain performance as well as competitive power of the organization, making cost minimization an essential managerial priority. These indicates that transportation decisions are always guided by economic performance indicators, particularly in cost-sensitive and operationally constrained markets (Denant-Boemont et al., 2025; Banihashemi and Khalilzadeh, 2020).

On the other hand, the findings analyzed from the cadres interviewed show a growing awareness of the environmental impacts in general and especially among transportation decision-makers. Interviewers highlighted the environmental consequences of transportation activities that usually includes carbon emissions, high fuel consumption. Environmental initiatives are taken into considerations and added in the activities only when they aligned with cost reduction objectives or external regulatory pressures (Slattery et al., 2021).

To have managing the cost–environment trade-off much easier, technology emerged could be one of the factors that could help. As the interviewed mangers highlighted the use of route optimization and transportation management systems as well as performance monitoring tools as these could help in reducing fuel consumption, improving vehicle utilization and minimizing unnecessary travel. These technologies help to simultaneously achieve both the cost efficiency and the environmental improvements. Moreover, this totally align with the previous studies and Literature review section that emphasis the role of digital transformation in enhancing both transportation efficiency and reducing environmental impact (Gursoy, 2010).

Mainly showing the technology recognized benefits that could positively affect the whole organization on the other hand there is a significant financial and operational barriers to its adoption. High investment costs, training requirements and system complexity were cited as the main key challenges, these could be much more significant for smaller organizations and firms operating in emerging markets, furthermore these constraints limit the extent to which technological solutions can be (Burnham et al., 2021). This observation supports the existing literature which highlights that any advancements in technological alone are insufficient to ensure sustainable transportation outcomes (Denant-Boemont et al., 2025)

The findings shows the importance of managerial perception as well as the organizational culture in order to shape the transportation decisions. Cadres interviewed emphasized that decision-making is influenced not only by technical and financial factors but also by the organizational priorities, performance evaluation criteria and leadership management, these made it more likely to be integrated into the transportation decisions process. These all reinforcing the role of organizational context in managing the cost–environment trade-off (Hwang & Kim, 2019; Bertalero et al., 2020).

Finally, the findings indicate that the absence of broader structural and cultural change while technology and managerial awareness contribute to improved environmental performance but are insufficient. Participants stated and highlighted that deeply rooted cost-oriented performance metrics and operational pressures continue to constrain environmentally responsible decision-making. This shows the significant need for much more integrated combine approaches that contain technological adoption with changes in organizational culture, managerial incentives and strategic priorities (Slattery et al., 2021; Banihashemi and Khalilzadeh, 2020).

Practical Implications

The findings offer practical guidance for transportation and supply chain managers as well as the logistics directors that are seeking to balance both of our main variables cost efficiency with environmental responsibility. Organizations should integrate environmental performance indicators into decision-making related to the transportation processes to ensure sustainability considerations are added alongside cost objectives. Digital technologies could simultaneously help in reduce costs and emissions only when supported by appropriate training. In addition, embedding sustainable activities within the organizational strategy could obviously enhance managerial commitment to environmentally responsible. Policymakers may further support through regulations and incentives that reduce the financial burden of sustainable transportation initiatives, particularly in cost-sensitive markets.

Theoretical Implications

This study contributes to the literature by advancing understanding of the cost–environment trade-off in transportation decisions from a perspective of a qualitative managerial. The findings stated the importance of the managerial perception as well as the organizational context especially in shaping transportation outcomes. By demonstrating that cost efficiency and environmental responsibility require deliberate integration rather than isolated consideration, the study supports the development of more holistic frameworks for sustainable decision-making for the transportation processes.

CONCLUSION, LIMITATIONS AND FUTURE RECOMMENDATION

Generally, this study is conducted and made in order to explore how transportation decision-makers manage and prioritize the trade-off between cost efficiency and environmental impact within supply chain operations specifically in the transportation processes. Transportation remains one of the most critical and complex components in the logistics systems and processes, as it directly affects organizational competitiveness while simultaneously contributing to environmental level of impact. By adopting a qualitative research approach, this study provided in-depth insights into managerial perceptions.

The findings clarify and highlight that the cost considerations remains to be the dominate in the transportation decision-making processes. Managers always prioritize cost-related factors, as they are directly linked to both the operational performance and the customer satisfaction. On the other hand, environmental considerations are much more recognized by the mangers and organizations, but it remains secondary and are frequently incorporated only when they align with cost reduction objectives or regulatory requirements.

The study as well revealed that advancement in technology play a significant role in moderating the cost–environment trade-off. Digital tools and automation enable the organizations to improve efficiency while simultaneously reducing the level of emissions. However, technology alone is insufficient to resolve the trade-off.

Finally, the study confirms and highlight that the decision-making related to the transportation processes is not purely technical but deeply embedded within organizational constraints. The trade-off between the two variables which are cost and environmental impact is shaped by managerial priorities, financial pressures and the broader institutional environment in which organizations operate.

As with any research, this study faced some limitations that should be acknowledged and taken into considerations in the future researcher papers. First, the qualitative nature of the research limits the generalizing process of the findings data. While the study provides rich findings that obviously may not be representative of all industries, geographical regions and countries. Future research could adopt a mixed-methods approach to validate and extend the findings through adding quantitative data collected and analyzed.

Second, the study mainly focuses on a specific regional and organizational context, which may affect and influence the transportation decision-making process dynamics. Differences in regulation as well as the infrastructure development of the country itself may affect and change how cost and environmental considerations are specially balanced. We recommend future studies should explore diverse geographical regions to capture a broader range of decision-making contexts and have more easier generalizing process.

Finally, future research could explore longitudinal design in the data collection processes in order to examine how transportation decision-making changes over time in response to regulations changes, technological advancements, this would obviously enhance understanding of how organizations transition toward more sustainable transportation practices while maintaining economic competitiveness.

REFERENCES

Bai, Q., Miralinaghi, M., Labi, S., & Sinha, K. C. (2020). Methodology for analyzing the trade-offs associated with multi-objective optimization in transportation asset management under uncertainty. Computer-Aided Civil and Infrastructure Engineering, 36(4), 381–401. https://doi.org/10.1111/mice.12637

Banihashemi, S. A., & Khalilzadeh, M. (2020). Time–cost–quality–environmental impact trade-off resource-constrained project scheduling problem with DEA approach. Engineering, Construction and Architectural Management, 27(9), 2813–2836. https://doi.org/10.1108/ECAM-05-2020-0350

Bertalero, G., Rosa, A., & Chiara, B. D. (2020). Analysis of outsourcing conditions for freight transport and logistics among manufacturing companies: insights from a review of data and a field investigation. Transportation Research Procedia, 45, 459–466. https://doi.org/10.1016/j.trpro.2020.03.039

Bowden, C., & Galindo-Gonzalez, S. (2015). Interviewing when you're Not Face-To-Face: The use of email interviews in a phenomenological study. International Journal of Doctoral Studies, 10, 79–92. http://ijds.org/Volume10/IJDSv10p079-092Bowden0684.pdf

Burnham, A., Muratori, M., & Hunter, C. (2021). Comprehensive total cost of ownership quantification for vehicles with different size classes and powertrains. Argonne National Laboratory. https://doi.org/10.2172/1780970

Denant-Boemont, L., Faulin, J., Hammiche, S., & Serrano-Hernandez, A. (2025). Bargaining for the last mile cost and environmental preferences of stakeholders: An economic experiment. Transportation Research Procedia, 82, 251–270. https://doi.org/10.1016/j.trpro.2024.12.041

Farooq, M. B., De Villiers, C., Auckland University of Technology, & The University of Auckland, and University of Pretoria. (2017). Telephonic Qualitative Research Interviews, when to consider them and how to do them. Meditari Accountancy Research, 25(2), 291– 316. https://repository.up.ac.za/server/api/core/bitstreams/f3366279-fc84-4f56- 8b42-cba961dfd8ad/content

Gray, L. M., Wong-Wylie, G., Rempel, G. R., Cook, K., Athabasca University, & University of Athabasca. (2020). Expanding qualitative research interviewing strategies: Zoom video communications. The Qualitative Report, 25(5). https://pdfs.semanticscholar.org/d782/8a504edee06948d3b47c40506be7caea88bc.p df

Gursoy, M. (2010). A method for transportation mode choice. Scientific Research and Essays, 5(7), 613–624. https://doi.org/10.5897/SRE.9000152

Halsnaes, K., Some, S., & Pathak, M. (2023). Beyond synergies: understanding SDG trade-offs, equity and implementation challenges of sectoral climate change mitigation options. Sustainability Science, 18(2), 451–467. https://doi.org/10.1007/s11625-023-01322-3

Hauschild, M. Z., McKone, T. E., Arnbjerg-Nielsen, K., Hald, T., Nielsen, B. F., Mabit, S. E., & Fantke, P. (2022). Risk and sustainability: trade-offs and synergies for robust decision making. Environmental Sciences Europe, 34(1). https://doi.org/10.1186/s12302-021-00587-8

Hwang, T., & Kim, S. T. (2019). Balancing in-house and outsourced logistics services: effects on supply chain agility and firm performance. Service Business, 13(3), 531–556. https://doi.org/10.1007/s11628-018-00394-x

Khorsandi Karimi, S., Jalali Naini, S. G., & Sadjadi, S. J. (2021). An integration of environmental awareness into flexible supply chains: A trade-off between costs and environmental pollution. Environmental Science and Pollution Research, 28(23), 29428–29446. https://doi.org/10.1007/s11356-021-13454-z

Kim, K.-S. (2022). Methodology of non-probability sampling in survey research. American Journal of Biomedical Science & Research, p. 616. https://doi.org/10.34297/AJBSR.2022.15.002166

Lindgren, B., Lundman, B., & Graneheim, U. H. (2020). Abstraction and interpretation during the qualitative content analysis process. International Journal of Nursing Studies, 108, 103632. https://doi.org/10.1016/j.ijnurstu.2020.103632

Neuendorf, K. A. (2017). The Content Analysis Guidebook (Second Edition). SAGE Publications, Inc. https://howardaudio.wordpress.com/wp-content/uploads/2018/01/content-analysis-in-the-interactive-media-age.pdf

Oliver, S. (2015). Advantages of concurrent preparation and reporting of systematic reviews of quantitative and qualitative evidence. Journal of the Royal Society of Medicine, 108(3), 108–111. https://doi.org/10.1177/0141076815575231

Pham, L. (2018). A Review of key paradigms: positivism, interpretivism and critical inquiry. Preprint. https://doi.org/10.13140/RG.2.2.13995.54569

Rahman, M. S. (2016). The Advantages and Disadvantages of using qualitative and quantitative approaches and methods in language “Testing and Assessment” research: A literature review. Journal of Education and Learning, 6(1), 102. https://doi.org/10.5539/jel.v6n1p102

Slattery, M., Gao, A. L., & Wan, Y. (2021). Life cycle assessment of environmental impact of disposable drinking straws: a trade-off analysis with marine litter in the United States. Science of the Total Environment, 817, 153016. https://doi.org/10.1016/j.scitotenv.2022.153016

Stankov, I., Meisel, J. D., Sarmiento, O. L., Delclòs-Alió, X., Hidalgo, D., Guzman, L. A., Rodriguez, D. A., Hammond, R. A., & Roux, A. V. D. (2024). Uncovering physical activity trade-offs in transportation policy: A spatial agent-based model of Bogotá, Colombia. International Journal of Behavioral Nutrition and Physical Activity, 21(54). https://doi.org/10.1186/s12966-024-01570-1

Tavasszy, L. A., de Bok, M., Alimoradi, Z., & Rezaei, J. (2020). Logistics decisions in descriptive freight transportation models: A review. Journal of Supply Chain Management Science, 1(3–4), 73–84. https://doi.org/10.18757/jscms.2020.1992

Walentynowicz, M., Schneider, S., & Stone, A. A. (2018). The effects of time frames on self-report. PLoS ONE, 13(8), e0201655. https://doi.org/10.1371/journal.pone.0201655

Wang, S., Song, R., Xu, Z., Chen, M., Di Tanna, G. L., Downey, L., Jan, S., & Si, L. (2024). The costs, health and economic impact of air pollution control strategies: a systematic review. Global Health Research and Policy, 9(1). https://doi.org/10.1186/s41256-024-00373-y

Wang, X., & Cheng, Z. (2020). Cross-sectional studies: strengths, weaknesses, and recommendations. Chest, 158(1), S65–S71. https://doi.org/10.1016/j.chest.2020.03.012

SMART/DIGITAL SUPPLY CHAINS

Bridging Information and Innovation in Green Supply Chains: The Case of Saudi Arabia

Safinaz Abourokbah, Mohammad Asif Salam, Nada Badawi

King Abdulaziz University, Saudi Arabia

ABSTRACT

Purpose of this paper

This research aims to explore how supply chain information integration (SCII) improves green supply chain innovation performance (GSCIP) by analysing essential mediating processes and boundary conditions in supply chains. The study specifically aims to (1) evaluate the direct and indirect impact of SCII on GSCIP, (2) investigate the mediating role of green supply chain learning (GSCL) and assess the moderating influence of green entrepreneurial orientation (GEO), and (3) analyse the sequential mediation of green absorptive capacity (GACAP) and employee green creativity (EGC). By addressing these objectives, the study seeks to provide a comprehensive explanation of the importance of digital information integration for green innovation performance in manufacturing supply chains. This study examines Saudi manufacturing firms and addresses the need for context-specific research on sustainability and logistics, especially in rapidly evolving economies with high environmental and digital transformation goals.

Design/methodology/approach

The proposed research model was examined using partial least squares structural equation modelling (PLS-SEM), which is particularly appropriate for predictive research, complex models, and emerging research contexts (Hair et al., 2021). The investigation used a two-stage process: first, evaluating the measurement model for reliability and validity; second, assessing the structural relationships and testing the hypotheses. To strengthen the robustness and practical relevance of the findings, the study integrates Importance–Performance Map Analysis (IPMA) and Necessary Condition Analysis (NCA) with PLS-SEM. IPMA was used to identify the relative importance and performance of key antecedents influencing GSCIP, while NCA was applied to determine whether specific constructs represent necessary conditions for achieving high levels of green innovation performance. This multi-method analytical approach enables a deeper understanding of both sufficient and necessary drivers of GSCIP within supply chains.

Findings

The findings reveal that SCII has a significant and positive impact on GSCIP. SCII enables manufacturing firms to enhance environmental transparency, coordinate sustainability-related decisions, and support green innovation initiatives across SCPs. The results further demonstrate that GSCL plays an important mediating role, highlighting that information integration must be transformed into shared understanding and collective learning to generate innovation outcomes. The role of GEO as a moderator strengthens the SCII-GSCL relationship, suggesting that firms with proactive, sustainability-oriented strategic postures are better positioned to enhance learning mechanisms when they benefit from information integration. In addition, the study identifies a significant sequential mediation effect: SCII enhances GACAP, which, in turn, stimulates EGC, ultimately leading to improved GSCIP. This finding underscores the importance of organizational capabilities and employee-level creativity in translating knowledge flows into green innovations.

Value

This paper offers several original contributions to green supply chain management literature. First, it advances understanding of green innovation by explaining how SCII translates into GSCIP through both organizational and individual-level mechanisms. Second, by integrating KBV and DCT, the study provides a multi-theoretical framework that clarifies the roles of knowledge

transformation and dynamic capabilities in sustainability-driven innovation. Third, the combined use of PLS-SEM, IPMA, and NCA offers novel methodological insights by distinguishing between sufficient and necessary conditions for green innovation performance. Finally, the study enriches empirical knowledge by focusing on Saudi manufacturing firms, an underexplored context undergoing rapid digital and environmental transformation.

Research limitations/implications

This study is subject to several limitations. The cross-sectional research design restricts causal inference, suggesting that future studies could adopt longitudinal approaches to capture dynamic learning and innovation processes. The data were collected from a single country and industry context, which may limit generalizability.

Practical implications

The findings provide clear guidance for supply chain managers and policymakers. Managers should prioritize supply chain information integration as a strategic capability rather than a purely technological investment. Establishing structured learning mechanisms and enhancing GACAP can help firms convert shared information into innovative outcomes.

Keywords: supply chain, information integration, green absorptive capacity, innovative performance, green supply chain learning, employee creativity, Vision 2023.

INTRODUCTION

Recent market evidence shows that products with environmental or sustainability claims have grown significantly faster than their conventional counterparts in recent years, underscoring the business move toward sustainability-oriented offerings (Qu et al., 2022). These shifts compel supply chain (SC) managers to reconfigure networks around GI-oriented strategies, yet the substantial investments in technology, human capital, and financing that green innovation (GI) requires often exceed firms' internal resources, constraining their ability to innovate independently (Al-Swidi et al., 2024, Ullah et al., 2024). To enhance green innovation performance (GIP) under these conditions, firms must go beyond organizational boundaries and collaborate proactively with supply chain partners (SCPs) to access complementary capabilities and resources (Idrees et al., 2025). Such collaborations can strengthen information integration by pooling critical data on resource use, environmental impacts, and regulatory requirements (Jalil et al., 2025). Supply chain information integration (SCII)—the alignment of information systems and sustainability-related data across SCPs (Lyu et al., 2022)—can streamline sustainable SC processes, reduce waste, improve resource efficiency, and support superior performance (Haq & Cao, 2024). As a result, SCII mechanisms are pivotal for achieving green supply chain innovation performance (GSCIP), enabling firms to shrink environmental footprints, reduce costs, build competitive advantage, comply with regulations, address stakeholder expectations, and support long-term sustainability (Idrees et al., 2025).

Even though some studies have explored how information technology and information exchange enhance innovation outcomes (Jalil et al., 2025; Lin & Wu, 2025), there remains limited clarity regarding the mechanisms through which these practices translate into green supply chain innovation performance (GSCIP) within green supply chain management (GSCM) and broader sustainable business practices. In particular, prior work has rarely, if ever, investigated how SCII interacts with GSCL to drive GSCIP. Addressing this gap, the present study investigates the relationship between SCII and GSCIP, with GSCL as a mediator and GEO as a moderator, responding to the scarcity of research on GEO's role in reinforcing the SCII–GSCL linkage. In addition, much of the existing literature focuses on direct effects and overlooks firms' capabilities to absorb, transform, and convert knowledge into novel ideas when employees are empowered with that knowledge. In this regard, GACAP and EGC may represent critical intermediate mechanisms in the GIP process. By concentrating on the Saudi manufacturing sector—where firms face growing pressure and incentives to adopt sustainable practices—this study highlights the importance of a strategic, knowledge-intensive approach to achieving superior GSCIP.

Furthermore, although the knowledge-based view (KBV) is frequently employed to explain competitive advantage in sustainable supply chains, few studies have applied this lens to understand how technology and information, as strategic resources, shape the development of specific capabilities that underpin GIP. This gap leads to the following key research question:

RQ1. How and under what conditions does SCII enhance GSCIP in Saudi manufacturing firms?

RQ2**.** How does SCII, as a knowledge-based system, foster GSCL and ultimately lead to GSCIP?

RQ3. Does GEO moderate the SCII–GSCL relationship, and what is its ripple effect on GSCIP?

RQ4. Do GACAP and EGC act as sequential mediators in the relationship between SCII and GSCIP?

By answering these questions, this study contributes to the literature in different ways. It integrates DCT and KBV theories to demonstrate the effect of SCII on GSCIP. The KBV emphasizes the importance of sharing (SCII), acquiring (GACAP), and applying strategic green knowledge (GSCL) that collectively lead to GSCIP. By establishing GACAP and EGC as a fundamental sequential mediating capability, the findings deepen theoretical insight into knowledge as a strategic resource that underpins sustainable innovation. Thus, a firm's capability to adapt to environmental change by reconfiguring its strategies (green entrepreneurial orientation (GEO) accelerates the conversion of integrated knowledge (SCII) into actionable learning (GSCL), ultimately driving innovation (GSCIP).

Theoretical background and hypothesis development

Grounded on KBV, information is regarded as a primary strategic resource that firms can leverage to generate value and achieve a sustained competitive advantage (Grant, 1996; Hou et al., 2025). Complementing this view, the DCT perspective emphasizes that the positive effect of SCII on green innovation performance stems from firms' ability to sense environmental challenges, reconfigure resources, and continuously adapt to challenges by reshaping organizational processes, enhancing operational efficiency, and supporting environmentally responsible solutions (Martínez Falcó et al., 2025). Therefore, firms with higher levels of SCII are better at assimilating diverse environmental information, improving green innovation decision-making, and enhancing green innovation performance. Accordingly, this study proposes that SCII is a crucial driver of green innovation performance:

H1: *SCII enhances GSCIP.*

SCII, GSCL, and GSCIP.

The increasingly dynamic business environment and heightened environmental awareness among stakeholders require firms to engage in learning with supply chain partners in order to strengthen environmental sustainability strategies and practices (Agyabeng-Mensah et al., 2024). SC learning is the systematic process of acquiring, integrating, and applying information to improve SC performance and competitive advantage (Haq & Cao, 2024). GSCL is a procedure that facilitates the collection and reciprocal exchange of essential information and expertise with SCPs about waste reduction, energy efficiency, and cooperation to establish an environmentally sustainable SC (Pham et al., 2023). Its effectiveness depends on information exchange and integration. As firms learn from collective knowledge and insights gained through information sharing, new insights are combined with existing knowledge to enhance decision-making, innovation capabilities, and sustainability performance (Junejo et al., 2025).

Based on these arguments, we hypothesize:

H2: *SCII positively influences GSCL.*

GSCL involves knowledge sharing, joint problem-solving, and continuous learning among upstream and downstream partners, enabling firms to access diverse green technology resources and capabilities (Guo et al., 2020). This external knowledge acquisition and

cooperation between SCPs strengthen the firm's technological base and support the development of GI (Hou et al., 2025). Prior studies indicate that GSCL facilitates both green process and product innovation. While GSCL enhances green process innovation by improving coordination, aligning operational standards, and supporting the adoption of environmentally friendly technologies and practices across interconnected firms, it also enhances firms' green product innovation by enabling early problem identification, improving eco-design decisions, and aligning product attributes with environmental requirements through close interaction with SCPs (Pham & Pham, 2025). Based on these arguments, we hypothesize:

H3: *GSCL enhances GSCIP.*

SC entities generate vast amounts of data within SC, including SCPs and information on environmental performance indicators. These activities can strengthen relationships and mutual trust among SCPs, provide access to valuable knowledge resources, and foster more collaborative innovation (Idrees et al., 2025). Guo et al. (2020) proved that SC learning serves as a mediator that enhances GI. Another study by Qiao et al. (2023) provides evidence that digital capability plays a crucial role in enhancing GSCL, which serves as a strategic resource that facilitates GI. Because GI often involves uncertainties in selecting appropriate environmental practices or technologies and validating their cost-effectiveness (Sun et al., 2025), SCII and GSCL serve as critical mechanisms to reduce these uncertainties by facilitating structured information exchange, inter-organizational collaboration, and informed decision-making (Qiao et al., 2023). Thus, we hypothesize:

H4: *SCII indirectly and positively affects GSCIP through GSCL.*

The moderating role of GEO.

Entrepreneurial orientation is a firm's ability to engage in innovative, proactive, and risk-taking behaviors, enabling it to explore new opportunities and gain competitive advantages (Lumpkin & Dess, 1996). GEO extends this concept by incorporating sustainability-driven initiatives into business strategies that leverage resources (such as SCII) (Idrees et al., 2025) to facilitate environmentally friendly innovations. As GEO enables firms to reconfigure resources to develop new products and promote learning processes, particularly in areas related to green innovativeness, proactiveness, and risk-taking (Teece, 2016). Firms that embrace GEO have a motivation to enhance their learning mechanisms, which encourage exploration and risk-taking in technological innovation, fostering cooperation between SCPs and supporting the exchange and integration of knowledge across organisational boundaries (Wang et al., 2023). Therefore, it is proposed that:

H5: *GEO positively moderates the relationship between SCII and GSCL, such that the relationship is stronger when GEO is high (vs. low).*

Moderated mediation hypothesis

Grounded on the core principles of DCT (Teece et al., 1997) and the KBV (Grant, 1996), this study perceives SCII as a knowledge source and GSCL as dynamic learning mechanisms that facilitate the translation of SCII into GSCIP. Firms that effectively leverage knowledge sharing can enhance continuous learning and adaptive innovation (Makhloufi et al., 2024). The effectiveness of this process is influenced by contextual enablers such as GEO. GEO reinforces the firm's strategic posture toward sustainability and innovation, enabling organizations to better leverage integrated SC knowledge. GEO fosters an internal climate that supports green entrepreneurial behavior, thereby strengthening the organization's capacity to identify, absorb, and utilize technological and market knowledge related to sustainability and transform this green knowledge and capabilities into actionable practices (Wang et al., 2023). Through this mechanism, GEO drives organizations to adopt proactive environmental initiatives that respond to the increasing expectations of customers and stakeholders who prioritize long-term ecological sustainability. Accordingly, this study proposes that GEO strengthens the impact of SCII on GSCIP by enhancing the firm's capacity to convert information into innovation through GSCL. Thus, we hypothesize:

H6. *GEO moderates the indirect effect of SCII on GSCIP via GSCL, such that the mediation is strengthened when GEO is high.*

SCII, GACAP, and EGC.

GACAP refers to a firm's capability to acquire, assimilate, and utilise structured environmental knowledge to support problem-solving and decision-making (Dinibutun, 2024). Organisations with high GACAP recognise the value of novel external ideas and integrate them with pre-existing knowledge, enabling them to promptly detect opportunities and adapt to changing market demands (Difrancesco et al., 2022). However, effective GACAP development depends on a systematic process that enables organisations identify, assimilate, and redeploy available external knowledge as internal knowledge and capabilities, strengthening interaction mechanisms, R&D activities, and managerial decision-making (Qu et al., 2022). Thus, organisations may improve their GIP by incorporating structured information-sharing processes, thereby enabling them to internalise and use green knowledge more effectively. Accordingly, we propose that:
H7: *SCII influences GACAP positively.*

GACAP equips firms with heightened awareness of environmental issues and enables them to build a competitive advantage by deploying resources more effectively and sustainably (Qu et al., 2022). In parallel, employee creative behaviour has become increasingly important for organisational success as customers grow more attentive to environmental and social impacts (Murad & Li, 2025). In this context, EGC is a key mechanism through which organisations generate and implement novel eco-friendly ideas that respond to shifting market expectations and, ultimately, enhance performance (Liu & Liu, 2023; Ma et al., 2025). Accordingly, GACAP can be conceptualised as a critical antecedent that supports and stimulates EGC within firms. To be more specific, if firms leverage their environmental expertise, they may enhance employees' green creativity to address volatile market conditions and strengthen their organizations' ability to address the escalating environmental and ecological challenges of their operations (Murad & Li, 2025). Thus, the following hypothesis is proposed:
H8: *GACAP affects EGC positively.*

Effective information sharing can cultivate trust-based, collaborative relationships with SCPs, which in turn strengthen learning processes and support the development of green, creative, and innovative outcomes (Oke et al., 2022). When firms possess strong GACAP, they are better able to absorb and translate external sustainability-related information into usable knowledge, thereby equipping employees with the insights needed to stimulate green creativity (Iqbal et al., 2023) and to generate innovative solutions consistent with sustainability objectives (Ma et al., 2022; Qu et al., 2022). Building on this reasoning, we hypothesize the following:
H9: *GACAP mediates the relationship between SCII and EGC.*

METHODOLOGY

Sampling technique

This research focused on full-time managers of SCs in Saudi Arabia's industrial sector. The rationale is that SC managers were selected as key informants because of their direct involvement in strategic innovation projects and in the management of supply chain operations. They have the best grasp of how their companies measure supply chain innovation results because of their position. We used a non-probability purposive sampling strategy, targeting SC managers employed in manufacturing firms that either hold ISO 14001:2015 certification or are in the process of obtaining it. This approach was accompanied by snowball and convenience sampling.
Questionnaire Design and Data Collection

This research used a self-administered online survey to examine the causal linkages between the variables. This approach was chosen because the study was confirmatory, using empirical data to validate or refute the relationships established in the literature review. This study used verified English survey questions, mainly derived from previous studies. The initial survey questions were formulated in English and then back-translated into Arabic via the back-

translation method (Brislin, 1980). The translation can lead to potential bias stemming from translation difficulties, which was mitigated by evaluating the questionnaire by three SC experts. We sent a letter outlining the study purpose to participants, and informed consent was written at the beginning of the survey (do you agree to participate in this survey). Anonymity was ensured to mitigate common-method bias (Podsakoff et al., 2003), as no questions related to personal information were included. A total of 165 was collected, and because all questions need to be answered, only three responses were removed owing to discrepancies, extreme regularity, or inconsistent patterns, resulting in 162 eligible responses for the study.

DATA ANALYSIS

This study adopted partial least squares structural equation modelling (PLS-SEM) because of its strong predictive orientation and its suitability for models involving complex relationships, smaller sample sizes, and emerging research contexts (Hair et al., 2021; Henseler, 2018; Richter et al., 2023). The empirical analysis was conducted using SmartPLS 4.0 to estimate and evaluate the proposed research model (Sarstedt et al., 2021). Following established guidelines, the analysis proceeded in two sequential stages. First, the measurement model was assessed using confirmatory factor analysis to establish convergent and discriminant validity. Second, the structural model was evaluated to test the hypothesized relationships by examining path coefficients (β), their statistical significance (t-values), and the explained variance (R^2) within the theoretical framework (Hair et al., 2021). Participants were predominantly male (87.2%), with females comprising 12.8%, indicating that the SC managers' roles are male-dominated. Regarding work experience, the majority of respondents had 1–10 years (35.1%), followed by 20 years (34.6%). The majority had work experience in a green organisation for 1–10 years (68.5%). Furthermore, regarding the firm's age, most firms are over 10 years old (66.7%) and have more than 2000 employees (32.7%). Moreover, firms that had ISO 14001-2015 certification (52.5%).

Results

Measurement Model

This study assessed the measurement model following the r*ecommendations of* Hair et al. (2021).

Reliability

The results indicate that the measurement model demonstrates satisfactory reliability. After removing indicators with inadequate loadings (SCIISR1, SCIISR3, SCIIT6, GACAP3, GSCL3, EGC2, EGC6, GEO2, GSCIP3, and GSCIP6), the remaining items exhibited standardized factor loadings ranging from 0.756 to 0.924, exceeding the recommended minimum threshold of 0.708 (Hair et al., 2021). All retained indicators were statistically significant at the 5% level, with corresponding t-values surpassing the critical value of 1.96, as assessed using a two-tailed test (Sarstedt et al., 2021). Internal consistency reliability was further supported by multiple criteria. Specifically, Cronbach's alpha, Dijkstra–Henseler's rho, and composite reliability values for all constructs exceeded the acceptable benchmark of 0.70, confirming the robustness and consistency of the measurement scales employed in this study (Hair et al., 2021).

Table 1. Reliability and convergent validity results.

Variables	Items	FL	VIF	Cronbach's alpha	Rho_a	Composite reliability	Average variance extracted (AVE)
Green Absorptive Capacity	GACAP1	0.844	2.974	0.906	0.910	0.930	0.729
	GACAP2	0.880	3.507				
	GACAP4	0.879	3.311				
	GACAP5	0.901	3.793				
	GACAP6	0.756	1.698				
	GEO1	0.896	3.824	0.911	0.912	0.934	0.739

Green Entrepreneurial Orientation	GEO2	0.854	3.102				
	GEO3	0.875	2.741				
	GEO4	0.869	2.820				
	GEO5	0.800	2.135				
Green Supply Chain Learning	GSCL1	0.916	3.864	0.925	0.925	0.947	0.817
	GSCL2	0.924	4.482				
	GSCL4	0.920	3.812				
	GSCL5	0.853	2.277				
Employees' Green Creativity	EGC1	0.772	1.652	0.883	0.889	0.92	0.743
	EGC3	0.891	2.783				
	EGC4	0.909	3.199				
	EGC5	0.870	2.789				
Supply Chain Information Integration	SCIIT1	0.909	2.946	0.903	0.907	0.928	0.721
	SCIIT2	0.885	3.675				
	SCIIT3	0.833	3.076				
	SCIIT4	0.879	3.051				
	SCIIT5	0.88	1.978				
	SCIISR2	0.92	1.673	0.848	0.848	0.908	0.768
	SCIISR4	0.855	2.79				
	SCIISR5	0.834	2.519				
Green Supply Chain Innovation Performance	GSCIP1	0.853	2.71	0.91	0.912	0.931	0.692
	GSCIP2	0.819	2.425				
	GSCIP4	0.882	3.257				
	GSCIP5	0.856	2.581				
	GSCIP7	0.811	2.33				
	GSCIP8	0.765	1.908				

Note: SCIIT: Supply Chain Information Integration (information technology); SCIISR: Supply Chain Information Integration (information sharing); GACAP: green absorptive capacity; EGC: employee green creativity; GSCIP: green supply chain innovation performance; FL: Factor loadings; VIF: Variance inflation factors.

Validity

Discriminant validity was assessed using both the Fornell–Larcker criterion and the heterotrait–monotrait ratio (HTMT), in line with current methodological recommendations of Hair et al. (2021). The results confirm that the square root of each construct's AVE exceeds its correlations with other constructs, and all HTMT values fall below the conservative threshold of 0.80. Collectively, these findings provide strong evidence that the measurement model demonstrates satisfactory discriminant validity.

Table 2. Discriminant validity results: Fornell–Larcker and HTMT.

Variables	GACAP	EGC	GEO	GSCL	SCIISR	SCIIT	GSCIP
ACAP	***0.854***	0.676[h]	0.759 [h]	0.712 [h]	0.592[h]	0.531 [h]	0.738 [h]
EGC	0.608	***0.862***	0.689 [h]	0.632 [h]	0.500 [h]	0.329 [h]	0.553 [h]
EOR	0.692	0.616	***0.859***	0.723 [h]	0.585 [h]	0.464 [h]	0.683 [h]
GSCL	0.655	0.572	0.664	***0.904***	0.782 [h]	0.571 [h]	0.722[h]
SCIISR	0.518	0.425	0.508	0.685	***0.876***	0.817 [h]	0.820 [h]
SCIIT	0.479	0.297	0.421	0.522	0.719	***0.849***	0.713 [h]
SCIP	0.671	0.497	0.623	0.665	0.724	0.648	***0.832***

Note: N: 162; SCIIT: Supply Chain Information Integration (information technology); SCIISR: Supply Chain Information Integration (information sharing); GACAP: green absorptive capacity; EGC: employee green creativity; GSCIP: green supply chain innovation performance; h: values of the heterotrait–monotrait ratio (HTMT).

Structural Model

Following Hair *et al*. (Hair et al., 2021), we examine the VIFs for each construct to assess multicollinearity among the independent variables in the structural model. If the VIF is greater than 5, indicating multicollinearity (Kock, 2015). The VIF values ranged from 1.652 to 4.482, indicating the absence of CMB. Furthermore, the coefficient of determination (R^2) was used to assess the model's accuracy. R^2 values can be categorised as weak, moderate, and substantial, with thresholds of ≥ 0.25, ≥ 0.50, and ≥ 0.75, respectively (Hair et al., 2021). The R^2 values were 0.296 for GACAP (weak), 0.369 for EGC (moderate), and 0.602 for GSCL and 0.628 for GSCIP (moderate). Next, Q^2, a predictive sample reuse approach (Sarstedt et al., 2021), was used to assess the model's predictive significance. The blindfolding procedure's ability to accurately reconstruct the observed data using the model and PLS parameters is quantified by Q^2. When $Q^2 > 0$, the data are predictive (Fornell & Cha, 1993; Hair et al., 2021). The Q^2 values for GACAP, EGC, GSCL, and GSCIP were 0.286, 0.142, 0.570, and 0.577, respectively, indicating that all variables had sufficient predictive relevance.

Hypothesis Testing

To evaluate the hypotheses, SmartPLS 4.0 was employed. Bootstrapping with 10,000 iterations was used to evaluate the reliability and validity of sub-construct weights and the statistical significance of path coefficients (Hair et al., 2021). The comprehensive results of hypothesis testing are presented in Table 3.

Table 3. Structural model results.

Variables Relationship	**Path coefficients**	**95% BCA confidence interval**	**T statistics**	**Effect size (f^2)**	**Decision**
Direct effect					
GACAP -> EGC	0.607***	(0.450,0.721)	8.989	0.585	Accepted
EGC -> GSCIP	0.166*	(0.027,0.300)	2.377	0.048	Accepted
GSCL -> GSCIP	0.210**	(0.053,0.351)	2.774	0.052	Accepted
SCII -> GACAP	0.544***	(0.400,0.665)	8.037	0.421	Accepted
SCII -> GSCL	0.449***	(0.294,0.600)	5.727	0.373	Accepted
SCII -> GSCIP	0.547***	(0.409,0.668)	8.306	0.446	Accepted
Specific indirect effect					
SCII -> GACAP -> EGC	0.331***	(0.217,0.441)	5.754		Partial
GACAP -> EGC -> GSCIP	0.101*	(0.013,0.203)	2.050		Partial
SCII -> GSCL -> GSCIP	0.094*	(0.032,0.183)	2.494		Partial
SCII -> GACAP -> EGC -> GSCIP	0.055*	(0.009,0.115)	2.016		Partial

Note: *$|t| \geq 1.65$ at p 0.05 level; **$|t| \geq 2.33$ at p 0.01 level; ***$|t| \geq 3.09$ at p 0.001 level; BCA = Bias-corrected and accelerated; EGC: employees' green creativity; GACAP: green absorptive capacity; GSCIP: green supply chain innovation performance; SCII: supply chain information integration.

There is a positive and significant effect from SCII on GSCIP (β = 0.547, t = 8.306, $p < 0.001$, f^2 = 0.446), confirming **H1**. Moreover, the path coefficient for SCII on GSCL was also significantly positive (β = 0.449, t = 5.727, $p < 0.00$, f^2 = 0.373), which confirms **H2**. GSCL significantly impacted GSCIP positively (β = 0.210, t = 2.774, $p < 0.010$, f^2 = 0.052), which support **H3**. Additionally, the indirect effect of SCII on GSCIP through GSCL (β = 0.094, t = 2.494, $p < 0.05$) was significant. These results support **H4,** which posits that GSCL partially mediates the SCII–GSCIP relationship.

In addition, there was a positive and significant relationship between SCII and GACAP (β = 0.544, t = 8.037, $p < 0.001$, f^2 = 0.421), supporting **H7**. GACAP had a positive relationship with EGC (β = 0.607, t = 8.989, $p < 0.001$, f^2 = 0.585), which support **H8**. Moreover, the positive

and indirect effect of SCII on EGC via GACAP (β = 0.331, t = 5.754, p < 0.001) indicates that GACAP partially mediates the link between SCII and EGC, which confirms **H9**. Additionally, **H10** was supported by the considerably positive path coefficient for EGC on GSCIP (β = 0.166, t = 2.377, p < 0.05, f^2 = 0.048). Furthermore, the results reveal a positive and significant indirect effect of GACAP on GSCIP through EGC (β = 0.101, t = 2.050, p < 0.05), indicating that EGC partially mediates the relationship between GACAP and GSCIP, and confirming H11. Furthermore, the results indicate that none of the control variables (firm size and employees' work experience in green organization) exerted a statistically significant influence (p>0.05) on GSCIP.

Effect size (f^2) was used to determine the extent to which each predictor explained variance in the structural model. The guidelines for measuring f^2 values indicate that minor (0.02), medium (0.15), and high (0.35) impacts of the exogenous latent variable (Cohen, 1988) while the values below 0.02 imply the absence of an effect (Hair et al., 2021). From Table 3, SCII recorded a high effect size (0.446) on GSCIP, GSCL (0.373), and GACAP (0.421). Moreover, GSCL and EGC have a small effect size (0.052) and (0.049), respectively, on GSCIP, while GACAP has a high effect on EGC (0.585).

Moderation analysis

Hypothesis 5 posited that GEO would moderate the positive relationship between SCII and GSCL, with the relationship being more pronounced under high (versus low) GEO conditions. To show the effect of GEO, bootstrapping procedures were employed to estimate the moderating effect via confidence intervals (CIs) (Hair et al., 2022). The analysis demonstrated that the influence of SCII on GSCL was statistically significant when GEO was a moderator of this relationship (β = 0.126, t 2.758, p<0.006), confirming GEO's positive moderating role. Further supporting this, Figure 2 illustrates the simple slope plot, revealing that GEO amplifies the positive SCII–GSCL relationship. In particular, the interaction effect was stronger at high GEO (+1 SD; simple slope = 0.575, t = 6.110, p < 0.001) in comparison to low GEO (−1 SD; simple slope = 0.323, t = 3.704, p < 0.001), which indicates that GEO significantly enhances the impact of SCII on GSCL, thereby supporting **H5**.

Moderated Mediation Analysis

The study further proposed that GEO moderates the indirect effect of SCII on GSCIP (via GSCL), with a stronger positive mediation under high GEO conditions (**H6**), with results detailed in Table 4. The findings revealed that the index value of GEO for the moderated mediation effect is significant (β = 0.126, 95% CI = [0.036, 0.214]). Moreover, the results revealed a significant and stronger indirect effect of SCII on GSCIP at a higher level of GEO (Path = 0.120, t = 2.617, p < 0.01) compared to a low level (Path = 0.068, t = 2.091, p < 0.05). These findings and the slope analysis presented in Table 4 and Figure 2 confirm that with an increased level of GEO, the indirect relationship from SCII to GSCIP via GSCL is enhanced. Thus, **H6** was supported.

Table 4. Bootstrap analysis results for the conditional indirect effect.

	Path coefficient	**Confidence interval**		**T statistics**	**P values**
		2.50%	**97.50%**		
SCII -> GSCL -> GSCIP conditional on GEO at +1 SD	0.120	0.041	0.223	2.617	0.009
SCII -> GSCL -> GSCIP conditional on GEO at -1 SD	0.068	0.020	0.154	2.091	0.037
SCII -> GSCL -> GSCIP conditional on GEO at Mean	0.094	0.032	0.183	2.494	0.013

Note: SCII: supply chain information integration; GSCL: green supply chain learning; GEO: green entrepreneurial orientation; GSCIP: green supply chain innovation performance.

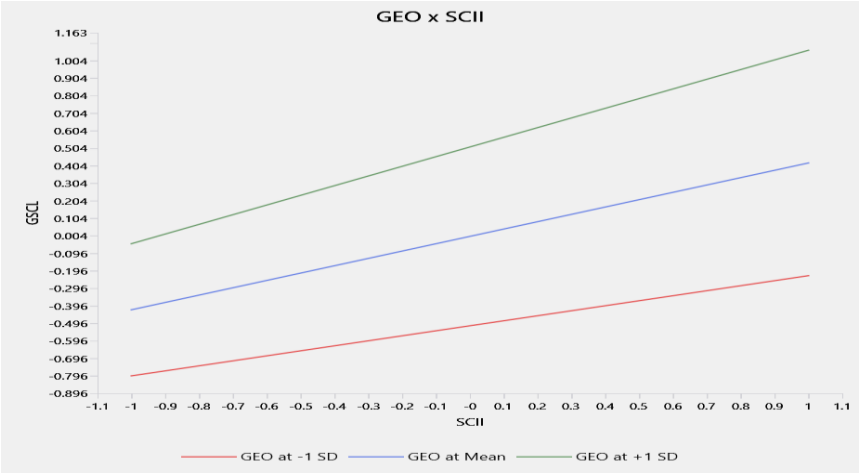


Figure 2. The Moderating Graph

Serial Mediation

The analysis examined whether GACAP and EGC operate sequentially in transmitting the effect of SCII to GSCIP. The findings show a significant indirect pathway from SCII to GSCIP through GACAP and EGC (β = 0.026, t = 2.081, p < 0.05), supporting **H12**. At the same time, SCII retained a strong and positive direct influence on GSCIP when both mediators were included in the model (β = 0.547, t = 8.306, p < 0.001, f^2 = 0.446). These results indicate partial mediation, suggesting that higher levels of SCII strengthen GACAP, which, in turn, stimulates employee green creativity and contributes to enhanced GSCIP.

Table 5. Serial mediation.

SCII→ GSCIP		**Relationship**	**Indirect Effect**	**Confidence Interval (Lower Bound)**	**Confidence Interval (Upper Bound)**	**T Statistics**
Total Effect	**Direct Effect**					
0.696***	0.547 ***	H12: (SCII→ GACAP→ EGC→ GSCIP)	0.026*	0.007	0.058	2.081

Note: SCII: supply chain information integration; GACAP: green absorptive capacity; EGC: employees' green creativity; GSCIP: green supply chain innovation performance.

DISCUSSION

This study seeks to support supply chain managers in identifying key drivers and strategic conditions for achieving superior green supply chain innovation performance. Accordingly, a conceptual framework is developed to examine the antecedents of GSCIP within the Saudi manufacturing context, with particular attention to the role of supply chain information integration as a direct driver and as an indirect driver through green supply chain learning and green absorptive capacity, as well as the moderating influence of green entrepreneurial orientation.

Theoretical implications

This study adds to the literature through several contributions to the GSCM, primarily within the context of Saudi manufacturing firms. Along with Vision 2030, this study provides new insights into how Saudi manufacturers manage resources and capabilities to attain GSCIP, emphasizing SCII's role in fostering environmental collaboration and sustainability practices. By aligning operational strategies with sustainability goals, this research highlights SCII's strategic importance role in improving competitiveness and achieving GSCIP. Finally, this study proposes an integrated framework in which SCII serves as an accelerator that boosts GSCIP through two

paths: organizational and employee. The individual path, SCII boosts GACAP, which then stimulates EGC, finally leading to improvements in GSCIP, despite past studies examining the separate interactions among SCII, GACAP, and EGC (Makhloufi et al., 2024). Our results indicate that companies with robust information-sharing systems and elevated GACAP are better equipped to promote EGC, thereby facilitating the creation of sustainable business solutions. Moreover, this study revealed that firms with an entrepreneurial mindset will enhance GSCL, which, in turn, will strengthen the SCII-GSCIP relationship.

Practical implications

This study provides guidance for organizations to develop policies that foster GI by creating a conducive environment for integrating information with SCPs. Effective management integration and utilization of SC information can help firms reduce raw material consumption, optimize resource use, conserve natural resources, and enhance efficient use of resources, thereby preserving natural resources and safeguarding the environment for future generations. This process simultaneously achieves economic and environmental benefits, thereby improving overall GSCIP. In summary, this study emphasises that the synergistic impact of GSCL, GACAP, and EGC is essential for translating SCII into concrete green innovation outcomes. Consequently, companies can effectively adapt to fluctuating market conditions and environmental challenges, thereby attaining a competitive edge through ongoing green innovation that fosters both enduring corporate success and environmental sustainability.

Limitations and future research

This study outlines several contributions to GSCM; however, it has some limitations. First, we used cross-sectional data to test our hypotheses. While this approach offers a snapshot of the relationships between SCII, GEO, GSCL, GACAP, EGC, and GSCIP, it does not capture the effect of these linkages over time. Longitudinal research should be conducted to systematically examine the progression of correlations among variables, thereby enhancing understanding of causal processes and long-term impacts. Secondly, the data concentrated on Saudi firms, which may restrict generalisability. The unique economic policies and stable environment of Saudi Arabia, especially its government-driven sustainable projects, may influence SCII's role in achieving GSCIP. To enhance generalisability, future studies could conduct cross-national comparisons and examine regulatory, cultural, and economic contexts to discern both globally and context-specific determinants of green innovation performance. Finally, although green supply chain learning, green absorptive capacity, and employee green creativity were examined as key mediating mechanisms, alternative pathways remain underexplored. Future studies may consider sustainable collaboration among supply chain partners as an additional mediator, alongside technological innovation capabilities, to capture a more comprehensive explanation of how SCII drives green innovation outcomes.

REFERENCES

Agyabeng-Mensah, Y., Baah, C., & Afum, E. (2024). Do the roles of green supply chain learning, green employee creativity, and green organizational citizenship behavior really matter in circular supply chain performance? *Journal of Environmental Planning and Management*, *67*(3), 609–631. https://doi.org/10.1080/09640568.2022.2130036

Ansong, A., Andoh, R. P. K., Ansong, L. O., Hayford, C., & Owusu, N. K. (2025). Toward employee green creativity in the hotel industry: Implications of green knowledge sharing, green employee empowerment and green values. *Journal of Hospitality and Tourism Insights*. https://doi.org/10.1108/JHTI-08-2024-0867

Chen, Y.-S. (2008). The Driver of Green Innovation and Green Image – Green Core Competence. *Journal of Business Ethics*, *81*(3), 531–543. https://doi.org/10.1007/s10551-007-9522-1

Pham, T., & Pham, H. T. (2025). Effects of supply chain learning on green innovation and moderating role of green transformational leadership. *International Journal of Emerging Markets*, *20*(5), 2132–2153. https://doi.org/10.1108/IJOEM-02-2022-0268

Comparative Evaluation of AMR- and OHT-Based Material Transport Integrated with AS/RS in Semiconductor Manufacturing Factory

Koh Taeyoung, Chang YoonSeok

Korea Aerospace University, Korea

ABSTRACT

This study introduce an Net Present Value (NPV) based economic analysis to compare two material transfer and storage/picking configurations in a semiconductor manufacturing line. Using operator-based transport with manual racks as the baseline, two automated alternatives were configured – by integrating Automated Storage/Retrieval System (AS/RS) with either Automated Mobile Robot (AMR) or Overhead Hoist Transfer (OHT), while keeping the outbound release pattern and station processing times constant to isolate the effects of each alternative. Performance was assessed using throughput and transfer-resource indicators (i.e. utilization and transport task time). The results were monetized into hard savings (labor cost reduction) and soft savings (value of additional processable volume) to compute NPV. The automated alternatives improved throughput relative to the baseline. Although AMR and OHT achieved comparable throughput, differences were observed in their transport execution characteristics. The NPV analysis confirmed the economic attractiveness of both automated options and showed differences in their investment and operating cost structures influence the relative ranking of the alternatives.

Keywords: AS/RS, AMR, OHT, NPV

INTRODUCTION

Recently, manufacturing and logistics sites have faced rising operational complexity driven by multi-product, high-variability production, shorter lead-time requirements, and increasingly stringent safety and quality regulations (Herrera-Vidal, Coronado-Hernandez & Maheut, 2025). From an intralogistics perspective, internal material flow should be understood not as isolated functions such as “storage” or “transport,” but as a continuous process that delivers the right item to the right destination at the right time and seamlessly connects it to subsequent operations (Placzek & Osieczko, 2024).

In this context, automation is increasingly adopted not merely to replace labor, but to enhance space efficiency, operational stability, traceability, and inter-process synchronization. AS/RS enables high-density storage and automated inbound/outbound operations, while OHT provides reliable, high-frequency transport through ceiling-rail-based routes. AS/RS enhances space utilization—particularly valuable in high-cost cleanroom/manufacturing space (Ellithy et al., 2024)—and strengthens inventory accuracy and traceability by managing storage at the cell/location level with item-status mapping (Low, Sim & Lew, 2024). OHT, in turn, alleviates floor-level congestion by relocating transport flows to the overhead domain, thereby preserving valuable floor space for high value-added processing equipment while maintaining predictable transport performance through highly repeatable rail-based paths (Yamaha Robotics, n.d.-c; Muratec, n.d.-c).

However, quantitative evidence remains limited on how different transport alternatives (manual operator-based transfer vs. AMR/OHT) and their integration with AS/RS affect system-level performance within a specific production-line context. Therefore, this study investigates inter-process material transfer in a semiconductor manufacturing line (named, ICOS–EVI–QA) and quantitatively compares scenarios in terms of system performance by capturing changes in travel distance and resource load and their implications for throughput and operational stability. By doing so, the study provides practical decision support for selecting transport and storage–supply configurations under constrained space and stringent cleanliness/safety requirements.

LITERATURE REVIEW

Ferrari, Campanale, Carlin & Mangano (2024) evaluated the performance of a multi-level shuttle-based AS/RS in terms of time and energy consumption. The authors integrated task-sequence optimization algorithm into simulation framework to construct various warehouse configurations and operating conditions, which were validated using discrete-event simulation (DES). Eder (2024) analytically examined the throughput improvement achievable with a multiple-capacity lift in a multi-level shuttle-based AS/RS. The study proposed a simple formula-based approach that combines a cycle-time model between the lift and shuttle with a queueing model and verified its accuracy by comparing it with simulation results.

Reveliotis & Masopust (2018) demonstrated that deadlocks arising from zone-occupancy constraints in guidepath-based material handling systems, such as AGV (Automated Guided Vehicle) and OHT, can be prevented through appropriate traffic management, ensuring that all vehicles can be returned to their home locations. Schmaler, Hammel & Schubert (2020) investigated a static AMHS simulation approach for semiconductor fabs, motivated by the observation that the workload of an OHT-based AMHS varies with changes in the product mix. Their model used the planned product mix as a key simulation inputBenzoni, Yugma & Bect (2023) studied future-information-based dispatching to improve OHT task assignment in semiconductor manufacturing. They developed a model that jointly considers future transport arrivals and vehicle idle times, and proposed an operational policy to reduce waiting and assignment times.

Existing AS/RS research, focusing on shuttle- and robot-based systems, has mainly concentrated on estimating internal equipment cycle time, throughput, and energy consumption, or on improving local parameters such as speed settings, movement policies, and task-sequence optimization. While these studies provide insights for design and operation of AS/RS as a standalone system, the performance of semiconductor manufacturing lines is also strongly influenced by inter-process transport methods and labor deployment structures.

Therefore, this study conducts a line-level comparative evaluation of how the choice of transport entity (operator, AMR, or OHT) and its integration with AS/RS affect system performance in the ICOS–EVI–QA line. Unlike prior studied that focus on optimizing individual transport system, this research evaluates — manual transport and automated transport (AMR, OHT) alternatives under controlled and identical conditions. The study thereby provides quantitative evidence on the performance impact of automation adoption and the relative differences among transport alternatives.

METHODOLOGY

This study proposes a methodology that combines discrete-event simulation (DES) with an NPV based economic evaluation to compare alternative material transfer and storage/picking configurations in a semiconductor manufacturing line. The core objectives are to (1) quantitatively assess how the adoption of automated transport and storage systems affects operational performance - particularly throughput- and resource load structure (utilization), and (2) evaluate whether such performance changes translate into sufficient investment benefits using cash-flow-based economic indicators (NPV).

The overall evaluation procedure consists of three steps. First, a simulation model is developed to represent the process flow and the transport alternatives, and each case is replicated under a common set of input conditions. Second, key operational outcomes primarily- throughput and utilization- are derived to enable interpretation of relative performance as well as bottleneck locations and load concentration patterns. Third, improvements observed in the simulation are monetized by distinguishing hard savings (direct cost reductions) from soft savings (value creation through additional processable volume enabled by time savings). Based on these monetized benefits, an NPV-based economic –analysis is conducted to provide an integrated assessment of the economic feasibility of each alternative.

The scope of this study covers the operational segment of the process flow ICOS → EVI → QA → outbound, focusing on (i) the material transfer section from ICOS outbound generation to the inputs to EVI and QA, and (ii) the storage and picking interface within the EVI/QA area. To evaluate how different combinations of transport alternatives (operator / AMR / OHT) and storage–picking modes (manual rack / AS/RS) affect the production flow, the experiment is designed so that only the transport and storage modes vary while processing times and the outbound release pattern are constant.

Notably, the model is structured to capture the impacts of transport/storage changes—such as delays in process feeding, waiting, and resource saturation—rather than changes in the intrinsic processing capability of the stations. Accordingly, the performance improvement considered in this study does not simply refer to reduced processing times; instead, it includes increased throughput driven by smoother material flow under the identical processing conditions, as well as improved operational stability resulting from reduced overload of specific resources.

This study considers three scenarios (Cases 1–3), using Case 1 as the baseline and comparing Cases 2 and 3 as alternative configurations.

- Case 1 (Baseline) assumes the current operation. Material transfer between ICOS and EVI is performed by operators (e.g., manual transport using hand carts), and storage and picking in the EVI/QA area are conducted using manual racks. This case serves as the reference point representing pre-automation performance and the labor-dependent load structure.
- Case 2 (AMR + AS/RS) replaces the ICOS–EVI transfer with AMRs and adopts an AS/RS-based storage–picking interface. AMRs are modeled as mobile resources with route-selection and collision-avoidance rules where waiting or congestion may occur depending on operating conditions. Because AMRs travel along ground-level routes, they must share physical space with floor aisles and shop-floor movements; thus, operational constraints may vary with aisle availability and the degree of flow separation. This case evaluates the effects of free-path autonomous transport.
- Case 3 (OHT + AS/RS) replaces the ICOS–EVI transfer with OHT while applying the same AS/RS interface as in Case 2. OHT is modeled as a rail-based resource (including one-way tracks), capturing traffic constraints such as merging and waiting. Since OHT utilizes ceiling-mounted rails, it alleviates floor-level congestion and preserves valuable floor space for high value-added activities such as equipment placement, operator movement, and buffer/picking areas. This case evaluates the effects of fixed-route, rail-based transport.

Because Cases 2 and 3 control the storage–picking mode (AS/RS) and vary only the transport mode (AMR vs. OHT), the impact of transport selection on throughput and resource load structure can be compared more directly. Moreover, the two alternatives exhibit a structural difference in space utilization (floor-aisle vs. overhead); therefore, this study discusses the implications of transport selection for facility layout and flow design alongside a performance comparison.

The simulation model was structured by functionally categorizing system elements into transfer resources and fixed resources. Transfer resources refer to mobile resources that transport materials (totes/lots) between ICOS and EVI: operators in Case 1, AMRs in Case 2, and OHTs in Case 3. Fixed resources refer to stationary resources such as processing equipment and storage/picking facilities, including ICOS outbound generation, processing at EVI/QA, and storage racks (manual racks or AS/RS). This classification was adopted to interpret where performance differences arise across transport alternatives—specifically, to diagnose via utilization whether changes in throughput are driven by the movement/waiting characteristics of transfer resources or constrained by the processing and queueing structure of fixed resources. The specific parameter settings for transfer and fixed resources used in the simulation are summarized in Table 1.

To ensure comparability across scenarios, ICOS outbound releases were generated at a constant inter-arrival time to eliminate demand variability, and the processing times at the EVI and QA

stations were fixed to minimize sources of variation unrelated to the transport alternatives. In addition, distance and layout conditions (e.g., manual-rack travel distances and AS/RS configurations) were set to be identical or correspondingly matched across scenarios according to the comparison purpose. Queueing rules and basic operating policies (e.g., FIFO) were also standardized so that policy differences did not affect the results.

Table 1 : Parameter values for transfer and fixed resource

Category	Resource	Parameter	Value
Transfer resource	Operator (Hand cart)	Number of operators	ICOS: 5man EVI: 5man QA: 4man
		Walking speed	0.7m/s
		Loading / Unloading time	30s / 20s
	AMR	Number of AMRs	2EA
		Speed	1m/s
		Payload capacity	1Tote
		Loading / Unloading time	20s / 20s
	OHT	Number of AMRs	2EA
		Speed	2m/s
		Payload capacity	1Tote
		Loading / Unloading time	15s / 15s
Fixed resource	Common (All cases)	ICOS output inter-arrival	1,200s
		EVI process time	1,800s
		QA process time	800s
	Case 1	Manual rack	EVI: 9.5m QA: 3.5m
	Case 2	AS/RS	12.5m (2EA)
	Case 3	AS/RS	12.5m (2EA)

The main contribution of this study is to provide an NPV-based economic evaluation that supports investment decision-making beyond simple operational performance comparisons. Specifically, the analysis monetizes changes in operational outcomes across cases - particularly changes in throughput improvement- to estimate annual benefits. It evaluates economic feasibility using NPV (Net Present Value) based on a cash-flow framework that incorporates both investment and operating costs.

Costs are classified into capital expenditures (CAPEX) and operating expenditures (OPEX).

- CAPEX (capital expenditures) includes equipment purchase and installation costs required to deploy AMR, OHT and AS/RS. In the analysis, CAPEX is treated as a one-time cash outflow in Year 0.
- OPEX (operating expenditures) includes recurring annual costs such as maintenance, electricity/charging, and operating labor costs. While Case 1 (baseline) is labor-intensive and thus dominated by labor expenses, Cases 2–3 may incur additional maintenance and energy-related costs due to equipment operation. Accordingly, annual OPEX is estimated for each case and the incremental difference relative to the baseline is incorporated in the economic evaluation.

Benefits are categorized into hard saving (direct cost reduction) and soft saving (value creation).

Hard saving refers to items that result in an actual reduction in cash expenditures through automation. In this study, hard saving is quantified as the annual labor costs that can be eliminated through automated alternatives (Cases 2–3), using the baseline (Case 1) labor requirement for material transport. T_{run}^{labor} (hr/day) denote the baseline daily transport labor time, N (days/year) the annual operating days, and c_{labor} ($/hr) the hourly labor cost.

Soft saving captures value creation that arises when increased processing capability enables additional volume to be handled, even if time savings do not translate directly into immediate cost reductions. In this study, the annual soft saving for alternative case k is quantified by converting the additional processable volume—derived from throughput improvements relative to the baseline—into monetary value. Let ΔQ_{year} denote the annual additional number of totes that can be processed under case k relative to the baseline; it is obtained by scaling the throughput increase to an annual basis under the assumed operating schedule (e.g., three shifts per day and N operating days per year) and applying the volume realization factor α to reflect that the additional processable volume may not fully materialize as an actual annual output increase (e.g., $\alpha = 0.75$). Let V_{tote} denote the unit economic value created by processing one additional tote, typically derived from the assumed contents per tote and the value per chip. Let β be the value realization rate reflecting the extent to which the realized additional volume is converted into economic value such as revenue or contribution margin, considering market, demand, and operational constraints (e.g., $\beta = 0.5$).

The annual hard saving and soft saving for alternative case k are defined as:

$$B_{k,year}^{hard} = T_{run}^{labor} \times N \times c_{labor} \qquad (k = 2,3) \qquad (1)$$

$$B_{k,year}^{soft} = (\Delta Q_{run} \times 3 \times N \times \alpha) \times V_{tote} \times \beta \qquad (k = 2,3) \qquad (2)$$

The annual net cash flow (NCF) for each case is defined as total benefits—composed of hard and soft saving—minus operating expenditures (OPEX). CAPEX is treated as an initial cash outflow in Year 0, while the annual NCF is applied for subsequent years. Economic feasibility is evaluated using net present value (NPV), which discounts annual cash flows over the analysis horizon at a discount rate r. These are formulated as follows:

$$NCF_k = \left(B_{k,year}^{hard} + B_{k,year}^{soft}\right) - OPEX_k \qquad (3)$$

$$NPV_k = -CAPEX_k + \sum_{t=1}^{T} \frac{NCF_k}{(1+r)^t} = -CAPEX_k + \Delta NCF_{k,year} \times (P/A, r, T) \qquad (4)$$

This study present the simulation model structure, the experimental scenario design, the KPI derivation approach, and the NPV-based economic evaluation framework for assessing alternative material transfer and storage/picking configurations. The next section reports the simulation results (throughput and utilization) and, based on these outcomes, evaluate the investment feasibility of each case using NPV.

RESULTS

Throughput, measured per run (8 hours, one shift), was 120 totes in Case 1, while both Case 2 and Case 3 achieved 132 totes. Thus, the automated alternatives (Cases 2–3) increased throughput by 12 totes per shift (approximately 10%) relative to the baseline. This improvement is attributed to smoother material flow resulting from changes in the transport mode and the storage/picking interface under the same processing times and outbound release conditions. The identical throughput observed in Case 2 (AMR) and Case 3 (OHT) indicates under the experimental settings of this study, the transport mode itself did not primarily differentiate throughput; rather, the application of the storage interface (AS/RS) and overall flow improvements were the dominant drivers of throughput gains.

Transfer utilization was 32.93% in Case 1, 48.39% in Case 2, and 45.06% in Case 3. Because the number of transfer resources differs across scenarios—four operators in Case 1 versus two AMRs and two OHT vehicles in Cases 2 and 3, respectively—utilization is interpreted as an indicator of workload concentration on the available resources rather than an absolute measure of efficiency. Accordingly, efficiency is evaluated by interpreting utilization together with the actual time spent on transport tasks (cumulative labor hours for operators or operating hours for automated vehicles).

In terms of time spent on transport, the transfer labor time in Case 1 was 10.54 hours. This value represents cumulative operator labor hours for a single run, calculated by summing the travel/transport time for the four operators involved in the transfer task. In the automated scenarios, operator-based transport is eliminated and vehicle operating time becomes the relevant indicator. The AMR operating time in Case 2 was 7.74 hours, and the OHT operating time in Case 3 was 7.21 hours, confirming that the automated alternatives complete he transport task in less time than the baseline. Relative to Case 1, the AMR scenario achieves a time reduction of approximately 26.6%, while the OHT scenario achieves approximately 31.6%. Moreover, under the same fleet size (two units), OHT exhibits about a 6.9% shorter operating time than AMR, suggesting that OHT is a more efficient transport option under the experimental conditions considered.

Overall, the automated alternatives (Cases 2–3) increase throughput by about 10% while performing transport with fewer resources (two units) and reduced transport task time. Although AMR and OHT achieve the same throughput level, differences in operating time and transfer utilization indicate that the choice of transport mode fluence transport execution efficiency and operational constraints (e.g., floor-aisle sharing versus fixed overhead routing) rather than the final throughput itself. These operational results provide key inputs to the subsequent economic evaluation, in which annual benefits - additional processable volume and labor-related savings- are quantified.

Table 2 : Overview of Simulation Results

KPI (per run)	Case 1	Case 2	Case 3
Throughput	120 Tote	132 Tote	132 Tote
Transfer Resource	Operator(4man)	AMR(2EA)	OHT(2EA)
Transfer Utilization	32.93%	48.39%	45.06%
Transfer Labor Time	10.54hr	-	-
Transport Operating Time	-	7.74hr	7.21hr
EVI Operator Distance	1,698m	738m	738m
QA Operator Distance	2,583m	3,001m	3,001m

BENEFIT ANALYSIS

The baseline daily transport labor time was estimated as T_{run}^{labor} = 31.62 hours/day. The hourly labor cost was set to c_{labor} = 11 \$/hour by applying an overhead factor of 1.3 to the base wage to account for indirect costs, allowances, and benefits (base wage 8.5 \$/hour × 1.3). With the annual operating days set to N = 300 days/year, the transport labor cost can be replaced under the automated alternatives.

The unit value V_{tote} is converted based on the contribution margin per chip (m). Specifically, the contribution margin is set to m=0.35 \$/chip, and the tote composition is assumed to be 1 tote = 4 bundles, 1 bundle = 10 trays, and 1 tray = 160 chips. Accordingly, the number of chips per tote is 6,400 chips. In addition, to conservatively reflect the extent to which the additional processed volume is converted into actual economic value, a value realization rate of $\beta = 0.5$ is applied.

From a cost perspective, CAPEX was estimated to include the initial investment required to deploy the AS/RS and transport equipment, including equipment purchase, installation, and commissioning. In this study, $CAPEX_{AS/RS}$ = 664,300 $, $CAPEX_{AMR}$ = 103,080 $, and $CAPEX_{OHT}$ = 371,420 $ were applied.

Annual OPEX was defined as recurring costs required for maintenance and operation. For a parsimonious yet conservative estimation, this study applied a CAPEX-based proportional rule: annual maintenance and software update costs were assumed to be 10% of the investment cost, and annual operating costs (operational support and other operating-related expenses) were assumed to be 5% of the investment cost, resulting in total annual OPEX equal to 15% of CAPEX. Applying this rule to each subsystem yields $OPEX_{AS/RS}$ = 99,645 $/year, $OPEX_{AMR}$ = 15,462 $/year, and $OPEX_{OHT}$ = 55,713 $/year.

Table 3 : Annual Benefits and Cost Inputs by Case

Category	Case	Value
$B_{k,year}^{hard}$	Case 2, 3	104,346 $/year
$B_{k,year}^{soft}$	Case 2, 3	9,072,000 $/year
CAPEX	Case 2 (AS/RS+AMR)	767,380 $
	Case 3 (AS/RS+OHT)	1,035,720 $
OPEX	Case 2 (AS/RS+AMR)	115,107 $/year
	Case 3 (AS/RS+OHT)	115,358 $/year

NPV was computed using a discount rate of r = 8% over an analysis horizon of T = 5 years. For each alternative Case k, NPV was calculated by treating the initial investment $CAPEX_k$ as a cash outflow in Year 0 and assuming a constant annual incremental net cash flow $\Delta NCF_{k,year}$ for the subsequent years, as expressed below. The uniform-series present-worth factor (P/A, 0.08, 5) was applied : 3.9927.

Table 4 : Annual Net Cash Flow and NPV by Case

Category	Case	Value
ΔNCF	Case 2	9,061,239 $/year
	Case 3	9,020,988 $/year
NPV	Case 2	35,411,429 $
	Case 3	34,982,379 $

Accordingly, under the assumptions of this study (i.e., identical throughput-based soft saving and identical hard saving structure), both Case 2 and Case 3 yield substantially positive NPVs, while Case 2 exhibits a slightly higher NPV than Case 3 due to its relatively lower initial investment and annual operating cost.

CONCLUSION

This study presents a simulation-based evaluation framework for comparing alternative material transfer and storage/picking configurations in a semiconductor manufacturing line and extends the analysis to an NPV-based economic assessment to enable an integrated comparison of the alternatives. To ensure comparability across scenarios, the outbound release pattern and station processing times were consistently controlled, thereby isolating the operational impacts of transport mode selection and changes to the storage interface.

The results show that the automated alternatives improve material flow relative to the baseline and increase effective throughput. While AMR- and OHT-based configurations exhibited similar throughput levels under the experimental conditions, differences were observed in transport execution characteristics, suggesting that transport mode selection may influence transport efficiency and operational constraints (e.g., floor-aisle sharing versus overhead routing) rather than the final throughput itself. Moreover, by distinguishing operational outcomes into direct cost reductions (hard saving) and value creation from additional processable volume (soft saving) and incorporating them into a cash-flow model, this study presents an integrated evaluation structure that links operational metrics to investment decision-making.

From a practical perspective, the proposed framework improves the interpretability of alternative comparisons by explicitly linking operational performance metrics to an economic outcomes. Future work should refine the modelling of transport-mode-specific congestion and interference mechanisms and enhance generalizability by extending the analysis to broader conditions, including demand variability, alternative layout assumptions, and sensitivity analyses on key parameters. In addition, quantifying space-related benefits and layout flexibility enabled by OHT's overhead utilization and integrating these factors into the economic evaluation would further strengthen the applicability of the framework to real-world automation investment and facility planning decisions.

REFERENCES

Herrera-Vidal, G., Coronado-Hernández, J. R., & Maheut, J. (2025). Complexity management challenges in the industry 4.0 era: A systematic review in production systems. *Results in Engineering*, *26*, 105329.

Płaczek, E., & Osieczko-Potoczna, K. (2024). Current state of knowledge and research needs of intralogistics.

Ellithy, K., Salah, M., Fahim, I. S., & Shalaby, R. (2024). AGV and Industry 4.0 in warehouses: a comprehensive analysis of existing literature and an innovative framework for flexible automation. *The International Journal of Advanced Manufacturing Technology*, *134*(1), 15-38.

Low, A. K. J., Sim, K. S., & Lew, K. L. (2024). Review on automated storage and retrieval system for warehouse. *J. Informat. Web Eng.*, *3*(3), 77-97.

Eder, M. (2024). Analytical examination of shuttle-based storage and retrieval systems with multiple-capacity lifts. *The International Journal of Advanced Manufacturing Technology*, *133*(9), 5053-5064.

Ferrari, A., Campanale, C., Carlin, A., & Mangano, G. (2025). Performance assessment of a multi-level shuttle system: an optimisation-embedded simulation study on time and energy consumption. *Journal of Simulation*, *19*(4), 411-426.

Reveliotis, S., & Masopust, T. (2019, July). Some new results on the state liveness of open guidepath-based traffic systems. In *2019 27th Mediterranean Conference on Control and Automation (MED)* (pp. 398-404). IEEE.

Schmaler, R., Hammel, C., & Schubert, C. (2020, December). Static AMHS simulation based on planned product mixes. In *2020 Winter Simulation Conference (WSC)* (pp. 1688-1699). IEEE.

Benzoni, A., Yugma, C., & Bect, P. (2023). Vehicle look-ahead dispatching for Overhead Hoist Transport system in semiconductor manufacturing. *IEEE Transactions on Semiconductor Manufacturing*, *36*(1), 130-138.

Ferrari, A., Campanale, C., Carlin, A., & Mangano, G. (2025). Performance assessment of a multi-level shuttle system: an optimisation-embedded simulation study on time and energy consumption. *Journal of Simulation*, *19*(4), 411-426.

Banks, J., Pachano, M. A., Thompson, L., & Hanny, D. (2007). *RFID Applied* (Chapter 6: The Business Case for RFID, pp. 159–194). John Wiley & Sons.

Automated Detection of Picking Movements with an Infrared Camera: A Technological Feasibility Study

Peik Bremer[1], Yannic Henz[1], Luca Cannava[2]

1: Technical University of Applied Sciences Würzburg-Schweinfurt, Germany; 2: Politecnico di Milano

INTRODUCTION

Order picking accounts for more than 50% of a warehouse's operating costs (de Koster et al., 2007). One way to improve productivity in order picking is to use parts-to-picker systems that automatically supply stationary picking workstations with goods. However, high investment costs, capacity constraints and low flexibility and scalability, which are typical of most automated systems (Labus and Gajšek, 2018), mean that picker-to-parts approaches still dominate in warehouses (Grosse et al., 2015). Picker-to-parts means that personnel move within the warehouse to collect items from storage bins (Winkelhaus et al., 2021). Fully automated (pickerless) picking systems have not yet established themselves on the market (Marchet et al., 2015; Winkelhaus et al., 2021).

The use of "paper and pen" in order picking is declining. A recent survey of US warehouses shows that only 44% of respondents still use printed picking lists (Michel, 2024). Technologies used to support the picking process include devices such as handhelds or smart wearables, pick-by-light, pick-by-voice (Battini et al., 2015) and, more recently, pick-by-vision. Regardless of the type of paperless picking solution, a general picking process begins with a warehouse management system that provides picking orders consisting of one or more order lines. The systems for paperless picking present the order lines (material number, storage bin, and quantity to be picked) to the picker one after the other. The system requires user interaction to confirm both the correct picking location and the desired quantity (Schwerdtfeger, 2010). Also, performance assessments in order picking do not only consider the time to complete the task, but also quality characteristics such as correct location and intended number of items (Zhang et al., 2022).

As the degree of interaction with the device is crucial for both efficiency and employee acceptance (Vanheusden et al., 2023), consideration should be given to a picking support system with minimal user interaction, i.e., displaying the order line on a smart wearable while the storage bin and picking quantity are automatically confirmed in the background without the picker having to actively intervene. This kind of automation can be achieved in two fundamentally different ways. The first is to equip the warehouse with an abundance of sensors, comparable to the "Amazon Go" concept for supermarkets in which the removal of goods from shelves is automatically identified by artificial intelligence based on sensor fusion data (Ives et al., 2019). The second, more lightweight way, is to equip order pickers with sensors. The sensors should facilitate three key tasks on-the-fly: (a) detecting picking movements, (b) confirming that items were picked from the intended storage bin, and (c) verifying that the correct number of items have been picked. In this paper, we focus exclusively on grasp detection as a necessary but not sufficient building block of automatic picking-movement recognition.

Specifically, we ask the question whether it is feasible to use an infrared (IR) camera to automatically detect picking movements. The objective is to understand if this technology reaches Technology Readiness Level (TRL) 4, for which a component and/or breadboard validation in laboratory environment is required (Mankins, 1995).

The rest of the paper is organized as follows: The literature review section looks at camera-based approaches for detecting grasping movements during order picking and aims to identify the key issues that the feasibility study should focus on. The methodology section explains how the feasibility study is designed. In the results section, the findings from the experiments are discussed and compared with the results of the literature review. The article concludes with a recommendation on how to proceed with the further analysis and development of this novel technological option.

LITERATURE REVIEW

After a brief introduction to picking support, the literature review looks at the basics of detecting grasping movements. In particular, the techniques for detecting grasping movements with cameras are discussed, with a focus on IR imaging. Finally, this section analyzes the challenges and opportunities of IR-based detection in warehouse environments and addresses the gaps in current research that need to be addressed in a feasibility study.

Picking is the costliest and error-prone warehouse process (de Koster et al., 2007), which requires cost-efficient and effective picking support. Existing support technologies such as pick-by-RF terminal, pick-by-voice or pick-by-vision all require an active interaction of the user with the device to control the quality of the picking, i.e. to check whether the removal from the designated storage location has taken place and the correct number of items has been removed (Battini et al., 2015). Simply transferring user interaction to a smart wearable does not necessarily bring advantages in terms of picking speed, as Gerpott and Kurt (2020) have shown in a comparison between pick-by-smartwatch and pick-by-list. However, since pick-by-smartwatch was subjectively preferred by the participants in their study for reasons of user-friendliness, a smart wearable for displaying picking information in combination with passive (background) quality control of picking is a sensible research option. In Winkelhaus et al.'s (2021) categorization of picking support technologies, this approach is considered a hybrid picking system in which human workers still play the main role, but are freed from tedious tasks such as repetitive, stereotypical interactions with a user interface.

Understanding how humans grasp objects is fundamental to many applications, from medical rehabilitation to robot programming. Since the manipulation of objects by robotic hands is less relevant for grasp recognition, we focus on approaches working on the development of grasp taxonomy and sensor-based methods for grasp recognition.

With 21 degrees of freedom, the human hand is very complex. In its basic form, grasping an object during the grasping process means "holding [an] object still", a cautious activity without movement on contact (Bullock et al., 2013). Depending on whether the palm of the hand is also in contact with the object or it is only held by the fingers, it is a "power grip" or a "precision grip" (Napier, 1956). Further elaborate grasp categories can be formed by considering which fingers (including "virtual fingers" controlled as a unit) are used in grasping the object and which parts of the finger are in contact with the object (Santello et al., 1998). Overall, this simple activity evolves into a taxonomy of 33 different types of static and stable grasps performed by a single hand (Feix et al., 2016). However, Mason et al (2001) have shown that most grasping activities involve a basic posture with slight variations in finger positions. Three kinematic synergies (flexion of the metacarpophalangeal joints of fingers 3 to 5 so that the fingers bend towards the palm, cupping or hollowing of the palm to increase the contact area and the adaptability of the hand to the shape of the object with simultaneous forward flexion of the wrist, which brings the hand closer to the object, and rotation, flexion and adduction of the thumb across the palm to meet the fingers) explain the majority of grasps (Jarque-Bou et al., 2019).

Activity profiling for a wide range of applications, from pervasive computing to health research, can rely on unobtrusive body-worn sensors of various types (e.g. inertial sensors, inclinometers, galvanic skin resistance) in combination with classification algorithms and heuristics (Preece et al., 2009). Activities are context-dependent, i.e. similar movements can correspond to different activities depending on the context, e.g. the location of the worker. Niemann et al (2021) have shown that contextual information (e.g., the worker stands in front of a rack) increases the performance of activity recognition.

Sensor arrays integrated in gloves deliver information straight from the human hand with high spatial resolution (Dipietro et al., 2008). Kinect-style RGB-depth cameras use IR projection to provide real-time 3D hand tracking data that is largely independent of illumination (Lei et al., 2012). Hand motions can also be synthesized from capturing full body and object motion (Ye and Liu, 2012).

Detecting grasping with cameras can build on classical, pre–deep learning approaches that rely on explicit, handcrafted visual cues such as color, motion, or shape rather than learned features. Hand segmentation, the process of separating the hand region from the background, typically produces a binary mask or contour that serves as a foundational preprocessing step for tasks such as gesture recognition, hand-pose estimation, or grasp-phase detection. When color models are properly adapted to lighting and skin-tone variations, skin color can provide a robust cue for hand segmentation (Kakumanu et al., 2007). Once the hand region is extracted, contour tracking or optical flow analysis can be confined to this area, reducing noise and computational cost.

Kass et al. (1988) introduced active contour models, or "snakes," which iteratively minimize an energy function to fit object boundaries and are effective for contour-based hand localization and finger-boundary refinement under moderate noise or partial occlusion. Recognizing that hands deform during grasping, Cootes et al. (1995) extended this concept through active shape models, which learn the statistical patterns of shape variability from training images to represent deformable yet anatomically constrained hand shapes.

To characterize the dynamic aspects of grasping, optical flow provides the distribution of apparent pixel velocities between consecutive frames, representing motion fields around the hand or manipulated object (Horn and Schunck, 1981). During the pre-shape phase, when fingers open and orient toward an object, the flow field exhibits *divergent* motion; during closure, when the hand envelops the object, the flow field becomes *convergent* toward the palm. Such motion descriptors enable systems to detect grasp initiation and release even without explicit 3-D reconstruction.

Finally, probabilistic models such as the condensation algorithm allow tracking of deformable hand silhouettes and dynamic grasp motions in cluttered scenes. By propagating conditional densities through a particle filter, these models achieve real-time performance and maintain robustness under occlusion or background noise (Isard and Blake, 1998).

More recently, detecting grasping employs deep-learning methods that learn spatial and temporal representations of the hand directly from image data rather than relying on handcrafted features. Avola et al. (2022) propose an end-to-end framework that jointly estimates the 3D hand pose and shape from single RGB images, enabling accurate keypoint-based hand gesture recognition. To ensure physically plausible predictions, their model integrates geometric priors about the hand's anatomical structure into a CNN architecture, constraining bone lengths and articulation to reconstruct both joint positions and hand surface deformation, thereby improving robustness in realistic grasp and interaction scenarios.

To reduce computational effort and improve performance in complex scenes, Kanis et al. (2023) provide a multi-stage transformer that employs attention mechanisms to model both local hand details and global scene context, achieving high accuracy and robustness in cluttered or occluded environments through a single-stage model that removes the need for separate localization and pose estimation steps.

These works illustrate the shift from conventional convolutional networks toward transformer-based and spatiotemporal architectures, which better capture long-range dependencies and contextual relations between the hand, object, and scene. Recent surveys emphasize that such models, including CNNs, 3D-CNNs, and attention-based transformers, albeit complex and costly, form the current state of the art in hand-pose and grasp detection, as they integrate both visual appearance and motion cues to handle occlusion, lighting variation, and fine-grained finger articulation (Oudah et al., 2020) (Woo et al., 2023),

To enhance robustness beyond RGB-based vision, multimodal approaches integrate complementary sensing modalities such as IR and depth with traditional RGB input. These methods mitigate key weaknesses of both classical and deep-learning techniques—particularly sensitivity to illumination changes and partial occlusion. D'Eusanio et al. (2020) demonstrated that fusing RGB, depth, and IR data significantly improves dynamic hand-gesture classification in automotive environments, maintaining stable recognition under varying lighting conditions. Similarly, Benitez-Garcia et al. (2021) and Birkeland et al. (2024) reported enhanced performance and invariance using multi-input or thermal-imaging setups for gesture and grasp

recognition. These multimodal systems therefore form a transitional bridge between handcrafted and learned representations, enabling accurate grasp detection in complex, real-world scenarios where single-modality approaches remain unreliable.

Within multimodal sensing, IR imaging has attracted growing interest as a robust modality for human activity and gesture recognition, owing to its insensitivity to visible illumination and its ability to capture heat signatures independently of ambient light. Unlike RGB imaging, IR inherently preserves privacy by omitting fine visual textures and facial features, making it appealing in healthcare, surveillance, and ergonomic monitoring contexts. However, IR systems face challenges such as lower spatial resolution, thermal noise, and sensitivity to background temperature drift. In hand/gesture domains, Birkeland et al. (2024) presented a thermal video dataset and a lightweight CNN achieving over 95 % gesture accuracy under various frame conditions (Birkeland et al., 2024) and Wang et al. (2025) proposed a thermal gesture recognition system optimized for embedded devices that operates reliably under non-illuminated conditions.

In order picking, camera-based gesture recognition is attractive for hands-free, human–system interaction, but the logistics-specific evidence base is thin. Industrial results on hand–object interaction show that RGB–Depth–thermal fusion improves hand/object separation and interaction cues under challenging illumination and occlusion—insights that transfer directly to warehouses with reflective racks and glove use (Zhang et al., 2021). Logistics reviews likewise argue that human-centred interfaces (including gestures) are a key lever for Order Picking 4.0, yet note persistent environmental challenges (clutter, variable lighting) that motivate multimodal sensing (Winkelhaus et al., 2021). A broader survey on human activity recognition in production and logistics underscores the same point: vision methods can support activity/interaction recognition on the shop floor, but warehouse-specific gesture control remains an open research need (Reining et al., 2019).

A notable exception is the approach of Grzeszick et al. (2016), in which the pickers wear a smartphone on their chest with the camera facing outwards. The activity recognition, i.e. the distinction between walking and picking, is based on a sensor array, i.e. the acceleration sensor, the gyroscope and the magnetic field sensor of the smartphone. The camera provides images of the picked object and aims to either recognize the GTIN barcode on the object in EAN-13 symbology or identify the object directly using a CNN approach. This approach, which is close to the idea presented in this paper, raises two questions: First, in business applications, only barcode-based object recognition is robust enough, as variants of a product (e.g. hair color nuances) are difficult to recognize directly. This requires the barcode to be presented to the camera, possibly after the product has been realigned. Secondly, only the smartphone's sensor array on the chest is used to detect picking, i.e. body movements are evaluated to classify a picking movement of the dominant hand. Although hand motions can be synthesized from capturing full body and object motion (Ye and Liu, 2012), this approach requires a complex machine learning setup to be selective, suggesting that a more lightweight concept, i.e. not relying on deep learning, that smoothly integrates into the picking flow, is still a research need.

From the reviewed literature, three implications for warehouse-based grasp detection emerge: (1) robustness against lighting variation, (2) tolerance to object deformation and occlusion, and (3) computational simplicity compatible with wearable systems.

METHODOLOGY

Feasibility studies can be conceptualized through several complementary frameworks. Bowen et al. (2009) define feasibility as a pre-evaluation stage that examines practical, contextual, and procedural readiness across eight dimensions to determine whether an intervention or system is suitable for broader testing. In contrast, the MRC/NIHR framework (Eldridge et al., 2016) focuses on methodological feasibility, clarifying the preparatory role of feasibility and pilot studies before full-scale trials. Frameworks from implementation science—for example RE-AIM (Glasgow et al., 1999) and CFIR (Damschroder et al., 2009)—extend the concept toward long-term adoption and sustainability of interventions in organizational contexts. In technology development, human-centered design principles (ISO 9241-210) and TRLs provide structured

ways to evaluate technical maturity and usability, complementing the more process-oriented social-science models.

To assess the technical feasibility of the camera-based sensing prototype, this study draws on the TRL framework, originally developed by NASA (Mankins, 1995), providing a nine-point ordinal scale describing the maturity of a technology. Empirical reviews confirm TRL's continued relevance as a cross-domain indicator of technological maturity and integration risk (Mankins, 2009; Olechowski et al., 2020). The experiments are conducted as desktop laboratory experiments, which is consistent with the stated goal of achieving TRL 4, i.e. component and/or breadboard validation in a laboratory environment (Mankins, 1995). From this perspective, the absence of warehouse realism (e.g. shelves, bins, gloves, occlusion, time pressure) is appropriate.

Fig. 1: LMC2 Control Panel

Our acceptance criteria for TRL 4 are that grasps are successfully detected (1) largely independent of the objects' size and geometry, (2) robust against object deformation, and (3) in a reproducible manner. Reproducibility at TRL 4 is operationalized as consistent correct classification across ten repeated trials per object type. We also aim to understand the influence of ambient lighting and secondary effects, such as reflection or flare, but do not consider these acceptance criteria at the chosen technology readiness level, as they depend on the application environment.

Detecting grasp movements

In our experiments, we use the Leap Motion Controller 2 (LMC2), an IR, stereo-vision camera system for tracking hand and finger movements. An earlier version of the system already has been shown to achieve high performance in both accuracy and repeatability of results (Weichert et al., 2013). The LMC2 uses two IR cameras and LEDs to detect the position, orientation, and movement of hands and fingers in a certain range. The device creates a real-time, high-resolution 3D model of the hands and their joints (**Fig. 1**), allowing users to interact with computers, virtual reality (VR), and augmented reality (AR) environments through natural hand gestures, or in our case, to track the movement of the fingers in relation to the LMC2's position.

To differentiate arbitrary hand movements from a grasp, we define a stable grasp as a configuration in which the positions of the thumb, index finger, and middle finger relative to each other remain within narrow tolerances for at least one second. This grasp corresponds to the

"prismatic 2 finger" precision grasp in Feix et al.'s (2016) taxonomy. Because a grasp is only considered stable after at least one second, random short-term constellations of the fingers in the relevant positions can be excluded. Since we use finger joint coordinates to describe a grasp, we can focus the feasibility study on a single grasp from the taxonomy. Other grasps are simply different configurations of finger joint coordinates.

For data collection and handling, a low-code programming tool (Node-Red) was used. The LMC2 provides a data stream via a TCP connection, which is converted into a string for parsing into a JSON structure. If the parser encounters "Frame ID:", the following ID is extracted and assigned to the frame identifier in the JSON structure. For hand position data, the parser looks for lines starting with "Handfläche:" and extracts the x, y, and z coordinates. Fingers can be located in the data stream by the name of the finger followed by a colon, e.g. "Zeigefinger:" for the index finger. Subsequent lines, then, contain the x, y, and z coordinates for the joints of this finger, with the fingertip at the end of the array. These values are then stored under the corresponding finger in the JSON structure. We conduct a data quality check on each JSON object to avoid using incomplete data in subsequent processes. The data quality check penalizes objects if data for a finger and/or for one or more joints of a finger is missing and only allows objects to pass if they are at least 80% complete.

The JSON object includes the frame ID, hand position, and joint coordinates for each finger of interest, offering a clear and organized format that represents the complete hand configuration for each frame. The coordinates are normalized by scaling them to a range between 0 and 1, based on predefined minimum and maximum values for each coordinate (x-axis: -500 to 500, y-axis: 0 to 1,000, and z-axis: -300 to 400; all values in mm). The boundary values used for normalization define the range in which the LMC2 provides data and were identified through experiments. The normalization process starts with the palm position, then processes each finger and its respective joints. This normalization replaces absolute coordinates with relative coordinates in a fixed coordinate system, making the data consistent, easier to analyze, and providing important preprocessing for potential machine learning applications.

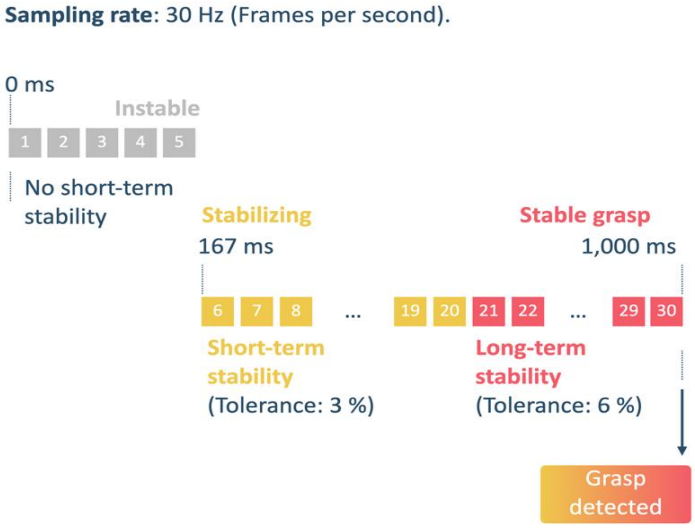


Fig. 2: Grasp detection algorithm

The Node-Red flow monitors the pairwise Euclidean distances (T-I, T-M, I-M) between the fingertips of the thumb (T), index finger (I), and middle finger (M). Detecting a grasp requires analyzing time periods rather than individual data sets (**Fig. 2**). For short-term stability, we examine 15 consecutive data sets to avoid overinterpreting isolated data sets caused by random movements. If the distances remain within a defined tolerance (3% standard deviation; this threshold was determined from the variance in sampling data from a still hand), we establish

short-term stability. When both criteria are met for at least two of the three fingers, we consider the movement stable enough ("truly stable") to start the grasp timer. We assert longer-term stability if the distances in the following 25 data sets remain within a larger tolerance interval (6% standard deviation). Using both short- and longer-term stability criteria helps filter out involuntary movements such as slight finger tremors. Not requiring all three fingers accounts for small movements of a finger, such as sliding up or down on the object being held. If the grasp timer reaches 1,000 ms while the finger positions remain truly stable, we identify the movement as a grasp and set the corresponding grasp labels in the JSON objects to 1. If the finger positions are no longer truly stable, we reset the grasp timer and assign 0 to the grasp labels.

EXPERIMENTAL RESULTS

Initial desktop experiments were conducted with various objects to determine whether grasp detection is independent of the object being grasped and whether object conditions, such as size, shape, or surface structure, pose any problems. In line with the objective of demonstrating component-level feasibility at TRL 4, we conducted experiments and recorded ten trials for each object type. In total, 30 trials (3 object types × 10 repetitions) were conducted. Each trial lasted approximately eight seconds. During the first approximately five seconds, arbitrary hand movements were performed without executing a grasp, in order to assess the system's ability to avoid false-positive classifications. In the remaining approximately three seconds, a deliberate grasp movement was performed. The LMC2 captured up to 60 frames per second, but the data quality check reduced the amount of data, still leaving more than 30 data sets per second.

All sensor data were recorded as JSON objects (about 240 objects for each trial) and subsequently analyzed to verify whether (i) non-grasp movements were correctly classified as non-grasps and (ii) the intended grasp movements were correctly detected. The ten trials per object type are sufficient at TRL 4 to demonstrate general technical capability and identify systematic limitations, although they are not intended to provide statistically representative performance metrics.

We used three objects: A matchbox (measuring 7 cm × 4 cm × 3 cm, weighing 9 g) representing small and lightweight objects, a deformable and reflecting ball (diameter of 10.5 cm, weighing 143 g), and a candle (19 cm long, 2.5 cm diameter, weighing 66 g) featuring a smooth and glossy surface. While the matchbox was unproblematic, both ball and candle presented problems for the LMC2. Low contrast (i.e., difficulties to distinguish between the object and the fingers) and reflection/flare in the frames the LMC2 captured are directly related to the limitations of the IR technology the LMC2 uses. To eventually reach a higher TRL, this limitation needs to be tested in more detail in real warehouse environments (ambient lighting, different types of products and/or packaging). However, at TRL 4, we were still able to collect enough data from each experiment to test the algorithm

In none of the experiments the arbitrary movements of the hand in the initial five seconds were classified as grasps (0% false-positive rate). On the other hand, all grasp movements in the remaining three seconds were correctly identified (100% detection rate). What varied between identified grasps of an object, were for how long the algorithm reported stable grasp ("hold time") and the standard deviations of the distances T-I, I-M, and T-M of the fingertips ("stability").

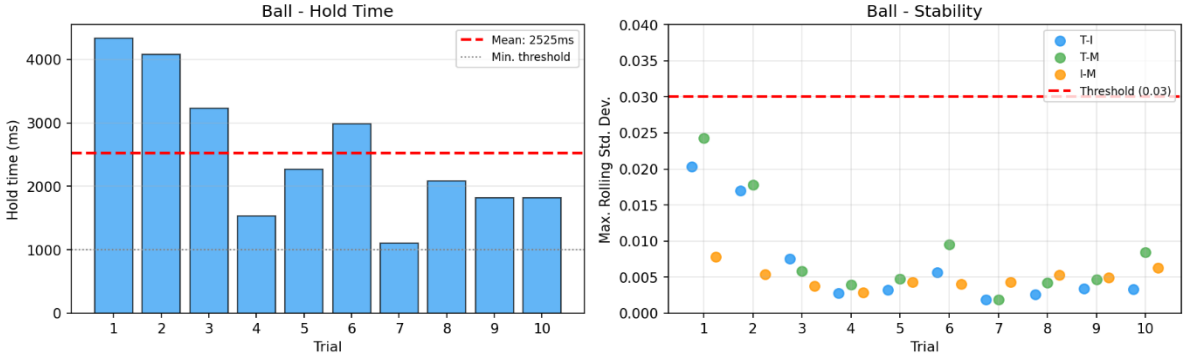


Fig. 3: Hold time and stability results for the ball object (n = 10)

Fig. 3 shows the results for the ball. The mean hold time was 2,525 ms, but varied substantially, with a minimum value in experiment 7 just above the 1,000 ms threshold defined in the algorithm. Except for the first two experiments, the stability was far from the 3% short-term stability threshold.

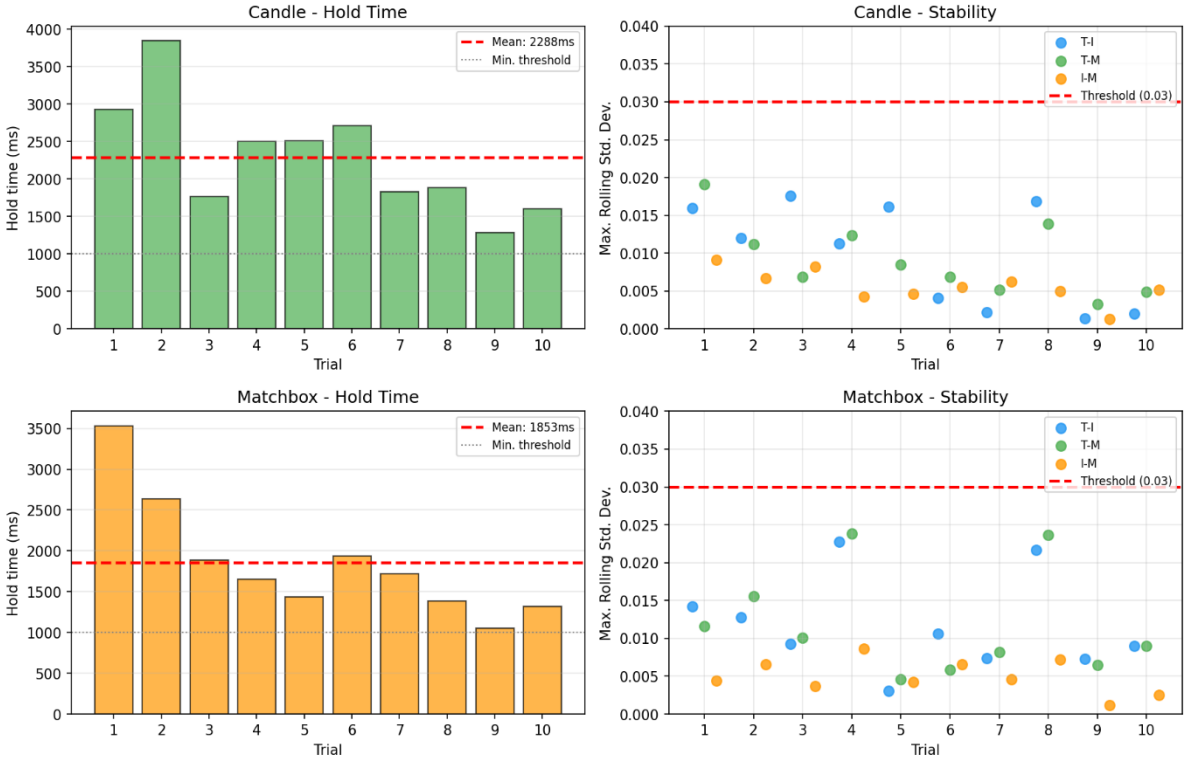


Fig. 4: Hold time and stability for candle and matchbox objects (n = 10 per object)

Fig. 4 shows the results for the matchbox and the candle. The hold time results for the candle were the most uniform of the three objects, while its stability results show a higher standard deviation for T-I and T-M distances than for I-M, indicating sliding of the thumb on the smooth object surface compared to the other two fingers. Even when sliding occurred, a stable grasp was correctly identified. A similar result was obtained for the matchbox. Here, sliding was most likely not triggered by surface characteristics but by the small size of the object. Detailed analysis of individual trials suggests that experiments aiming for a higher TRL should use carefully selected objects to better understand the influence of the objects on the algorithm.

CONCLUSION AND OUTLOOK

The study provides TRL-4 evidence that IR finger tracking can effectively support automatic grasp detection in order-picking process. In a controlled laboratory setting, stable precision grasps were consistently identified, while arbitrary non-grasp movements were not misclassified. This indicates that the temporal stability of fingertip distances is a valid metric to evaluate its feasibility. The results demonstrate that reliable grasp detection can be achieved without using machine learning techniques, suggesting that low-complexity sensing components can serve as foundational building blocks for technological development.

This study has significant implications for both academic and empirical domains. From an academic perspective, this paper offers a logistics-specific feasibility assessment that connects grasp-detection design choices to an evaluation logic based on TRL. The findings encourage research that prioritizes computationally simple and scalable sensing components and presents a replicable template for emerging picking technologies. From an empirical perspective, the results indicate that IR-based grasp detection can serve as a wearable support system for picking processes, aimed at minimizing the need for explicit user confirmations.

The experiments show that the algorithm functions effectively, even with challenging objects such as a deformable ball. However, it cannot be concluded that the 0% false-positive rate and 100% detection rate would hold under real warehouse conditions, which would provide appropriate environments above TRL 4.

While this work helps address a significant gap in academic literature, it also came with certain limitations. Firstly, the observed sensitivity to object and surface characteristics (e.g., minimum size, low contrast, reflection, glare) highlights the importance of making item-aware design choices and implementing operational safeguards before moving on to in-warehouse validation. Restricting these features may narrow the solution's scope, but it could also yield valuable feedback for validating the proposed technology. Secondly, this study is limited by its laboratory setting, which does not consider warehouse-specific factors (e.g., the position of racks and bins, walking and reaching patterns, glove usage, and varying lighting conditions). As a result, the performance observed in this study should be considered as preliminary evidence rather than as a general estimate of technological performance in real-world conditions. Despite this study has its own limitations, it represents a preliminary attempt to address a recent need from both scholars and practitioners. Thus, the results of this study can be a starting point for several future research directions: (a) testing the approach in increasingly real-world warehouse setting; (b) testing the solution by expanding the item set across size, packaging, surface reflectance, and shape; (c) integrates grasp detection with complementary quality-control functions (e.g., storage confirmation and quantity verification) to enable a comprehensive evaluation of the picking process.

ACKNOWLEDGEMENTS

The authors would like to thank the Hans-Wilhelm Renkhoff Stiftung for supporting this research.

REFERENCES

Avola, D., Cinque, L., Fagioli, A., Foresti, G.L., Fragomeni, A. & Pannone, D. (2022) 3D hand pose and shape estimation from RGB images for keypoint-based hand gesture recognition. *Pattern Recognition*, 129, 108762.

Battini, D., Calzavara, M., Persona, A. & Sgarbossa, F. (2015) A comparative analysis of different paperless picking systems. *Industrial Management & Data Systems*, 115(3), 483-503.

Benitez-Garcia, G., Prudente-Tixteco, L., Castro-Madrid, L.C., Toscano-Medina, R., Olivares-Mercado, J., Sanchez-Perez, G. & Villalba, L.J.G. (2021 Jan 07) Improving Real-Time Hand Gesture Recognition with Semantic Segmentation. *Sensors (Basel)*, 21(2), 356.

Birkeland, S., Fjeldvik, L.J., Noori, N., Yeduri, S.R. & Cenkeramaddi, L.R. (2024) Video based hand gesture recognition dataset using thermal camera. *Data in Brief*, 54, 110299.

Bowen, D.J., Kreuter, M., Spring, B., Cofta-Woerpel, L., Linnan, L., Weiner, D., Bakken, S., Kaplan, C.P., Squiers, L., Fabrizio, C. & Fernandez, M. (2009 May) How we design feasibility studies. *American Journal of Preventive Medicine*, 36(5), 452-457.

Bullock, I.M., Ma, R.R. & Dollar, A.M. (2013) A hand-centric classification of human and robot dexterous manipulation. *IEEE Transactions on Haptics*, 6(2), 129-144.

Cootes, T.F., Taylor, C.J., Cooper, D.H. & Graham, J. (1995) Active Shape Models-Their Training and Application. *Computer Vision and Image Understanding*, 61(1), 38-59.

D'Eusanio, A., Simoni, A., Pini, S., Borghi, G., Vezzani, R. & Cucchiara, R. (2020) Multimodal Hand Gesture Classification for the Human–Car Interaction. *Informatics*, 7(3), 31.

Damschroder, L.J., Aron, D.C., Keith, R.E., Kirsh, S.R., Alexander, J.A. & Lowery, J.C. (2009 Aug 07) Fostering implementation of health services research findings into practice: a consolidated framework for advancing implementation science. *Implementation Science*, 4, 50.

de Koster, R., Le-Duc, T. & Roodbergen, K.J. (2007) Design and control of warehouse order picking: A literature review. *European Journal of Operational Research*, 182(2), 481-501.

Dipietro, L., Sabatini, A.M. & Dario, P. (2008) A Survey of Glove-Based Systems and Their Applications. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, 38(4), 461-482.

Eldridge, S.M., Lancaster, G.A., Campbell, M.J., Thabane, L., Hopewell, S., Coleman, C.L. & Bond, C.M. (2016) Defining Feasibility and Pilot Studies in Preparation for Randomised Controlled Trials: Development of a Conceptual Framework. *PLoS One*, 11(3), e0150205.

Feix, T., Romero, J., Schmiedmayer, H.-B., Dollar, A.M. & Kragic, D. (2016) The GRASP Taxonomy of Human Grasp Types. *IEEE Transactions on Human-Machine Systems*, 46(1), 66-77.

Gerpott, T.J. & Kurt, A. (2020) Verbessert ein Pick-by-Watch-System Kommissionierungsleistungen gegenüber herkömmlichen Papierlisten. *Zeitschrift für Arbeitswissenschaft*, 75, 236–250.

Glasgow, R.E., Vogt, T.M. & Boles, S.M. (1999 Sep) Evaluating the public health impact of health promotion interventions: the RE-AIM framework. *American Journal of Public Health*, 89(9), 1322-1327.

Grzeszick, R., Feldhorst, S., Mosblech, C., Funk, Gernot A. & ten Hompel, M. (2016) Camera-assisted Pick-by-feel. *Logistics Journal: Proceedings*, 12, 1-8.

Horn, B.K.P. & Schunck, B.G. (1981) Determining optical flow. *Artificial Intelligence*, 17(1-3), 185-203.

Isard, M. & Blake, A. (1998) CONDENSATION—Conditional Density Propagation for Visual Tracking. *International Journal of Computer Vision*, 29(1), 5-28.

Jarque-Bou, N.J., Scano, A., Atzori, M. & Müller, H. (2019) Kinematic synergies of hand grasps: a comprehensive study on a large publicly available dataset. *Journal of NeuroEngineering and Rehabilitation*, 16(1), 63.

Kakumanu, P., Makrogiannis, S. & Bourbakis, N. (2007) A survey of skin-color modeling and detection methods. *Pattern Recognition*, 40(3), 1106-1122.

Kanis, J., Gruber, I., Krňoul, Z., Boháček, M., Straka, J. & Hrúz, M. (2023 Jun 12) MuTr: Multi-Stage Transformer for Hand Pose Estimation from Full-Scene Depth Image. *Sensors (Basel)*, 23(12), 5509.

Kass, M., Witkin, A. & Terzopoulos, D. (1988) Snakes: Active contour models. *International Journal of Computer Vision*, 1(4), 321-331.

Labus, N. & Gajšek, B. (2018) Use of ergonomic principles in manual order picking systems. Logistics & Sustainable Transport, 9(1), 11-22.

Lei, J., Ren, X. & Fox, D. (2012) Fine-grained kitchen activity recognition using RGB-D. *Proceedings of the 2012 ACM Conference on Ubiquitous Computing*, 208-211.

Mankins, J.C. (1995) *Technology Readiness Levels: A White Paper,* NASA, Office of Space Access and Technology.

Mankins, J.C. (2009) Technology readiness assessments: A retrospective. *Acta Astronautica*, 65(9-10), 1216-1223.

Marchet, G., Melacini, M., & Perotti, S. (2015). Investigating order picking system adoption: a case-study-based approach. *International Journal of Logistics Research and Applications*, 18(1), 82-98.

Mason, C.R., Gomez, J.E. & Ebner, T.J. (2001) Hand synergies during reach-to-grasp. *Journal of Neurophysiology*, 86(6), 2896-2910.

Michel, R. (2020) 2020 Warehouse/DC Operations Survey: COVID-19 pandemic hits, operations respond. *Logistics Management*, 11.11.2020). https://www.logisticsmgmt.com/article/2020_warehouse_dc_operations_survey

Napier, J.R. (1956) The prehensile movements of the human hand. *The Journal of Bone & Joint Surgery British Volume*, 38-B(4), 902-913.

Niemann, F., Lüdtke, S., Bartelt, C. & Ten Hompel, M. (2021 Dec 25) Context-Aware Human Activity Recognition in Industrial Processes. *Sensors (Basel)*, 22(1), 134.

Olechowski, A.L., Eppinger, S.D., Joglekar, N. & Tomaschek, K. (2020) Technology readiness levels: Shortcomings and improvement opportunities. *Systems Engineering*, 23(4), 395-408.

Oudah, M., Al-Naji, A. & Chahl, J. (2020 Jul 23) Hand Gesture Recognition Based on Computer Vision: A Review of Techniques. *Journal of Imaging*, 6(8), 73.

Preece, S.J., Goulermas, J.Y., Kenney, L.P.J., Howard, D., Meijer, K. & Crompton, R. (2009 Apr) Activity identification using body-mounted sensors--a review of classification techniques. *Physiological Measurement*, 30(4), R1-33.

Reining, C., Niemann, F., Moya Rueda, F., Fink, G.A. & ten Hompel, M. (2019) Human Activity Recognition for Production and Logistics—A Systematic Literature Review. *Information*, 10(8), 245.

Santello, M., Flanders, M. & Soechting, J.F. (1998) Postural hand synergies for tool use. *The Journal of Neuroscience*, 18(23), 10105-10115.

Wang, X., Ma, X., Gao, H., Wang, L. & Song, X. (2025) Thermal Imaging-Based Lightweight Gesture Recognition System for Mobile Robots. *Machines*, 13(8), 701.

Schwerdtfeger, B. (2010) *Pick-by-Vision: Bringing HMD-based Augmented Reality into the Warehouse,* Ph.D. thesis TU Munich, Munich.

Vanheusden, S., van Gils, T., Ramaekers, K., Cornelissens, T. & Caris, A. (2022) Practical factors in order picking planning: state-of-the-art classification and review. *International Journal of Production Research*, 1-25.

Weichert, F., Bachmann, D., Rudak, B. & Fisseler, D. (2013 May 14) Analysis of the accuracy and robustness of the leap motion controller. *Sensors (Basel)*, 13(5), 6380-6393.

Winkelhaus, S., Grosse, E.H. & Morana, S. (2021) Towards a conceptualisation of Order Picking 4.0. *Computers & Industrial Engineering*, 159, 107511.

Woo, T., Park, W., Jeong, W. & Park, J. (2023) A survey of deep learning methods and datasets for hand pose estimation from hand-object interaction images. *Computers & Graphics*, 116, 474-490.

Ye, Y. & Liu, C.K. (2012) Synthesis of detailed hand manipulations using contact sampling. *ACM Transactions on Graphics*, 31(4), 1-10.

Zhang, X., deVries, J., deKoster, R. & Liu, C. (2022) Fast and Faultless? Quantity and Quality Feedback in Order Picking. *Production and Operations Management*, 31(4), 1536-1559.

Zhang, Y., Müller, S., Stephan, B., Gross, H.-M. & Notni, G. (2021 Aug 23) Point Cloud Hand-Object Segmentation Using Multimodal Imaging with Thermal and Color Data for Safe Robotic Object Handover. *Sensors (Basel)*, 21(16), 5676.

Bridging the Green Gap: A Low-Cost Automation Strategy for Net-Zero Transition in Vietnamese SMEs

Dung Anh Vu[1], Kim Hua Tan[2]

1: VinUniversity; 2: University of Nottingham

INTRODUCTION

In light of the geopolitical tensions and pandemic-induced logistics vulnerabilities, the global supply chain and manufacturing operations are undergoing a historic structural realignment. For many Multinational Corporations (MNCs), the China as 'factory of the world' model has evolved into the 'China-plus-one' strategy (Basu and Ray, 2022). Due to its strategic geography, large domestic market and low labour costs, Vietnam has emerged as a primary beneficiary of the supply chain decoupling. Subsequently, MNCs in electronics, textiles, and automotive sectors have relocated their manufacturing operations in China to Vietnam. For the five years leading up to 2025 (2020-2025), Vietnam's Compound Annual Growth Rate (CAGR) was approximately 6.4% (World Economics, 2025).

Nonetheless, global regulators and consumers now demand manufacturers' full commitment to environmental excellence. Driven by the net-zero initiatives and ESG reporting compliance, decarbonization is a core operational directive for MNCs. Hence,
Vietnam's competitive advantage of low labour costs is no longer sustainable (Ngo, 2025). For example, MNCs such as Samsung and Apple are now fully committed to being carbon neutral across their entire supply chains (Scope 1, 2, and 3) (Apple, 2024). Consequently, Vietnamese manufacturers must comply with MNCs' requirements, i.e., provide verifiable carbon data or risk ineligibility from the MNCs' preferred hub under the China+1 strategy. As Vietnam solidifies its hub status and 2050 Net Zero target, it faces a significant "Green Wall" challenge: environmental regulations acting as trade barriers (Ngoc, et al. 2025).

Small and Medium Enterprises (SMEs) are the backbone of Vietnam's economy, representing more than 90% of businesses. However, most SMEs still rely on energy-intensive processes and aging machinery, generating high levels of waste (Chung et al., 2023). As MNCs tighten standards, local Tier 1, 2, and 3 SME suppliers' risk being "decoupled" from high-value orders. For many SMEs, the costly, high-tech "Industry 4.0" and automation solutions required to meet Net Zero targets are out of reach. Existing studies (Nguyen et al, 2016, Oliveira et al., 2018; Chung et al., 2025) indicated that the three primary barriers facing SMEs are a) high cost of new equipment and automation, b) lack of green innovation capabilities, and c) automation mismatch where high-tech systems lack the flexibility required for the diverse, small-batch production common in SMEs. Clearly, to address these challenges, a low-cost, green innovation approach is required.

This paper explores the potential of Karakuri Kaizen, a Japanese philosophy of "Low-Cost Automation" (LCA) (Katayama et al., 2015; Tan et al., 2022) as a bridge to the Net Zero transition in Vietnamese SMEs. Unlike modern robotics and automation systems that rely on external power, Karakuri utilizes natural forces like gravity, kinetic energy, and friction to automate operational tasks with zero electricity. In other words, SMEs can leverage Karakuri Kaizen to develop innovative, low-cost automation systems that boost productivity, cut costs, and, most significantly, lower their carbon footprint. The two main research objectives of this paper are:

- To understand the specific green challenges faced by Vietnamese manufacturing SMEs.
- To pilot test and validate Karakuri Kaizen as a viable framework for SMEs to achieve low-cost automation and sustainable green innovation.

To achieve the research objectives, this study employs a dual approach comprising stakeholder interviews with five SMEs and a pilot case study. The paper is structured into five sections to provide a comprehensive analysis of the findings. This research contributes to the field by

demonstrating how low-cost automation can facilitate the net-zero transition for Vietnamese SMEs, offering a strategic pathway to bridge the gap between industrial productivity and environmental sustainability.

Green, Innovation, and Automation: A Triad for Sustainable Manufacturing

Because automation requires significant electrical consumption, which can paradoxically increase Scope 2 emissions if the energy grid is not decarbonized, green manufacturing and automation are often viewed as contradictory (Zhan et al., 2018). However, for SMEs aiming for net-zero manufacturing, these two domains are fundamentally interrelated. Green manufacturing and automation are not mutually exclusive. Green manufacturing is defined not merely by carbon emissions, but by the incremental optimisation of resources - energy, materials, processes, and human effort - to achieve more with less. Automation could serve as the primary engine for the process optimisation. By replacing manual, inconsistent processes with precise, repeatable mechanised actions, SMEs inherently reduce variability that generates waste. Within a resource-constrained environment, every idling motor or defective component resulting from manual error represents a tangible carbon liability. Therefore, the goal for the many resource-constrained SMEs is not just "automation," but "green and low-cost automation" that improves productivity while maintaining a minimal energy footprint (Tan et al., 2022).

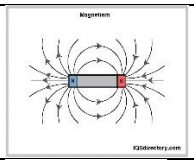
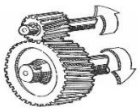
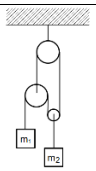
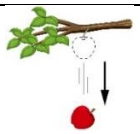
Consequently, innovation serves as an essential bridge between manufacturing sustainability and automated operations. In the context of a developing economy such as Vietnam, where financial resources are limited, the deployment of innovative Low-Cost Automation (LCA) strategies becomes a cornerstone for a viable net-zero transition. A significant portion of this innovative potential lies in the philosophy of Karakuri Kaizen, or LCA. As established in the seminal work by Tan et al. (2022), Karakuri Kaizen is the practice of using simple mechanical devices to automate shop-floor manual operations without electricity, sensors, or complex programming. It leverages the laws of physics, such as gravity, friction, centrifugal force, inertia, and springs, to create zero electric power automation. Table 1 lists some common Karakuri Kaizen mechanisms.

Karakuri Kaizen emphasizes the application of creative ingenuity to mechanical simplicity, optimizing operational workflows to be both ergonomic and efficient (Katayama et al., 2014; Murata et al., 2013). The primary utility of Karakuri Kaizen lies in its ability to effectively decouple human labour from automated machine functions; this segregation allows operators to eliminate non-value-added activities (waste) and prioritize value-added tasks within a specified timeframe. For instance, the deployment of low-cost gravity-fed shelving units exemplifies how basic mechanical principles can enhance productivity while ensuring adherence to first-in, first-out (FIFO) inventory protocols. When implemented strategically, Karakuri Kaizen facilitates efficient material handling, reduces cycle times, and mitigates occupational hazards. Furthermore, these systems contribute to significant cost reductions and process refinements by minimizing personnel strain and proactively eliminating defects.

Beyond these process refinements, Karakuri Kaizen offers distinct competitive advantages over complex automated systems. Moreover, Karakuri Kaizen is easier to maintain. Electrical automation systems will require specialists, such as an electrician, programmer, or mechanic, to fix problems. The 'mechanical transparency' of Karakuri Kaizen enables shop-floor operators to resolve issues without external intervention, thereby reducing operational downtime. Nevertheless, it must be noted that while these systems mitigate occupational hazards and costs, their capabilities remain inherently limited by their mechanical simplicity compared to the high-level logic of digital automation.

Table 1: Common Karakuri Mechanisms

Mechanisms	**Functions**	**Diagrams**
Spring	Accumulating recoverable mechanical energy (e.g., via counterweights) and strategically releasing it to automate tasks and reduce manual effort.	

Magnetic force	Utilizing magnetic attraction and repulsion to achieve precise positioning and motion control, effectively replacing complex powered actuators with simple, physics-based logic.	
Gear	Regulating the velocity of engagement and ensure the synchronized transmission of motion.	
Roller	Serving to decouple the object from static surface friction by providing a low-resistance path. Rollers ensure the consistent and efficient propagation of motion across the assembly line, maintaining the momentum required for autonomous operation.	
String and pulley	Inverting the direction of applied force, enabling the generation of an upward vertical displacement through a downward or horizontal input. The system can achieve a vector transformation of motion to lift loads with high precision.	
Gravity	Shifting an object's centre of gravity relative to its support base, the gravity system induces autonomous displacement, allowing for the passive transit of materials along a prescribed gradient.	

Despite the compelling theoretical benefits of Karakuri Kaizen in fostering carbon-neutral manufacturing, its practical integration into existing production lines is not a straightforward 'plug-and-play' endeavour. This is because the transition from traditional manual labour or high-energy automation to passive, mechanical systems requires a specialised form of green innovation that balances mechanical constraints with specific operational requirements (Tan et al., 2013; Katayama and Lin, 2019). For SMEs in developing economies, the successful 'roll-out' of these systems is often hindered by a lack of standardized design frameworks and the innovation gap required to translate physical laws into functional shop-floor automation solutions. Consequently, there is a need to investigate how these Karakuri Kaizen mechanisms can be systematically designed and deployed to maximize their sustainable impact. The following section details the research methodology employed in this study, outlining the empirical approach used to evaluate the design, implementation, and performance of Karakuri Kaizen systems within the specific context of Vietnamese manufacturing SMEs.

Research Methodology

This research employs a qualitative multiple-case study design to address two primary objectives: (a) to understand the specific green innovation challenges faced by Vietnamese manufacturing SMEs, and (b) to identify a practical, low-cost pathway for achieving net-zero manufacturing. A qualitative approach is particularly appropriate here as it allows for an in-depth exploration of "how" and "why" resource-constrained firms navigate the complex transition to sustainability within their specific socio-economic context. Hence, this study aligns with Yin's (2018) assertion that case studies are the preferred strategy when 'how' or 'why' questions are being posed about a contemporary phenomenon within its real-life context. Because integrating low-cost Karakuri mechanical automation involves complex socio-technical interactions and site-specific constraints, a case-based approach enables researchers to capture the nuanced 'how' of the technical setup and the 'why' behind specific organizational challenges. This method facilitates an in-depth exploration of the causal links between lean philosophy and shop-floor ingenuity that purely quantitative surveys might overlook.

Stage 1: Multiple-Case Inquiry

The first stage involved on-site visits to five SMEs across key manufacturing hubs in Hanoi, Vietnam (see Table 2). This study employed semi-structured interviews as the primary data collection method. This approach was selected for its inherent flexibility, allowing for a balanced dialogue that follows a consistent thematic framework while providing the 'interpretive space' for managers to elaborate on unique socio-economic or regional contingencies (Yin, 2018). To investigate green innovation challenges, we posed six targeted questions to managers focusing on the tension between regulatory compliance and financial viability, and the impact of legacy manufacturing infrastructure on eco-efficiency. We further examined the influence of international supply chain pressures versus domestic market demands, the availability of green and lean operations techniques, and the overarching conflict between short-term operational survival and long-term sustainable strategic investment. To ensure data triangulation and depth, two semi-structured interviews were conducted per visit with the factory owner and the production manager. Each recorded session lasted between 60 and 120 minutes, focusing on operational bottlenecks and carbon reduction awareness.

Table 2: Profile of Participating SMEs

Company	**Sector**	**Size (Employees)**	**Primary Market**	**Interview Duration**
SME-A	Plastic Injection Moulding	85 (Small)	Domestic / Tier 2	110 mins
SME-B	Electronic Components	140 (Medium)	Export (MNC)	95 mins
SME-C	Metal Stamping & Tools	45 (Small)	Domestic	120 mins
SME-D	Garment & Textiles	210 (Medium)	Export (EU/USA)	80 mins
SME-E	Automotive Spare Parts	115 (Medium)	Tier 1 Supplier	105 mins

The qualitative data gathered from the semi-structured interviews were processed in NVivo to ensure rigorous data management and transparent coding. Following the principles of thematic analysis, the transcripts were systematically coded to identify recurring patterns, barriers, and drivers specific to the Vietnamese context. These findings were subsequently synthesised into a conceptual 4-stage net-zero pathway, providing a strategic roadmap tailored for manufacturing SMEs to transition from baseline compliance to carbon neutrality.

Stage 2: Pilot Case Study & Karakuri Kaizen Implementation
A SME-C (Metal Stamping) was selected for a two-week *Karakuri Kaizen* pilot implementation. The firm was a willing participant due to rising electricity costs and increasing pressure from a key Japanese client to reduce its carbon footprint. A project team comprises of the factory owner, factory manager, production supervisor and shopfloor operators. It was established to work on the Karakuri Kaizen, which consists of three stages as proposed by Tan et al. (2022), which include: a) Gemba Genbutsu observing and analysing the process where the problem lies; b) Developing a Karakuri solution; and c) Implement the solution.
During the identification phase, the scrap removal station was identified as a high-waste area because it relied on a mid-size 2kW motorized conveyor that ran continuously to move metal offcuts, resulting in excessive energy consumption and high maintenance requirements. Additionally, an operator must monitor the conveyor system, which frequently stalls to load irregularities that trigger the motor's safety cut-off. The operator will have to load and unload heavy scrap metal until the motor is back on.

The performance of the Karakuri solution was evaluated through a "before and after" comparison focused on three critical metrics: energy consumption, carbon impact, and operator well-being. First, energy consumption was quantified using a plug-in power meter to compare the power usage of the original motorised conveyor with that of the gravity mechanical chute. Second, the carbon impact was determined by applying the specific Vietnamese grid emission factor to the total energy saved, providing a verifiable figure for carbon reduction. Finally, worker well-being is assessed subjectively through self-reporting, utilizing the Borg RPE (rating of perceived exertion) scale (Borg, 1982), which ranges from 6 to 20.

From Interview Insights to Pilot Implementation

The interviews conducted across five diverse SMEs (SME-A through SME-E) revealed a consistent tension between the desire to "go green" and the practicalities of resource constraints. While all five firms expressed acute awareness of the "green wall," particularly in the export-oriented electronics and textile sectors, the path to net zero was described as a high-stakes hurdle that must be overcome.

The primary findings suggest that carbon reduction is viewed not as an environmental choice but as a strategic requirement that taps into the global supply value chain. However, three recurring themes emerged: investment inertia, green innovation capabilities, and mistrust of automation. These insights directly informed the development of the 4-stage net-zero pathway (see Table 3), serving as the bridge between awareness and the challenge of LCA implementation covered in Stage 2 of the study. Some key insights and notable quotes from the interviews are: a) SME-A: *"We see the solar panels on the MNC factories next door, but for us, the investment and interest rates for such a project would swallow our annual profit. We need a better way to cut down energy consumption but maintain our productivity."; b)* SME-B: *"The MNCs send us spreadsheets to fill out regarding carbon footprint. We know how much electricity we pay for, but we don't know how much the carbon footprint of the components we bought from our suppliers is."; c)* SME-C: *"Automation usually means robots from Japan or China. If a sensor or component breaks, the line will stop for a week or more while waiting for a part. We prefer automation solutions that we can fix with a simple tool."* The synthesis of these qualitative insights yielded the following strategic framework, designed to guide resource-constrained SMEs through a low-cost, net-zero transition.

Table 3: The 4-Stage Net-Zero Pathway for Vietnamese SMEs

Stage	**Focus**	**Key Actions**	**Tools & Methods**	**Expected Outcome**
1. Diagnostic	Carbon Awareness	Identify "Energy Hotspots" and map intensive manual tasks operations.	Gemba Walk, Energy Audits, Carbon Footprint Checklists.	A prioritised list of operations wastes and carbon drivers.
2. Alignment	Lean-Green Innovation	Streamline processes by innovative automation systems.	Value Stream Mapping (VSM), 5S, Elimination of unnecessary transport.	A Lean foundation ready for Karakuri Kaizen
3. Innovation	Karakuri Implementation	Design and install zero-power mechanical devices to replace motorized/manual tasks.	Karakuri Kaizen (LCA), Gravity-fed chutes, Counterweight lifters.	Reduction in Scope 2 emissions & capital savings.
4. Verification	Scaling & Reporting	Measure energy savings and document data for MNC client compliance.	Before/After performance metrics	Green Supplier status; expansion to other production lines.

Low-Cost Automation Pilot Implementation

SME-C was selected for the pilot phase. Their feedback regarding the need for "easy maintenance, low-cost solutions" made them the ideal candidate to test a Karakuri Kaizen solution. Moreover, SME-C faced a dual challenge: rising electricity tariffs and a "Green Mandate" from its primary Japanese client requiring a 10% reduction in carbon intensity per part by 2027. During the Gemba walk, the material handling and scrap disposal station was identified as a

critical carbon emission hotspot. In this area, a 2kW motorized conveyor belt operated for 16 hours a day to transport heavy metal offcuts from the stamping press to a collection bin. Despite the intermittent nature of the scrap production, the motor ran continuously, resulting in significant idle waste and a high carbon footprint relative to the operations' value. The green innovation strategy is to shift from motorised solutions to an LCA-based solution aligned with the Karakuri Kaizen philosophy. The objective was to eliminate the motorised conveyor entirely and replace it with a zero-power mechanical system. After many trials and errors, the team decided on a **"**gravity-activated seesaw chute**"** Karakuri solution (see Figure 1). This mechanism uses the weight of the metal scrap to power its own movement. As scrap falls from the press, it collects in a small hopper balanced on a pivot. Once the weight reaches a specific threshold (10kg), the latch releases, and gravity tilts the chute, sliding the scrap into the bin. A counterweight then automatically returns the chute to its original position. This implementation took exactly 12 days, utilising recycled scrap aluminium sheets and stainless-steel springs already available in the factory's maintenance shop.

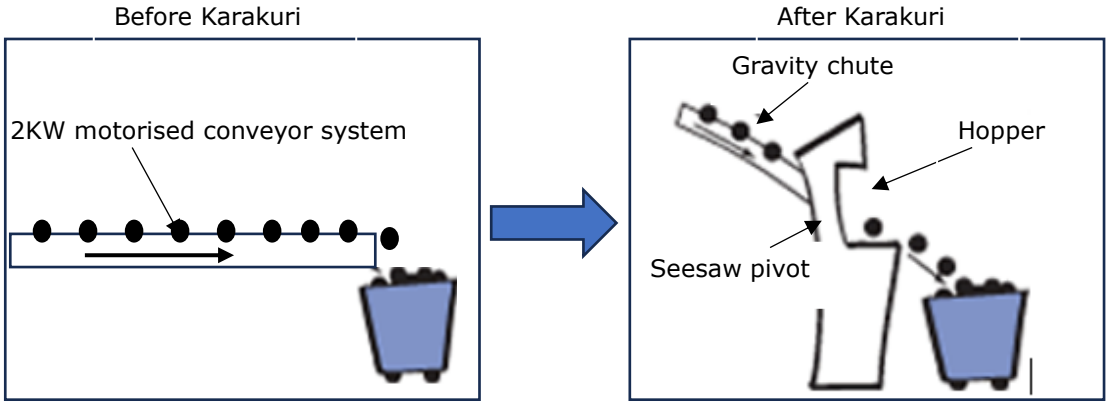


Figure 1: Gravity seesaw chute Karakuri Solution

The "before and after" analysis demonstrates that low-cost innovation can achieve high-impact green results. By removing the 2kW motor, the station's energy consumption is reduced to zero while maintaining the same functions (see Table 4).

Furthermore, the implementation fostered a sense of green ownership among the workers. Unlike a black-box robotic system, the mechanical nature of the gravity seesaw chute allowed operators to understand, repair, and even suggest improvements to the device. The Kaizen habit is essential to the 4-stage pathway developed in Stage 1, which moves the firm from simple awareness to active, sustainable innovation. This pilot proves that for resource-constrained SMEs, the path to being a green supplier is both financially viable and technically feasible through green innovation and mechanical ingenuity.

Table 4: Performance Comparison of Scrap Handling Station

Performance Metric	**Before (Motorized Conveyor)**	**After (Karakuri Kaizen)**	**Improvement (%)**
Energy Consumption	24 kWh / day	0 kWh / day	100%
Annual Carbon Footprint	~6,300 $kgCO_2e$	0 $kgCO_2e$	100%
Maintenance Frequency	Monthly (Motor/Belt)	Annual (Lubrication)	90%
Operational Noise	75 dB	40 dB	46%

Discussion and Conclusion

The transition toward net-zero manufacturing in Vietnam is frequently touted as a tough choice between maintaining a labour-intensive, carbon-heavy status quo or pursuing expensive, inflexible high-tech automation. This research addresses those challenges by introducing a sustainable path through the integration of Karakuri Kaizen and green innovation. Our pilot case study at SME-C serves as empirical evidence that the resource wall facing Vietnamese SMEs is not insurmountable. Using mechanical ingenuity and Karakuri Kaizen, local SMEs can successfully implement low-cost automation and navigate the green wall erected by global supply chains, transforming environmental compliance from an onerous cost burden into a distinct competitive advantage. The findings also propose a four-step net-zero pathway for Vietnamese SMEs.

From a theoretical perspective, this study contributes to lean and green literature (Dues et al., 2013; Garza-Reyes et al., 2018) by extending LCA's application to the specific context of a developing economy. Furthermore, this research identifies green innovation and the Karakuri Kaizen as critical assets that drive sustainable performance. Finally, the findings indicate that separating economic growth from carbon emissions is attainable even in developing countries through the application of Karakuri Kaizen.

The practical implications for Vietnamese manufacturers and policymakers are significant. For SME managers, this research demystifies net-zero transition by demonstrating that sustainability and automation can go hand in hand. Instead, firms can foster a self-sustaining ecosystem of internal innovation by training shop-floor workers in Karakuri Kaizen, thereby reducing dependence on expensive, energy-hungry technology. For MNCs, these findings suggest a shift from issuing carbon mandates to facilitating Karakuri workshops that upskill Tier 2 and Tier 3 SME suppliers. For policymakers, the 4-stage pathway offers an achievable blueprint for achieving net zero by 2050, ensuring that the vast majority of SMEs are not left behind in the country’s sustainability push.

Despite these promising results, this study has several limitations. The Karakuri Kaizen implementation was conducted at a single material-handling station; therefore, the cumulative impact on the factory's total carbon footprint requires longitudinal measurement. Additionally, while the mechanical nature of Karakuri is highly suitable for industries such as metal stamping, automotive, and electronics, its applicability may be lower in chemical-intensive sectors where thermal energy is the primary carbon driver. Future research should therefore explore digital-mechanical hybrids in which Karakuri is integrated with ultra-low-power IoT sensors to provide the digital traceability required by global ESG standards. Ultimately, if Vietnam can master the art of doing more with less, it will not only secure its place in the global supply chain but also set an example for sustainable manufacturing across ASEAN.

REFERENCES

- Apple (2024). Apples Carbon Removal Strategy White Paper. Jan 2024. https://www.apple.com/environment/pdf/Apples_Carbon_Removal_Strategy_White_Paper.pdf. Accessed on 21 Jan 2026.
- Basu, P., & Ray, P. (2022). China-plus-one: expanding global value chains. *Journal of Business Strategy*, *43*(6), 350-356.
- Borg, G. A. (1982). Psychophysical bases of perceived exertion. *Medicine & science in sports & exercise*, *14*(5), 377-381.
- Chung, L., Tan, K. H., & Nguyen, T. T. T. (2023, February). Is that Innovation? Unlocking Vietnamese MedTech SMEs Innovation Pathways. In *Intelligent and Transformative Production in Pandemic Times: Proceedings of the 26th International Conference on Production Research* (pp. 705-715). Cham: Springer International Publishing.
- Chung, L., Tan, K. H., & Yoshie, O. (2025). Sustainable circular economy: Unpacking the unintended consequences of digital transformation in Japanese SMEs. *Technological Forecasting and Social Change*, *221*, 124335.
- Dües, C. M., Tan, K. H., & Lim, M. (2013). Green as the new lean: How to use lean practices as a catalyst to greening your supply chain. *Journal of Cleaner Production*, 40, 93–100.

- Garza-Reyes, J. A., Kumar, V., Chaikittisilp, S., & Tan, K. H. (2018). The effect of lean methods and tools on the environmental performance of manufacturing organisations. *International Journal of Production Economics*, 200, 170–180.
- Katayama, H., & Lin, J. C. (2019). *Some advanced topics on innovation-focused lean/agile management*. In Proceedings of the 23rd Cambridge International Manufacturing Symposium, 26–27 September 2019.
- Katayama, H., Lin, J. C., & Wang, Y. C. (2015). *On development of Karakuri contrivance for green-lean production—through manual work evaluation by operations experts with AHP logic*. Proceedings of FAIM 2015, 1, 488–495.
- Katayama, H., Sawa, K., Hwang, R., Ishiwatari, N., & Hayashi, N. (2014). *Analysis and classification of Karakuri technologies for reinforcement of their visibility, improvement and transferability: An attempt for enhancing lean management*. In Proceedings of PICMET 2014: Infrastructure and Service Integration, pp. 1895–1906.
- Murata, K., Wakabayashi, K., Watanabe, A., & Katayama, H. (2013). Analysis on integrals of lean module technologies—the cases of visual management, Poka-Yoke and Karakuri technologies. *Research on E-Commerce Front*, 1(2), 21–29.
- Ngo, Q. H. (2025). *How Vietnamese Exporting SMEs Translate Green Practices into Export Performance Through Incremental and Radical Green Innovation*. SAGE Open, 15(2), 21582440251341988.
- Ngoc, T. H., Duc, H. C., & Hai, T. H. (2025). Circular economy policies in Vietnam: Assessing implementation and impact On green manufacturing. In *Green Transformation in the Context of Global Change* (pp. 51-60). CRC Press.
- Nguyen, V.K., Vu, D.A., & Nguyen, Q.N. (2016). R&D investment of Japanese multinational corporations in Vietnam through Green supply chain: Case of Ajinomoto. *Journal of Sustainability Science and Management*, 11(1), pp. 43-52.
- Oliveira, G. A., Tan, K. H., & Guedes, B. T. (2018). Lean and green approach: An evaluation tool for new product development focused on small and medium enterprises. *International Journal of Production Economics*, 205, 62–73.
- Tan, K. H., Denton, P., Rae, R., & Chung, L. (2013). Managing lean capabilities through flexible workforce development: A process and framework. *Production Planning & Control*, 24(12), 1066–1076.
- Tan, K. H., Katayama, H., & Manickavasagam, S. (2022). What is Karakuri Kaizen and How Does It Work?. In *International conference on production research* (pp. 25-32). Cham: Springer Nature Switzerland.
- World Economics (2025). Vietnam's GDP Growth Rate. https://www.worldeconomics.com/Countries-With-Highest-Growth/Vietnam.aspx#:~:text=COMPOUND%20ANNUAL%20GROWTH%20RATES:%202015,(2015%2D2025). Accessed on 21 Jan 2026.
- Yin, R.K (2018). *Case Study Research and Applications: Design and Methods*, Sage.
- Zhan, Y., Tan, K. H., Ji, G., Chung, L., & Chiu, A. S. (2018). Green and lean sustainable development path in China: Guanxi, practices and performance. *Resources, Conservation and Recycling,* 128, 240–249.

Digital Transformation Adoption and Sustained Logistics Performance in SMEs in Vietnam: The Mediating Role of Absorptive Capacity

My Thanh Tran Dinh, Ahmad Abareshi, Vinh V. Thai

School of Accounting, Information Systems and Supply Chain, RMIT University, Melbourne, Australia

INTRODUCTION

The contemporary business environment is increasingly characterised by VUCA - volatility, uncertainty, complexity, and ambiguity, which is driven by unstable markets, manufacturing uncertainty, data complexity, and ambiguity in managerial decision-making (El Hathat et al., 2023). In such conditions, firms face growing disruptions in their logistics operations due to geopolitical tensions, demand fluctuations, and rising logistics costs. These challenges are particularly acute for small and medium-sized enterprises (SMEs), which often operate with limited resources and flexibility. Logistics plays a critical role in cost efficiency, service reliability, customer satisfaction, and overall competitiveness (Taschner, 2016). Consequently, disruptions in logistics not only lead to delivery delays and cost increases but also threaten long-term performance and competitive advantage. In volatile environments, therefore, effective logistics becomes essential for maintaining their operation and competitive advantage.

In response to these challenges, digital transformation (DT) has been widely considered as a strategic solution that enables firms to reduce logistics costs, enhance operational efficiency, and thereby improve logistics performance over the long term (Nguyen, 2026). By adopting digital technologies, firms can increase information visibility, strengthen coordination across logistics activities, and improve decision-making quality in volatile and uncertain environments. Recognising the strategic importance of DT, the Vietnamese Government has introduced a range of national policies and resolutions that position enterprise digitalisation as a key national priority (e.g., the National Digital Transformation Program and Resolution 57-NQ/TW-2024).

Despite the growing recognition of DT as a critical enabler of firm performance, most previous studies have examined its impact on performance at a short term (e.g. Malodia et al., 2023). Consequently, limited empirical attention has been given to how DT enables firms to sustain performance, particularly logistics performance, in a stable and continuous manner over time, especially in a VUCA environment. In other words, the mechanisms through which DT is translated into sustained logistics performance remain insufficiently understood, particularly in the context of SMEs, which are highly vulnerable to external shocks (Eggers, 2020).

Although the relationship between DT and firm performance has been extensively examined (Malodia et al., 2023), the 'sustained' aspect of performance remains insufficiently explored in DT research. In addition, existing DT research has predominantly focused on the direct effects of DT on performance outcomes, whereas the link between information technology and absorptive capacity, and the mechanisms by which it influences performance, remains understudied (Ma et al., 2021). As SMEs are also more vulnerable to external shocks and supply chain disruptions (Eggers, 2020), it is argued that absorptive capacity becomes significantly important in enabling firms to translate DT adoption into sustained logistics performance. However, the mechanisms linking DT adoption to sustained logistics performance through absorptive capacity remain insufficiently examined empirically in the existing literature.

Therefore, to address research gaps regarding the mechanism of DT adoption and sustained logistics performance, this study aims to investigate the impact of DT adoption on sustained logistics performance among SMEs in Vietnam and shed light on the role of absorptive capacity towards this nexus. Grounded in the Resource-Based View and Dynamic Capabilities Theory, this study contributes to the literature on DT by shifting the focus from short-term operational outcomes to sustained logistics performance over time, while providing empirical evidence on the mechanisms by which DT is translated into sustained performance in SMEs in emerging economies.

LITERATURE REVIEW AND HYPOTHESIS DEVELOPMENT

Literature review

Digital transformation adoption

DT is defined as "the use of new digital technologies (such as social media, mobile technologies, analytics, and embedded devices) to enable major business improvements, including enhancing customer experience, streamlining operations, and creating new business models" (Fitzgerald et al., 2014, p. 1). Research on DT has attracted substantial scholarly attention over the past two decades. However, the existing literature has predominantly examined DT in the context of large enterprises, while empirical studies focusing on SMEs remain relatively limited (Sagala & Őri, 2024). Unlike large enterprises that can rapidly develop and deploy their own digital platforms, SMEs often rely on third-party digital platforms due to resource constraints and limited internal capabilities (Westerlund, 2020). As a result, the DT process in SMEs differs fundamentally from that in large firms and tend to lag behind larger firms in this process (Eller et al., 2020). Under such resource constraints, it is critical to understand how DT adoption contributes to performance outcomes through organisational capabilities, such as absorptive capacity, particularly in SMEs.

Absorptive capacity (AC)

AC refers to "the firm's ability to identify, assimilate, and exploit knowledge from the environment" (Cohen & Levinthal, 1990, p. 569). It is the ability to acquire, absorb, transform and exploit knowledge. Based on Cohen and Levinthal (1990)'s seminal work, there has been a great deal of research on the critical role of AC in SMEs. Empirical evidence suggests that AC of SMEs is considered a critical determinant of the adoption of information technology (Cuevas-Vargas et al., 2022). Therefore, AC is essential to the survival and growth of SMEs because it enables firms to maintain their competitive advantage and, ultimately, enhance organisational performance (Cuevas-Vargas et al., 2022).

Sustained logistics performance (SLP)

Logistics performance is defined as the efficiency and effectiveness associated with performing logistics activities. It has been measured by various attributes, including cost, delivery speed, delivery dependability, responsiveness, delivery flexibility and order fill capacity (Wang, 2018). However, most existing studies focus on measuring the contemporary logistics performance. This approach does not fully capture a company's ability to sustain, repeat, and improve logistics efficiency over time, especially in an increasingly volatile business environment.

In the literature, the concept of "sustained" is primarily discussed in the context of sustained competitive advantage, emphasising a firm's ability to maintain superior performance relative to competitors over an extended period (Barney, 1991; Roberts & Dowling, 2002). Although there is currently no clear definition of sustained performance or sustained logistics performance in the literature, this study adopts the attributes of sustained competitive advantage, in addition to dimensions of logistics performance, as a framework for measuring SLP. Hence, SLP encompasses not only traditional indicators such as accuracy, flexibility, reliability, and delivery speed, but also reflects consistency, continuous improvement and repeatability of logistics operations. Accordingly, SLP can be understood as a company's ability to consistently achieve, maintain, and improve logistics efficiency over time, even in the face of disruptions.

Theoretical background and hypothesis development

Resource-Based View and Dynamic Capabilities

This study draws on the Resource-Based View (RBV) and Dynamic Capabilities (DC) theory to explain the relationship between DT adoption, AC, and SLP. According to RBV, firms achieve sustained competitive advantage through valuable, rare, and inimitable resources and capabilities (Barney, 1991). In this context, DT adoption can be viewed as a strategic

organisational resource that enhances operational reliability, standardises processes, reduces errors, and ultimately strengthens sustained logistics performance.

In dynamic environments, resources alone are insufficient to maintain competitive advantage. DCs theory extends RBV by emphasising firms' abilities to integrate, build, and reconfigure competencies in response to environmental changes (Teece et al., 1997). Among these capabilities, AC is recognised as a critical dynamic capability that enables firms to acquire, assimilate, and apply external knowledge, which, in turn, encourages internal innovation activities. Drawing on DCs theory, this study further argues that AC serves as a key dynamic capability that enables firms to sense, assimilate, and apply external knowledge, thereby translating DT adoption into SLP over time.

Hypothesis development

Prior studies have indicated that DT has a positive effect on firm performance, e.g (Malodia et al., 2023). Empirical evidence also supports the relationship between DT and operational performance (Guo & Xu, 2021). Accordingly, DT may benefit firms by reducing transaction costs, increasing operating efficiency, and enhancing employee productivity. By introducing advanced technologies that optimise resource utilisation and improve overall efficiency, DT adoption could contribute to reducing costs of logistics operations, increase productivity, and improve service quality, and thus could improve logistics performance in the long term. This is particularly relevant for SMEs, where resource constraints necessitate the efficient use of logistics assets and adaptive operational practices. From these arguments, it can be argued that DT also plays a critical role in enhancing logistics performance in a sustained manner. Based on this elucidation, the first hypothesis is proposed:

H1. *DT adoption is positively associated with SLP in SMEs.*

The use of digital technologies could improve learning processes and enhance the firm's AC (Kastelli et al., 2022). It is stated that the adoption of digital technologies allows the firm to improve information access, foster collaboration, enable real-time decision-making, support innovation and expand knowledge. In this connection, it is argued that digital technologies can enhance the firm's AC. In an empirical study conducted in Colombia by Cuevas-Vargas et al. (2022) involving 145 small firms, it was found that ICT adoption helps companies assess and assimilate external knowledge. Similarly, Kastelli et al. (2022) conclude that digital capacity promotes a firm's AC by expanding knowledge resources and facilitating interaction. Therefore, the following hypothesis is put forward:

H2. *DT adoption is positively associated with AC in SMEs*

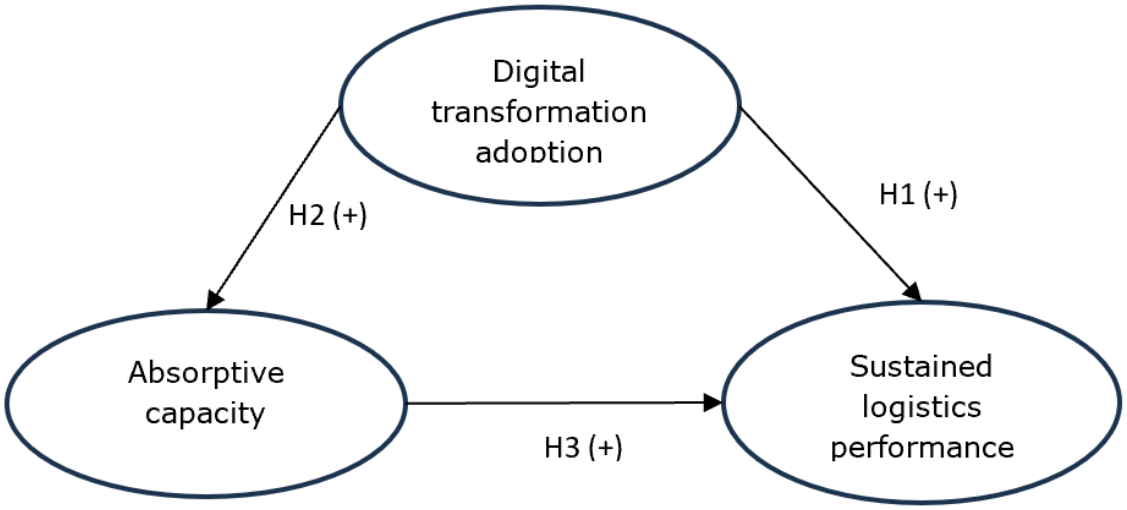
Recent research has posited that AC plays a vital role in promoting firm performance, and empirical studies, such as Ma et al. (2021), have found a positive association between AC and firm performance. This process would help the firm achieve a competitive advantage, which is critical to increasing profitability and enhancing firm performance. In addition, the adoption of digital technology within an organisation acts as an effective mechanism that supports AC-related knowledge processes. Accordingly, information technology enhances AC, which in turn translates into improved firm performance (Ma et al., 2021). Therefore, from a logistics operations perspective, AC is expected to play a crucial role in enhancing SLP by enabling firms to continuously identify, assimilate, and apply knowledge, thereby supporting the ongoing stabilisation of logistics operations over time. It is also suggested that organisational AC has a mediating role in leveraging the adoption of DT and SLP. Thus, this study proposes that:

H3. *AC is positively associated with SLP in SMEs*

H4. *AC mediates the relationship between DT adoption and SLP in SMEs.*

Building on hypothesis development, the conceptual model is proposed in Figure 1.

Figure 1. The conceptual model of the study



Source(s): Authors' own work

RESEARCH METHODOLOGY

Data collection and sampling

A survey-based research approach was employed in this study to collect data via a probability sampling from owner or senior manager in SMEs, as they were considered being the primary decision-makers for businesses. By using a simple random sampling method, the survey was administered to 700 SMEs through the Qualtrics platform .

Measurement of constructs

The measurement constructs in the proposed model were adopted from the existing literature. Based on the construct conceptualisation and prior validated scales, three constructs in the model were measured reflectively, meaning that indicators associated with a particular construct should be highly correlated with the others. The measurement scale for DT adoption was adapted from AlNuaimi et al. (2022). AC was measured using items derived from the well-validated scale developed by Cuevas-Vargas et al. (2022). The scale for SLP was developed by integrating established logistics performance dimensions identified in prior studies (Roberts & Dowling, 2002; Wang, 2018) with the notion of sustained performance outcomes as conceptualised by Barney (1991).

Design and administration of the research instrument

A survey questionnaire was developed based on the conceptual model. Respondents were asked to evaluate the level of agreement on each measurement item using a five-point Likert scale (1 = strongly disagree and 5 = strongly agree). The survey instrument underwent a forward-backward translation process to ensure equivalence between the original and translated versions. A pilot with a sample of 53 managers in SMEs was conducted to clarify the questionnaire's structure and identify weaknesses and ambiguities in its language. The finalised Vietnamese version of the questionnaire was distributed to the potential participants via the Qualtrics platform.

RESULTS

Demographic information

A total of 700 survey invitations were distributed, of which 240 usable responses were received on the Qualtrics platform after the cut-off date, yielding a response rate of 34%. After data screening (including identification of missing data, outliers, straight-line errors, non-normality, and multicollinearity), 214 valid responses were retained for further analysis. Table 1 presents demographic information of respondents in this study.

Table 1. Demographic profile of respondents

Group	N	%	Group	N	%
Firm size			*Position*		
Micro enterprise	15	7.0	Owner, Director, Vice Director	89	41.6
Small enterprise	73	34.1	Senior manager	43	20.1
Medium enterprise	102	47.7	Middle manager	21	9.8
Not state	24	11.2	Senior executive	27	12.6
Sector			Staff	9	4.2
Trade sector	36	16.8	Not state	25	11.7
Service sector	59	27.6	*Working experience in firm*		
Agricultural, forest & fishery sector	34	15.9	Less than five years	55	25.7
Manufacturing sector	27	12.6	5-10 years	86	40.1
Construction sector	18	8.4	11-20 years	41	19.2
Other	16	7.5	More than 20 years	7	3.3
Not state	24	11.2	Not state	25	11.7
Year of establishment			*Working experience in industry*		
Less than 5 years	15	7.0	Less than five years	20	9.3
5-9 years	59	27.1	5-10 years	83	38.7
10-19 years	61	29.0	11-20 years	65	30.4
More than 20 years	54	25.2	More than 20 years	21	9.9
Not state	25	11.7	Not state	25	11.7

Source(s): Authors' own work

Measurement model evaluation

The results in Table 2 indicate good internal reliability and a high level of convergent validity of measurement scales. The fit indices indicate a good fit to the data (CFI = 0.947, CMIN/df = 1.955, RMSEA = 0.067). Convergent validity was assessed using standardised factor loadings, composite reliability (CR), and average variance extracted (AVE).

Table 2. Evaluation of the measurement model

Constructs/Items	Factor loading	Cronbach's alpha	CR	AVE
Digital transformation adoption		0.923	0.921	0.624
DT1-Conversion of documents into digital formats	0.762			
DT2-Storage of organisational data on internal servers or cloud platforms	0.728			
DT3-Use of software systems to manage logistics processes	0.796			
DT4-Execution of cross-departmental transactions via digital platforms	0.779			
DT5-Execution of transactions with suppliers and regulatory bodies via digital platforms	0.832			
DT6-Execution of transactions with customers via digital platforms	0.863			
DT7-Integration of advanced digital technologies to implement new business models	0.729			

Absorptive capacity		0.877	0.879	0.648
AC1-Acquisition of new technological knowledge from external sources	0.744			
AC2-Internal sharing of acquired technological knowledge across the firm	0.800			
AC3-Integration of acquired technological knowledge with existing knowledge to generate new solutions	0.813			
AC4-Application of externally derived solutions to logistics operations	0.788			
Sustained logistics performance		0.882	0.883	0.521
SLP1-Sustained timely responsiveness to customer requirements	0.652			
SLP2-Continuous improvement in logistics cost control	0.649			
SLP3-Consistent and repeatable order fulfillment accuracy	0.815			
SLP4-Reliable service performance with low frequency of disruptions	0.751			
SLP5-Consistently safe delivery performance (without damage or loss)	0.809			
SLP6-Reliable and consistently on-time delivery performance	0.795			
SLP7-Consistent flexibility in handling customer requirements	0.711			

Source(s): Authors' own work

Finally, inter-construct correlations between different constructs, and the square root of AVE for each construct was compared to its correlation values with other constructs to examine the discriminant validity. Results shown in Table 3 demonstrate that the discriminant validity of the measurement model was satisfied.

Table 3. Results of discriminant validity

Construct	AVE	MSV	AC	DT	SLP
AC	0.648	0.421	**0.805**		
DT	0.624	0.421	0.649	**0.790**	
SLP	0.521	0.191	0.437	0.428	**0.722**

Source(s): Authors' own work

Structural model evaluation

Evaluation of direct effects

The direct effects were evaluated based on the significance of p-values, which were obtained using the Bootstrap procedure with 214 cases and 5,000 resamples. Results in Table 4 indicate that all three hypotheses were supported at a significant level of 5%.

Table 4. Results of direct effects evaluation

Hypothesis	Relationship			Estimate	S.E.	C.R.	P	Result
H1 (+)	DT	--->	SLP	0.137	0.055	2.516	**	Supported
H2 (+)	DT	--->	AC	0.563	0.066	8.471	***	Supported
H3 (+)	AC	--->	SLP	0.175	0.064	2.751	**	Supported

***p<0.001, **p<0.05 *Source(s): Authors' own work*

Evaluation of indirect effects

A test of the mediating effect of AC in the relationship between DT adoption and SLP proposed in the model was conducted by applying a bootstrapping method. Accordingly, an indirect effect was considered statistically significant if the bias-corrected 95% confidence interval did not

include zero. The results in Table 5 indicate that the direct path from DT adoption to SLP was significantly mediated by AC.

Table 5. Results of indirect effects evaluation

Hypothesis	Indirect path	Estimate	p-value	95% confidence intervals	
				Lower	Upper
H4	DT --> AC --> SLP	0.179	0.015	0.031	0.363

Source(s): Authors' own work

DISCUSSION

Firstly, the findings confirm a significant direct effect of DT adoption on SLP ($\beta = 0.137$, $p < 0.05$), supporting H1. The results indicate that DT not only enhances logistics efficiency in the short term but also contributes to maintaining and improving performance over time, even under unstable conditions. By digitising logistics-related processes, firms can enhance visibility and control over logistics flows, thereby reducing operational errors and disruptions. This is particularly relevant in Vietnam, where many SMEs rely on manual and fragmented systems, leading to high logistics costs (VietnamLogisticsReview, 2024). Thus, DT adoption can help systematise logistics operations, enabling firms to improve logistics performance in a more sustained manner. This result not only aligns with previous research (e.g. Malodia et al., 2023), but also extends prior research by focusing on a sustained attribute in performance. Therefore, rather than being viewed as a contemporary performance enhancer, DT should be understood as a foundational capability that enables SMEs to achieve stable and enduring logistics performance over time.

Secondly, the results show that DT adoption has a positive impact on AC ($\beta = 0.563$, $p<0.001$), supporting H2, implying that DT is not only a technical decision but also a strategic one, with DT adoption itself becoming as a mechanism to promote businesses' AC. By implementing digital systems (e.g., ERP), businesses can access external knowledge, thereby enhancing their capacity to acquire new knowledge. The finding also highlights that DT enables firms interact and establish relationships with the external environment by connecting with suppliers, customers and service providers through digital platforms. The relationship between DT adoption and AC can be clearly identified in SMEs. Despite resource constraints, SMEs benefit from organisational flexibility, flat structure, and direct and informal communication channels that support learning (Saad et al., 2017). These characteristics facilitate rapid information exchange and learning within and outside the firm as well. In this context, DT adoption can provide digital infrastructure and tools that enhance firms' ability to absorb and exploit external knowledge. This finding is also supported by prior studies showing that information technology positively contribute to the development of AC (Cuevas-Vargas et al., 2022) .

Thirdly, there is a statistically significant positive relationship between AC and SLP ($\beta = 0.175$, $p<0.05$), supporting H3. This means that AC acts as a learning capability that enables firms to SLP over time. Through AC, firms are better able to adapt to environmental changes, as well as to acquire and integrate external knowledge and experience into their logistics operations. As a result, AC supports not only improvements in logistics performance but also the ability to maintain performance stability and consistency over time. In the context of SMEs, this nexus could be explained that, by absorbing and continuous learning, AC is able to help SMEs adjust and adapt quickly to environmental changes that affect logistics operations. As a result, logistics performance becomes more sustained over time. In the extant literature, prior studies also asserted the positive relationship between AC and performance (e.g. Kastelli et al., 2022; Ma et al., 2021).

Lastly, the findings also highlight the mediating role of AC in the relationship between DT adoption and SLP ($\beta = 0.179$, $p<0.05$), supporting H4. This means that AC further enables the

contribution of DT adoption to the firms' SLP. It is explained that, in addition to the direct effect, the translation of DT adoption into SLP also depends on the firm's ability to learn and transform knowledge. In SMEs, due to resource limitations, most SMEs outsource and rely on third-party digital platforms (Westerlund, 2020); that means they depend on external technologies and solutions provided by technology providers. This requires SMEs to possess the knowledge and learning ability to acquire and absorb these digital technologies. Therefore, AC helps SMEs not only use digital tools effectively, but also understand how to operate, adapt and integrate them into existing logistics processes. This finding also highlights AC as a critical internal learning capability through which SMEs can overcome resource constraints. Although SMEs may lack the resources of large enterprises, strong AC enables them to leverage external knowledge more effectively, compensating for internal limitations. Therefore, AC plays a crucial role in supporting DT adoption, thereby translating into SLP in SMEs in a dynamic and uncertain environment.

CONCLUSION

Our study offers several theoretical implications. First, although the relationship between DT adoption and performance has been widely studied in the literature, there is a lack of research on how DT helps maintain performance stably, particularly in the context of disruption. Therefore, this study extends the DT literature by offering an understanding of sustained performance in DT adoption. Second, this study enriches the DT literature by shedding light on the mediating role of AC in explaining the mechanisms underlying DT adoption and SLP, especially in SMEs, which are often characterised by resource constraints and heightened vulnerability to disruptions. Our study reinforces DC theory by empirically demonstrating that AC functions as a critical learning capability that enables SMEs to reconfigure knowledge and derive sustained value from DT.

Practically, this study offers insights for SME owners and managers, particularly in emerging economies such as Vietnam. First, DT adoption was found to enhance SLP. Correspondingly, the recommendation is for SME owners to adopt a more systematic approach to DT that integrates digital technologies into logistics processes. Data virtualisation is a typical example of DT adoption in logistics management (Nguyen, 2026). By doing so, firms can reduce operational variability and improve the consistency of logistics performance, even under disruptive conditions. Second, the partial mediating role of AC suggests that SMEs should strengthen organisational learning capabilities. Owners and managers are encouraged to invest in digital training and promote cross-functional knowledge sharing that facilitate learning from logistics partners and digital platforms, ensuring that digital initiatives translate into sustained performance outcomes.

REFERENCES

AlNuaimi, B. K., Kumar Singh, S., Ren, S., Budhwar, P., & Vorobyev, D. (2022). Mastering digital transformation: The nexus between leadership, agility, and digital strategy. *Journal of Business Research*, *145*, 636-648.

Barney, J. (1991). Firm resources and sustained competitive advantage. *Journal of Management*, *17*(1), 99-120.

Cohen, W. M., & Levinthal, D. A. (1990). Absorptive capacity: A new perspective on learning and innovation. *Administrative Science Quarterly*, *35*(1), 128-152.

Cuevas-Vargas, H., Aguirre, J., & Parga-Montoya, N. (2022). Impact of ICT adoption on absorptive capacity and open innovation for greater firm performance. The mediating role of ACAP. *Journal of Business Research*, *140*, 11-24.

Eggers, F. (2020). Masters of disasters? Challenges and opportunities for SMEs in times of crisis. *Journal of Business Research*, *116*, 199-208.

El Hathat, Z., Zouadi, T., & Sreedharan, V. R. (2023). Strategizing a Logistics Framework for Organizational Transformation: A Technological Perspective. *IEEE Transactions on Engineering Management*, *71*, 7946-7967.

Eller, R., Alford, P., Kallmünzer, A., & Peters, M. (2020). Antecedents, consequences, and challenges of small and medium-sized enterprise digitalization. *Journal of Business Research*, *112*, 119-127.

Fitzgerald, M., Kruschwitz, N., Bonnet, D., & Welch, M. (2014). Embracing digital technology: a new strategic imperative. *MIT Sloan Management Review*, *55*(2), 1.

Guo, L., & Xu, L. (2021). The effects of digital transformation on firm performance: Evidence from China's manufacturing sector. *Sustainability*, *13*(22), 12844.

Kastelli, I., Dimas, P., Stamopoulos, D., & Tsakanikas, A. (2022). Linking Digital Capacity to Innovation Performance: the Mediating Role of Absorptive Capacity. *J Knowl Econ*, 1-35.

Ma, F., Khan, F., Khan, K. U., & XiangYun, S. (2021). Investigating the Impact of Information Technology, Absorptive Capacity, and Dynamic Capabilities on Firm Performance: An Empirical Study. *Sage Open*, *11*(4).

Malodia, S., Mishra, M., Fait, M., Papa, A., & Dezi, L. (2023). To digit or to head? Designing digital transformation journey of SMEs among digital self-efficacy and professional leadership. *Journal of Business Research*, *157*.

Nguyen, T. T. (2026). *Ảo hóa dữ liệu và nâng cao hiệu quả quản trị logistics trong doanh nghiệp*. Tap Chi Cong Thuong. Retrieved Feb 9 from https://tapchicongthuong.vn/ao-hoa-du-lieu-va-nang-cao-hieu-qua-quan-tri-logistics-trong-doanh-nghiep-423346.htm

Roberts, P. W., & Dowling, G. R. (2002). Corporate reputation and sustained superior financial performance. *Strategic Management Journal*, *23*(12), 1077-1093.

Saad, M., Kumar, V., & Bradford, J. (2017). An investigation into the development of the absorptive capacity of manufacturing SMEs. *International Journal of Production Research*, *55*(23), 6916.

Sagala, G. H., & Őri, D. (2024). Toward SMEs digital transformation success: a systematic literature review. *Information Systems and e-Business Management*, *22*(4), 667-719.

Taschner, A. (2016). Improving SME logistics performance through benchmarking. *Benchmarking: An International Journal*, *23*(7), 1780-1797.

Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. *Strategic Management Journal*, *18*(7), 509-533.

VietnamLogisticsReview. (2024). *Cơ hội và thách thức của ngành logistics Việt Nam trong bối cảnh chuyển đổi số*. Vietnam Logistics Review. Retrieved Feb 7 from https://vlr.vn/bai-3-co-hoi-va-thach-thuc-cua-nganh-logistics-viet-nam-trong-boi-canh-chuyen-doi-so-19776.html

Wang, M. (2018). Impacts of supply chain uncertainty and risk on the logistics performance. *Asia Pacific Journal of Marketing and Logistics*, *30*(3), 689-704.

Westerlund, M. (2020). Digitalization, Internationalization and Scaling of Online SMEs. *Technology Innovation Management Review*, *10*(4), 48-57.

The Effect of Artificial Intelligence in Hospitality Supply Chain Management

Anas Abbas, Balan Sundarakani

School of Business, University of Wollongong in Dubai, UAE

INTRODUCTION

The hospitality industry, a significant contributor to the global economy, faces increasing challenges in managing its supply chain effectively due to dynamic market conditions, fluctuating customer demands, and high operational costs. According to Grand View Research (2024), the hospitality sector has been undergoing a digital transformation, driven by technological advancements and the growing need for operational efficiency. One of the most promising innovations in this domain is Artificial Intelligence (AI), which has revolutionized the way organizations manage supply chain processes. AI-driven tools, such as Coupa's Procure-to-Pay (P2P) system, have emerged as game-changers, enabling businesses to optimize procurement, reduce costs, and enhance supplier performance through automation and predictive analytics. AI has found diverse applications across various industries, including manufacturing, healthcare, and retail, but its adoption in the hospitality sector remains relatively underexplored. The integration of AI into supply chain management (SCM) offers significant advantages, including real-time inventory management, demand forecasting, and streamlined procurement processes (Mukherjee et al., 2024). These capabilities are particularly relevant in the hospitality industry, where maintaining a balance between cost efficiency and high service quality is crucial. For instance, predictive analytics powered by AI can help hospitality businesses anticipate demand fluctuations, optimize stock levels, and prevent overstocking or stockouts, thereby ensuring better resource utilization (Ivanov & Dolgui, 2021).

Despite its potential, the adoption of AI in hospitality SCM is fraught with challenges. High implementation costs, data integration issues, and a lack of technical expertise are significant barriers to its widespread use. Additionally, concerns over data privacy and security have further complicated AI adoption in this sector (Alshahrani, 2023). These challenges are compounded by the unique characteristics of the hospitality industry, such as its reliance on seasonal demand, perishable goods, and the need for high levels of personalization in service delivery. As a result, many organizations remain hesitant to fully embrace AI- driven systems, opting instead for traditional procurement methods that are less efficient but more familiar (Ruel & Njoku, 2021).This research gap has been attempted to study in the ongoing funded research in the UAE and this research presents findings of the AI impact from thereof. The research is intended to study the effect of the deployment of AI in Coupa's P2P system on the phenomenon of procurement in the hospitality industry by highlighting cost savings, operational efficiency and supplier performance.

RESEARCH METHODOLOGY

This research uses the quantitative research design method to assess the correlations between the given AI- based P2P system and other factors such as operating efficiency, procurement performance, cost, and supplier performance. This is true according to Keith (2019), who noted that the quantitative method is ideal for relations, hypotheses, tests, and analysis. This was a structured quantitative data collection technique that produced numerical results; therefore, using structured questionnaires to obtain information from the participants enabled a systematic quantitative analysis of the participant's experience with the use of AI in procurement. As highlighted by Mertens & Recker (2023), the deductive approach is highly suitable in research rooted in theory because it creates an ability for a researcher to conduct various hypothesis testing within real-life scenarios. The deductive design is expected to contribute empirical evidence to the five Hypotheses (H1-H5) that are formulated from the literature concerning the application of AI in the procurement of hospitality services as theorized in Figure 1.

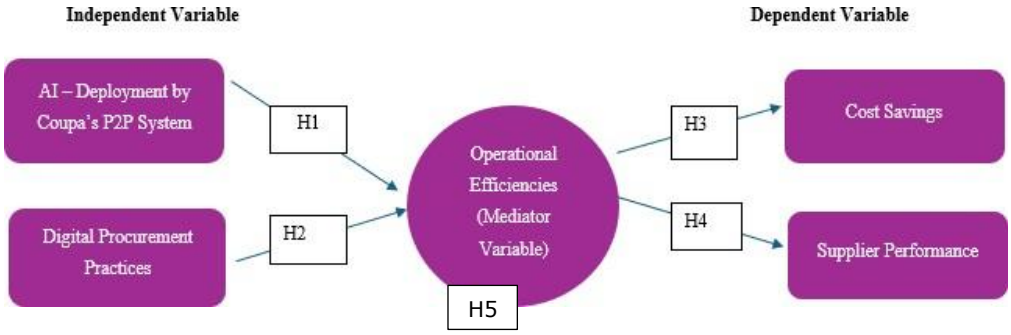


Figure 1. The theoretical model

This research employs the survey technique as one of the most effective methods of data collection. The default use of surveys in quantitative research is ideal since it involves the collection of large datasets from respondent groups that have been standardized to allow generalizations (Kircher & Zipp, 2022). The study commissioned a structured questionnaire that incorporates a Likert scale that measures participants' perceptions of AI in procurement, which offers an enhanced perception of perceptions towards the subject. Surveys also present primary research with procurement professionals increasing the face validity and presenting results that are closely related to the research questions. Using a structured questionnaire, quantitative data will be collected on participants' interaction with Coupa's Artificial Intelligence-driven P2P system. The questionnaire includes two sections: The first section gathers general information about each participant concerning age, experience, gender, and prior experience in using the P2P system for procurement purposes while the second section of questionnaire gathers data about participants' attitudes to the use of AI solutions in procurement processes using Likert scales (Aithal & Aithal, 2020). The target population in this study is the UAE hospitality industry personnel such as Procurement Officers, Managers, and IT professionals who have worked for at least six months in Coupa's P2P system or any similar platform. Quantitative research requires for a sample size of ten times (10X) the size of the construct for observations to be statistically significant; this study therefore targeted 150 respondents. Convenience sampling is used to reach out to participants and collect data from them which is easily available even though the target area in this study is an AI-based Coupa system (Aithal & Aithal, 2020). Although convenience sampling may cause selection bias, Kircher & Zipp (2022) pointed out that choosing the sample corresponds to the context of the investigation of hospitality procurement in the UAE and ensures model validity and sample bias corrected.

RESULTS AND DISCUSSION

The survey results were statistically analysed by using the Smart PLS software. Table 1 summarizes the age group distribution of respondents across four generational sample of Gen Z or Gen Y (1997-2012), Millennials (1981-1996), Gen X (1965-1980), and Baby Boomers (1946-1964). The participants from Generation Z were 29.2%, 20.8% were Millennials, which showed a significant population whose value is often underscored because of their different outlook and spending power (Dimock, 2019). Generation X comprised 21.5% which confirms their prominence as mid-career employees with work-family balance responsibilities. This group is 28.5%, very close to Generation Z thus making them still relevant especially in retirement and civil service

Table 1. Age Group

		Frequency	Percent	Valid Percent	Cumulative Percent
Age	Generation Z (1997-	38	29.2	29.2	29.2

	2012)				
	Millennials (1981-1996)	27	20.8	20.8	50.0
	Generation X (1965-1980)	28	21.5	21.5	71.5
	Baby Boomer Generation (1946-1964)	37	28.5	28.5	100.0
	Total	130	100.0	100.0	

As shown in Table 2, the Compliance Officers have the highest percentage (21.5%) owing to the increasing focus area of regulatory compliance in business as observed by Johnson, (2020). Finance Managers were 20 percent, showing that these professionals are heavily involved in the management of resources and the development of tactical objectives. The largest proportion of respondents belongs to Senior Managers (15,4%) with the governmental role in influencing companies' decisions. The IT Professionals were 10.8% representing growing importance of technical advancements in business processes with the representation of Procurement Officers at 9.2%, indicating their role in the supply chain and by the Food and Beverage team (12.3%), significant in customer relations services.

Table 2. Job Roles

		Frequency	Percent	Valid Percent	Cumulative Percent
Job Role in line of business	Finance Manager	26	20.0	20.0	20.0
	Senior Manager	20	15.4	15.4	35.4
	IT Professional	14	10.8	10.8	46.2
	Procurement Officer	12	9.2	9.2	55.4
	Compliance Officer	28	21.5	21.5	76.9
	Legal Office	14	10.8	10.8	87.7
	Food and Beverage Team	16	12.3	12.3	100.0
	Total	130	100.0	100.0	

Table 3 Years of Experience

		Frequency	**Percent**	**Valid Percent**	**Cumulative Percent**
Years of experience	0-5 years	31	23.8	23.8	23.8
	5-10 years	36	27.7	27.7	51.5
	10-15 years	29	22.3	22.3	73.8
	More than 15 years	34	26.2	26.2	100.0
	Total	130	100.0	100.0	

Table 3 experience of the respondents in the hospitality industry, with an equal distribution of the respondents. For Career, employees with 5 to 10 years of experience dominate the industry

at 27.7%, a clear sign that many businesses hire mid-level employees who are already competent to do their work but still have more potential to grow. 26.2% of the respondents are at or over 15 years implying that the sector has been able to retain experts with institutional experience, as highlighted by Aksoy et al. (2022). The respondents with 0–5 years of experience (23.8%) underscore early employee groups important for innovativeness and flexibility. Last, those with 10–15 years (22.3%) consider themselves essential as they offer both operational and strategic insights. It has also ensured that the industry workforce is well balanced with young people as well as the experienced, making it very strong representation.

The PLS SEM model results indicates the internal consistency and reliability of the measurement indicators across the study variables. For AI Deployment (AIDev), the indicator loadings (ranging from 0.79 to 0.85) demonstrate strong relationships between the indicators and the latent variable. Composite reliability (CR = 0.88) and Cronbach's Alpha (α = 0.84) confirm the high internal consistency of the construct. Furthermore, the average variance extracted (AVE = 0.75) exceeds the threshold of 0.50, indicating that a substantial proportion of variance is captured by the construct, supporting its convergent validity (Mertens & Recker, 2023). For Digital Procurement Practices (DPP), the loadings (0.88 and 0.91) reflect excellent indicator reliability. With CR of 0.93 and Cronbach's Alpha of 0.90, the construct demonstrates a high degree of consistency and reliability. Operational Efficiencies (OE) also show strong reliability, with indicator loadings ranging from 0.82 to 0.87. CR of 0.90, Cronbach's Alpha of 0.87, and Rho_A of 0.89 validate the internal consistency of this construct. Similarly, for Cost Savings (CS), the indicator loadings (CS1 = 0.89, CS2 = 0.84) demonstrate strong reliability. CR of 0.92 and Cronbach's Alpha of 0.88, along with Rho_A of 0.90, confirm that the construct is highly consistent. The AVE (0.81) indicates that the majority of variance is explained by the construct, underscoring its validity. These results are consistent with research by South et al. (2022), who highlight the importance of high AVE and CR in ensuring reliable measurement scales. Finally, for Supplier Performance (SP), indicator loadings (0.87 to 0.90) demonstrate strong relationships with the latent variable. CR (0.94), Cronbach's Alpha (0.91), and Rho_A (0.93) indicate excellent reliability. The AVE (0.85) further validates the construct by showing that it explains a substantial portion of the variance in the indicators. This supports findings by Miaha & Miab (2021), who emphasize the importance of reliability in supplier performance constructs.

Hypothesis Testing

Table 4. Hypothesis Testing

Hypothesis	Beta coefficient	p-value	Decision
H1: AI deployment (via Coupa P2P system) positively impacts operational efficiencies.	0.546	0.000	Accepted
H2: Digital procurement practices positively impact operational efficiencies.	0.496	0.000	Accepted
H3: Operational efficiencies positively impact cost savings.	0.502	0.000	Accepted
H4: Operational efficiencies positively impact supplier performance.	0.005	0.956	Rejected
H5: AI deployment (H1) and digital procurement practices (H2) positively impact operational efficiencies, which in turn lead to cost savings and improved supplier performance.	AI= 0.393 Digital Procurement = 0.286	0.000 (both)	Accepted

The Structural path model testing reveals that operational efficiencies significantly mediate the relationship between AI deployment and digital procurement practices with cost

savings. Both AI deployment via Coupa's P2P system ($p < 0.001$) and digital procurement practices ($p < 0.001$) positively influence operational efficiencies, which in turn significantly affect cost savings ($p < 0.001$). This supports the hypotheses that improved operational efficiencies lead to better cost outcomes, with operational efficiencies acting as a critical pathway through which AI and digital practices drive cost savings. Thus, H3 and the mediation hypothesis for cost savings are accepted. However, the analysis indicates that operational efficiencies do not significantly impact supplier performance ($p = 0.956$), leading to the rejection of H4. While both AI deployment and digital procurement practices positively affect operational efficiencies, operational efficiencies do not mediate the relationship between these factors and supplier performance. This suggests that while operational efficiencies are crucial for cost savings, they may not be as influential in improving supplier performance, highlighting a possible area for further investigation in future research.

The hypotheses illustrates the positive impact of AI Deployment and Digital Procurement Practices on Operational Efficiency and Cost Savings, reinforcing their critical role in driving operational and financial success in the hospitality sector. However, the limited influence of Operational Efficiency on Supplier Performance highlights a gap that requires further investigation, such as addressing industry-specific challenges like seasonal demand fluctuations and perishable inventory management. The practical implications of this model emphasize the necessity for hospitality organizations to invest in employee training and seamlessly integrate AI technologies with existing systems to maximize benefits. Additionally, fostering robust partnerships with suppliers and adopting tailored strategies can bridge the gap between operational improvements and supplier performance. Overall, the model demonstrates that while AI and digital transformation significantly enhance cost savings and operational workflows, achieving superior supplier outcomes requires a more comprehensive and collaborative approach.

CONCLUSION

In conclusion, this study emphasized the applicability of AI in the hospitality SCM and showed that integration of this technology can serve as an effective tool for increasing the productivity of supply chain entities, as well as improving guest experience. The efficiency of using AI systems in demand forecasting and automation predicts a reduction in costs within the operation processes. However, the integration of data, high costs of implementing the system, concern about data privacy, and displacement of workers through AI automation, are some of the issues that remain to be resolved on how AI can be helpful maximally. The results make a theoretical and practical contribution to the emerging field of AI in SCM and guide practitioners and policymakers. Hospitality organizations can benefit from the proposed strategies for creating efficiency, sustainability, and competitive advantage through the intelligent application of AI. This will, in turn, enhance the direct interactions that guests have and make the whole industry even more relevant to the developing world. Larger sample size to investigate how AI supports SCM in various environments, especially how the application of AI technologies in SCM can support to generalise the findings and the study replication in other countries.

REFERENCES

Aksoy, L., Choi, S., Dogru, T., Keiningham, T., Lorenz, M., Rubin, D., & Tracey, J. B. (2022). Global trends in hospitality. Journal of Business Research, 142, 957-973.

Alsetoohy, O., Ayoun, B., Arous, S., Megahed, F., & Nabil, G. (2019). Intelligent agent technology: what affects its adoption in hotel food supply chain management? Journal of Hospitality and Tourism Technology, 10(3), 286-310.

Al-Surmi, A., Bashiri, M., & Koliousis, I. (2022). AI-based decision making: combining strategies to improve operational performance. International Journal of Production Research, 60(14), 4464-4486.

Bhandal, R., Meriton, R., Kavanagh, R. E., & Brown, A. (2022). The application of digital twin technology in operations and supply chain management: a bibliometric review. Supply Chain Management: An International Journal, 27(2), 182-206.

Buhalis, D., & Sinarta, Y. (2019). Real-time co-creation and nowness service: lessons from tourism and hospitality. Journal of Travel & Tourism Marketing, 36(5), 563-582.

Chotaliya, H. M. (2024). Artificial intelligence and its use cases in procurement (Doctoral dissertation, Technische Hochschule Ingolstadt).

Cohen, J., Cohen, P., West, S. G., & Aiken, L. S. (2013). Applied multiple regression/correlation analysis for the behavioral sciences. Routledge.

Cooper, M. (2024). Adapting Procurement Practices to Disruptive Events: Lessons from Recent Supply Chain Disruptions.

Desjarlais, B., King, J., & Tigner, J. (2024). Leveraging Artificial Intelligence to Streamline and Automate Procurement Requirements Documents (Doctoral dissertation, Acquisition Research Program).

Dimock, M. (2019). Defining generations: Where Millennials end and Generation Z begins. Pew Research Center, 17(1), 1-7.

Flechsig, C., Anslinger, F., & Lasch, R. (2022). Robotic process automation in purchasing and supply management: A multiple case study on potentials, barriers, and implementation. Journal of Purchasing and Supply Management, 28(1), 100718.

Fosso Wamba, S., Guthrie, C., Queiroz, M. M., & Minner, S. (2024). ChatGPT and generative artificial intelligence: an exploratory study of key benefits and challenges in operations and supply chain management. International Journal of Production Research, 62(16), 5676-5696.

Grand View Research. (2024). Artificial intelligence market size, share, growth report 2030. Retrieved from: https://www.grandviewresearch.com/industry-analysis/artificial-intelligence-ai-market

Gupta, S., Modgil, S., Choi, T. M., Kumar, A., & Antony, J. (2023). Influences of artificial intelligence and blockchain technology on financial resilience of supply chains. International Journal of Production Economics, 261, 108868.

Hasan, R., Kamal, M. M., Daowd, A., Eldabi, T., Koliousis, I., & Papadopoulos, T. (2024). Critical analysis of the impact of big data analytics on supply chain operations. Production Planning & Control, 35(1), 46-70.

Herold, S., Heller, J., Rozemeijer, F., & Mahr, D. (2023). Dynamic capabilities for digital procurement transformation: a systematic literature review. International Journal of Physical Distribution & Logistics Management, 53(4), 424-447.

Ivanov, D., & Dolgui, A. (2021). A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. Production Planning & Control, 32(9), 775-788.

Kalesh, S., Kiratli-Schneider, N., & Schiele, H. (2024). Supplier connectivity: a study on how to gain supplier acceptance for the integration of digital supply chain systems. Supply Chain Management: An International Journal, 29(7), 83-96.

Kamble, S., Gunasekaran, A., & Dhone, N. C. (2020). Industry 4.0 and lean manufacturing practices for sustainable organisational performance in Indian manufacturing companies. International journal of production research, 58(5), 1319-1337.

Kong, L., Zheng, G., & Brintrup, A. (2024). A federated machine learning approach for order-level risk prediction in supply chain financing. International Journal of Production Economics, 268, 109095.

Lahiri, S. (2016). Does outsourcing really improve firm performance? Empirical evidence and research agenda. International Journal of Management Reviews, 18(4), 464-497.

Le, T. T., Nhu, Q. P. V., & Behl, A. (2024). Role of digital supply chain in promoting sustainable supply chain performance: the mediating of supply chain integration and information sharing. The International Journal of Logistics Management.

Lee, C. H., Son, B. G., & Roden, S. (2023). Supply chain disruption response and recovery: The role of power and governance. Journal of Purchasing and Supply Management, 29(5), 100866.

Modgil, S., Singh, R.K., & Hannibal, C. (2022). Artificial intelligence for supply chain resilience: learning from Covid-19. The International Journal of Logistics Management, 33(4), 1246-1268.

Mukherjee, S., Nagariya, R., Mathiyazhagan, K., Baral, M. M., Pavithra, M. R., & Appolloni, A. (2024). Artificial intelligence-based reverse logistics for improving circular economy performance: a developing country perspective. The International Journal of Logistics Management.

Nazam, M., Hashim, M., Baig, S. A., Abrar, M., & Shabbir, R. (2020). Modeling the key barriers of knowledge management adoption in sustainable supply chain. Journal of Enterprise Information Management, 33(5), 1077-1109.

Olan, F., Liu, S., Suklan, J., Jayawickrama, U., & Arakpogun, E. O. (2022). The role of artificial intelligence networks in sustainable supply chain finance for food and drink industry. International Journal of Production Research, 60(14), 4418-4433.

Richey Jr, R. G., Chowdhury, S., Davis- Sramek, B., Giannakis, M., & Dwivedi, Y. K. (2023). Artificial intelligence in logistics and supply chain management: A primer and roadmap for research. Journal of Business Logistics, 44(4), 532-549.

Ruel, H., & Njoku, E. (2021). AI redefining the hospitality industry. Journal of Tourism Futures, 7(1), 53-66.

Seo, H., Cho, H., & Jo, D. (2024). How do collaborative systems affect organizational agility and performance in supply chains?. Operations Management Research, 1-15.

Shahzadi, G., Jia, F., Chen, L., & John, A. (2024). AI adoption in supply chain management: a systematic literature review. Journal of Manufacturing Technology Management, 35(6), 1125-1150.

Sharma, R., Shishodia, A., Gunasekaran, A., Min, H., & Munim, Z. H. (2022). The role of artificial intelligence in supply chain management: mapping the territory. International Journal of Production Research, 60(24), 7527-7550.

Toorajipour, R., Sohrabpour, V., Nazarpour, A., Oghazi, P., & Fischl, M. (2021). Artificial intelligence in supply chain management: A systematic literature review. Journal of Business Research, 122, 502-517.

Vlachos, I., Zisimopoulos, A., & Tsoulfas, G. T. (2024). Digitisation of franchising supply chain impact on franchisor performance: a longitudinal case study of a coffee retail chain. International Journal of Physical Distribution & Logistics Management.

Wong, L. W., Tan, G. W. H., Ooi, K. B., Lin, B., & Dwivedi, Y. K. (2024). Artificial intelligence-driven risk management for enhancing supply chain agility: A deep-learning-based dual-stage PLS-SEM-ANN analysis. International Journal of Production Research, 62(15), 5535-5555.

Younis, H., Sundarakani, B., & Alsharairi, M. (2022). Applications of artificial intelligence and machine learning within supply chains: systematic review and future research directions. Journal of Modelling in Management, 17(3), 916-940.

Santos, J.B. and Cabral, S., 2022. Public procurement capabilities as engines for collaboration and enhanced performance in complex projects. International Journal of Operations & Production Management, 42(1), pp.32-58.

Wei, R., & Pardo, C. (2022). Artificial intelligence and SMEs: How can B2B SMEs leverage AI platforms to integrate AI technologies? Industrial Marketing Management, 107, 466-483.

Smart Food Safety Integration Mechanisms in Emerging Market Supply Chains: Coordination for Sustainability

Linh Thi Hai Tran[1], Hiep Pham[1], An Duong Thi Binh[2], Quan Dinh Hoang[3], Huy Truong Quang[1]

1: RMIT Vietnam, Vietnam; 2: CIRTech Institute, HUTECH University of Technology, Vietnam; 3: Mamo Payments, UAE

ABSTRACT

Purpose of the paper

This study investigates how smart supply chain integration mechanisms enhance sustainability and economic performance in emerging market food industries. Drawing on the Technology–Organisation–Environment (TOE) framework and Ecological Modernisation Theory, the study conceptualises digital food safety systems not merely as compliance tools but as inter-organisational integration mechanisms that enable information transparency, traceability, and coordination across supply chain actors.

Design/methodology/approach

The research employs a quantitative approach based on survey data collected from 243 food supply chain firms in Vietnam and China. Structural equation modelling (SEM) is used to analyse the relationships between multi-level enablers—including strategic leadership, organisational resource readiness, regulatory support, and supply chain alignment—and sustainability outcomes. Smart system practices, operationalised through quality standards implementation, digital ecosystem integration, and process robustness, are examined as mediating mechanisms.

Findings

The results indicate that smart supply chain integration practices play a significant mediating role between critical success factors and sustainability outcomes. Specifically, smart system practices mediate over 40% of the total effect of key enablers on decarbonisation initiatives. Furthermore, decarbonisation efforts significantly enhance firm-level economic performance, demonstrating that environmental improvements and economic efficiency can be mutually reinforcing in emerging market food supply chains.

Value/Originality

This study contributes to the supply chain and sustainability literature by extending the TOE framework to explain sustainability-oriented supply chain integration. It also provides empirical evidence on how digital food safety technologies can function as collaborative governance mechanisms that improve transparency, traceability, and coordination across supply chain tiers in emerging economies.

Research limitations/implications

The study is based on cross-sectional survey data from firms in Vietnam and China, which may limit causal inference and generalisability to other regions or industries. Future research could employ longitudinal data and comparative studies across additional emerging markets to further validate the proposed framework and explore dynamic sustainability transitions in supply chains.

Practical implications

The findings highlight the strategic importance of cross-tier collaboration, digital monitoring systems, and regulatory alignment in building resilient and sustainable food supply networks. Managers and policymakers should prioritise investments in digital traceability infrastructure, strengthen organisational readiness for smart system adoption, and foster supportive regulatory environments to accelerate decarbonisation and improve supply chain efficiency.

Keywords

Smart supply chain integration, digital food safety systems, sustainable performance, traceability, emerging markets.

INTRODUCTION

Achieving sustainable performance while safeguarding food safety presents an ongoing challenge for firms embedded in emerging market supply chains, especially given rising expectations for transparency, coordination, and digital capability (Lyng et al., 2024; Guidani et al., 2024). Food firms are increasingly pressed to adopt integration mechanisms that go beyond regulatory compliance to improve traceability, enhance visibility, and support environmental responsibility across supply chain tiers. In this evolving landscape, smart systems such as IoT-enabled monitoring, blockchain traceability, and AI analytics are gaining traction as enablers of inter-firm coordination and performance outcomes. However, there remains a limited empirical understanding of how such systems contribute to broader sustainability objectives through enhanced supply chain integration.

Critical success factors (CSFs), including personnel administration, strategic leadership, organisational resources, external support, and supply chain alignment, have long been recognised as key drivers of innovation and technology adoption (Glenisson et al., 2025; Eves et al., 2025). While their influence has been studied extensively at the firm level, less is known about how these factors operate across supply chain networks to support sustainability outcomes. Most prior research adopts a siloed perspective, often treating CSFs as isolated organisational enablers without fully considering how inter-organisational coordination, collaborative infrastructures, and ecosystem-level conditions jointly affect sustainability transitions (Zheng et al., 2017; Kirezieva et al., 2015a).

The emergence of smart food safety systems (SFSS) reflects a shift from compliance-based approaches to digitally integrated solutions that span supplier, processor, and retail interfaces. These systems not only mitigate operational risks but also facilitate real-time decision-making, reduce greenhouse gas emissions, and unlock new efficiencies (Agya, 2025; Duong et al., 2024; Nguyen and Li, 2022). For example, automated traceability can reduce resource waste and build trust among partners, while AI-powered analytics can enhance predictive planning for sustainable logistics and inventory control. Yet, research has rarely examined how smart safety practices operate as supply chain integration mechanisms that translate organisational and environmental enablers into tangible sustainability and financial outcomes, especially in the context of multi-tier networks in emerging economies such as Vietnam and China (Hassoun et al., 2023; Liu et al., 2021).

Existing literature has linked quality and safety systems to improved customer satisfaction and operational efficiency (Lu et al., 2021; Quang et al., 2016), but most studies treat economic and environmental performance as separate domains. Few studies connect smart system practices to broader supply chain integration and sustainability coordination, such as predictive food protection, digital monitoring, or blockchain-enabled assurance. Moreover, while food traceability has been shown to support compliance and consumer confidence (Anthony Jr et al., 2018; Shang et al., 2022), its role in enabling decarbonisation or cross-chain data sharing remains underexplored (Sharma et al., 2021).

To frame this analysis, we draw on the Technology-Organisation-Environment (TOE) framework (Tornatzky and Fleischer, 1990) and Ecological Modernisation Theory (EMT) (Hajer, 1995). TOE helps explain how firm-level resources, inter-firm relationships, and external institutional pressures shape technology adoption in supply chains. In this study, we reconceptualise smart food safety systems as integration mechanisms that enable digital visibility, coordination, and sustainability-oriented decision-making across supply chain actors. EMT complements this by viewing digitalisation not merely as an operational upgrade but as part of a broader governance shift where technological innovation and institutional alignment jointly drive ecological outcomes. By integrating these perspectives, we offer a multi-level understanding of how digital safety systems enable sustainable supply chain transitions, particularly in emerging markets.

The following research questions guide our investigation:

RQ1: How do smart supply chain integration drivers influence decarbonisation and economic efficiency in food firms?

RQ2: How do smart integration practices mediate the relationship between these drivers, decarbonisation, and performance outcomes?

This study advances the literature in several ways. First, it conceptualises smart food safety systems as integration mechanisms that go beyond compliance, enabling inter-firm coordination for both environmental and economic performance. Second, it introduces a layered view of critical success factors that spans not only internal firm conditions but also supply chain and policy environments, reflecting the complexity of sustainability governance in emerging markets. Third, using survey data from 243 food firms across Vietnam and China, the study provides rare empirical evidence on the role of digital transparency and cross-boundary coordination in shaping decarbonisation and economic outcomes. In doing so, it contributes to ongoing discussions on digital transformation, sustainable supply chain integration, and how technology adoption can serve both ecological and strategic goals in transitional economies (Liu et al., 2021; Nguyen and Li, 2022; Pakseresht et al., 2023). The findings offer actionable insights for both industry practitioners and policymakers working to future-proof food supply chains under growing regulatory, environmental, and market demands.

LITERATURE REVIEW

Underlying theoretical constructs

To build a strong theoretical foundation for examining the relationship between critical success factors, SFSMS practices, decarbonisation, and efficiency, our study draws on two complementary frameworks: the Technology-Organisation-Environment framework (Tornatzky and Fleischer, 1990) and the Ecological Modernisation Theory (Hajer, 1995). Together, these frameworks allow us to conceptualise how internal capabilities and external pressures shape technological adoption, and how such adoption contributes not only to environmental goals but also to operational performance.

First, the TOE framework provides a comprehensive lens to analyse the adoption of technological innovations by focusing on three dimensions: technological, organisational, and environmental contexts (Tornatzky and Fleischer, 1990). In the context of SFSMS, the 'technological dimension' examines the readiness and benefits of adopting Industry 4.0 tools such as IoT, blockchain, and AI, which are central to enhancing food safety and sustainability. The 'organisational dimension' considers internal factors like strategic leadership involvement, organisational resources readiness, and personnel capabilities, which determine a firm's capacity to implement these advanced systems. Finally, the 'environmental dimension' highlights external pressures such as regulatory requirements, market demands for sustainability, and competitive dynamics, which drive firms to adopt innovative practices. By accounting for the interplay between these dimensions, the TOE framework aligns well with RQ1 and RQ2, as it explains how critical success factors (e.g., governance, organisational resources, and external support) shape the adoption of SFSMS practices, which subsequently influence decarbonisation and economic efficiency.

In parallel, Ecological Modernisation Theory offers a useful lens through which to understand how technological innovations can reconcile environmental protection with continued economic development. Rather than viewing environmental regulation as a constraint, EMT suggests that modernisation, when paired with the right institutional and technological reforms, can lead to both ecological and economic improvements (Hajer, 1995). In this study, EMT helps explain how the adoption of SFSMS can catalyze both reducing emissions and improving resource efficiency, particularly in sectors like food production, where sustainability concerns intersect with consumer safety and operational complexity. This dual-theoretical grounding supports our multi-level investigation of how smart safety systems are embedded within organisational routines, how they reflect broader strategic and policy environments, and how they ultimately affect environmental and financial performance in food firms across emerging economies.

Smart Food Safety Management System

Smart Food Safety Management System's Practices

The Food Safety Management System (FSMS) provides a systematic approach to ensuring food quality and regulatory compliance of each business's operational contexts, organisational resources, and environment (Jacxsens et al., 2011). Nonetheless, the food safety regulations of the EU law (EC, 2002), the Code of Federal Regulation (FDA, 2001), the Codex (CAC, 2009), and ISO 22000 (ISO, 2005) focus on providing FSMS with critical components. These include *ecosystems, standard quality principles,* and *supplementary FSMS constituents*, including mechanisms for traceability, managing nonconformities, evidence-based verification, performance validation, and continuous system improvement. Throughout this study, they are utilised to deliver FSMS deployment measurement indicators. Recent works outlining the significance of blockchain, the Internet of Things, artificial intelligence, machine learning, augmented reality (AR), virtual reality (VR), and so forth are notable since they demonstrate how these cutting-edge and state-of-the-art technologies influence our current FSMS. Food firms may use these technologies to rectify food safety issues and promote customer trust in emerging market supply chains by increasing transparency, inter-organisational traceability, and integrity (Nguyen and Li, 2021). In this analytical framework, SFSMS encapsulates the strategic adoption of intelligent technologies and the deployment of forward-thinking design architectures, characteristic of Industry 4.0, to support the implementation of self-optimising and integration-driven mechanisms across multi-tier supply chain networks in emerging markets.

Specifically, *ecosystems* constitute the foundational structures and actions essential for preserving a hygienic environment throughout the food chain, which is critical for the safe manufacturing, processing, and distribution of food (ISO, 2005). Ecosystems play an essential part in supporting Quality standards with an effective FSMS. Instead of relying on raw materials, products, and production processes, such as Quality standards, Ecosystems address the sanitary operating environment, support quality assurance programmes administered by practices, and demonstrate a supportive method toward food safety (Nguyen and Li, 2021). BSI EN ISO 22002-1 (ISO, 2009) outlines a standardised set of guidelines specifically developed to govern practices within the general food manufacturing sector, addressing critical aspects such as the physical layout and environmental conditions of production facilities, the provision of maintenance and operational support, the identification and control of hazards, and the implementation of effective cleaning and sanitisation regimes (Lewis, 2003). Recent academic discourse has examined the operational deployment of SFSMS technologies as part of broader food safety integration mechanisms, including the integration of smart sensor-enabled apparatuses for the early detection of potential hazards and the facilitation of predictive maintenance, as well as the implementation of artificial intelligence and advanced information management technologies to strengthen the safety and dependability of food manufacturing operations (Liu et al., 2021).

Next, a scientific method, renowned as "Principles of Quality standards", has been conducted to determine specific threats and take precautionary measures against them to guarantee the food's safety and quality (Arvanitoyiannis et al., 2009). *Quality standards* entail seven principles that highlight how to develop a quality standard scheme that facilitates each operation in minimising the likelihood of failure to maintain food safety as a result of Codex (Nguyen and Li, 2021). The formulation of quality standard plans is guided by seven core principles: conducting hazard assessments, determining Critical Control Points (CCPs), defining critical thresholds, implementing monitoring procedures, initiating corrective measures, performing verification activities, and maintaining comprehensive records and documentation. Inarguably, Quality standards must be included in every FSMS because they ameliorate foodborne hazards (Nguyen and Li, 2021; Lewis, 2003). Emerging technologies, such as the Internet of Things (IoT) and blockchain-based security frameworks, have been increasingly integrated into food supply chains (FSC) to enhance and uphold higher quality standards (Anand and Saxena, 2022).

Traceability, nonconformity management, corroboration, validation, and capability enhancement are also covered by the FSMS, in addition to Ecosystem and Quality standards. The concept of traceability encompasses the systematic tracking of food items, animal feed, livestock, and associated substances throughout the supply chain, ensuring transparency and accountability at each stage (CAC, 2009; EC, 2002). Traceability systems systematically identify and record the volume and batch information of inputs and outputs, the chronology and locations of their logistical and processing events, and the procedures employed to integrate and analyse this information for effective supply chain oversight. Control of

nonconformity involves a formalised approach to detecting and addressing deviations from established safety parameters, including breaches of CCP limits and failures in maintaining Ecosystem operational control (Nguyen and Li, 2021). Therefore, food manufacturers must take corrective measures for potentially hazardous items, such as reprocessing, withdrawal, recall, destruction, and disposal. In addition, validation entails collecting evidence that a control measure or group of control measures effectively reduces risks (CAC, 2009). Employing various methods, procedures, tests, and other types of assessments, verification establishes whether or not a control measure has been efficacious in addition to monitoring (CAC, 2009). Furthermore, an organisation must conduct internal audits at predetermined intervals to evaluate the food safety management system's effective application, adequate management, and ongoing improvement based on verified data. Apparently, SFSMS has been continuously updated with smarter technologies. Hassoun et al. (2022) have introduced the term "Food Traceability 4.0", which they define as the use of blockchain, IoT, AI, and BD, as well as other Industry 4.0 technologies, to develop smart traceability systems from farm to fork. An advanced deep learning SFSMS proposed by Khan et al. (2020) makes use of the Internet of Things (IoT), blockchain, and artificial intelligence (AI) to facilitate the monitoring of meat products while also managing all user data and providing full traceability. It provides complete control over access permissions and may be adjusted on a case-by-case basis.

Smart Food Safety Management System’s Critical Success Factors

As highlighted by Liu et al. (2020), while the term "Industry 4.0" was coined in 2011, references to the term did not emerge in scholarly publications until 2018. It appears that the integration of safety management principles within the framework of Industry 4.0 has only recently garnered scholarly interest, having previously been largely overlooked in academic discourse. Previous studies addressing SFSMS deployment have conceptualised essential determinants as "critical success factors", subsequently categorising them as "critical elements". The purpose of identifying and scrutinising these factors is to reduce the likelihood of system inefficiencies and to facilitate sustained improvements in SFSMS performance" (De Boeck et al., 2018; Mensah and Julien, 2011). Under the umbrella of "essential factors", there remains an ambiguity in distinguishing between factors that hinder implementation and those that serve as indicators of progress. Thus, distinctive perceptions of the critical factors can cause misunderstandings. From a theoretical perspective, critical factors constitute strategic considerations that food companies must systematically re-evaluate to achieve and sustain operational excellence. The relevant literature must satisfy two requirements to derive a series of critical factors. Given the necessity of examining Sustainable Food Safety Management Systems (SFSMS) within their contextual settings, critical factors are first assessed across organisational, market, and macro-environmental levels. These identified factors subsequently inform the evaluation of operational effectiveness and supply chain coordination capability, which are critical for effective SFSMS integration. A summary of key factors derived from existing literature is presented in Table 1.

Authors			Kafetzopoulos & Gotzamani	Kirezieva et al.	Nguyen & Li	Duong et al.	Nguyen	Duong et al.
Year			2014	2015	2021	2023	2023	2024
Food Chain Segments			Nutrition, agricultural products, beverages	Fresh food	Food firms	Food firms		Food firms
Focus Country			Greece	Spain, Belgium, Norway	Vietnam	Vietnam, China	Vietnam, China	Vietnam
Organisational Level	Strategic leadership involvement	Dedication	X		X	X		
		Awareness	X		X	X		
		Food-safety culture						
	Personnel administration	Communication	X		X	X		
		Dedication						
		Training	X		X	X		
		Awareness	X		X	X		
		Engagement	X		X	X		
	Organisational resources		X					X
Market Level	Supply chain alignment			X	X	X	X	
	External support			X	X	X		
	Food protection protocols			X	X			

Smart Food Safety Management System and Its Link to Decarbonisation

The integration of SFSMS represents a transformative approach to ensuring food safety and advancing sustainability goals, including decarbonisation. Traditional FSMS have long served as the foundation for compliance with food safety regulations and quality standards (Nguyen and Li, 2021). However, the advent of Industry 4.0 technologies has redefined these systems, enabling a shift toward "smart" systems. SFSMS leverages tools such as smart sensors, cloud computing, artificial intelligence (AI), and real-time data analytics to provide end-to-end visibility across the food supply chain. These technologies facilitate continuous monitoring and proactive risk management, ensuring enhanced traceability and efficiency (Trivelli et al., 2019; Jin et al., 2020). For instance, smart sensors detect real-time changes in temperature or contamination, while cloud computing ensures rapid data processing and storage, supporting timely decision-making (Hassoun et al., 2022). Blockchain technologies, among other smart innovations, play a critical role in enhancing inter-organisational integration, supply chain alignment, and transparency by enabling immutable, decentralised records of transactions and product flows (Long et al., 2023).

In addition to improving food safety and quality, SFSMS significantly contributes to decarbonisation by optimising resource use and minimising waste throughout the supply chain. Real-time data analytics and predictive models streamline logistics and operations, reducing energy consumption and greenhouse gas emissions. For example, predictive analytics mitigates food spoilage and overproduction, two major contributors to emissions (Zhang et al., 2023). Moreover, SFSMS aligns with Sustainable Development Goals (SDG) 12 (Responsible Consumption and Production) and SDG 17 (Partnerships for the Goals) by promoting efficient resource use, transparent supply chains, and collaborative practices that amplify sustainability efforts (Mukherjee et al., 2024).

The concept of decarbonisation has evolved as a critical extension of sustainable development, reflecting an organisation’s commitment to reducing environmental impact (Shang and Luo, 2021; Feng et al., 2024; Li et al., 2023). In this context, SFSMS fosters long-term accountability and legitimacy by addressing key sustainability practices. These initiatives aim to promote environmental sustainability by reducing reliance on natural resources, curbing carbon emissions, improving energy utilisation, incorporating renewable energy into distribution processes, and strengthening waste management through recycling and eco-conscious packaging (Ishaq et al., 2024; Ngo et al., 2023; Zhang et al., 2022). By aligning operational strategies with these criteria, food firms can demonstrate their dedication to decarbonisation while achieving broader environmental and societal objectives through cross-tier supply chain coordination.

Adopting a holistic approach, as proposed by Chardine-Baumann and Botta-Genoulaz (2014), further underscores the multifaceted impact of SFSMS on sustainability. This approach enables organisations to integrate technological advancements with sustainable practices, fostering resilient supply chains and long-term environmental stewardship (Ngo et al., 2023; Lee et al., 2019). Thus, SFSMS not only enhances operational efficiency and consumer trust but also serves as a strategic enabler of carbon-neutral initiatives, aligning business objectives with global sustainability goals.

The Relationship Between SFSMS and Economic Efficiency

The adoption of Smart Food Safety Management Systems (SFSMS) has profound implications for enhancing economic efficiency in the food industry. The technological advancements of SFSMS provide real-time insights and predictive capabilities, streamlining operations and reducing inefficiencies (Trivelli et al., 2019; Jin et al., 2020). By ensuring precise monitoring and rapid response to potential risks, SFSMS reduces operational disruptions and minimizes costs associated with recalls, spoilage, or non-compliance penalties, directly contributing to improved financial outcomes (Nguyen and Li, 2021).

From a critical success factor perspective, standardised processes, effective leadership, and personnel administration within SFSMS frameworks are essential for boosting organisational productivity and profitability (Kirezieva et al., 2015a). These systems also promote smart integration and coordination across supply chain actors, enabling shared safety protocols and data-driven decisions that translate into improved margins and competitive positioning (Duong et al., 2023). Studies indicate that such collaborative supply chains, characterised by

shared information, technical support, and aligned safety protocols, outperform their counterparts in terms of economic metrics like profit margins, return on assets, and market share growth (Duong et al., 2023). Furthermore, the integration of SFSMS into supply chain operations leads to high-quality outcomes that strengthen market competitiveness and consumer trust, driving revenue growth and long-term business sustainability.

The governance of food safety through stringent regulatory enforcement is a key determinant of the financial sustainability and competitiveness of food-related enterprises. Effective administration of SFSMS involves inspections, audits, education, and supervision, ensuring adherence to both public and private safety standards. This regulatory compliance not only mitigates risks but also enhances operational efficiency, positioning firms as reliable players in the marketplace (Duong et al., 2024). While previous studies have rarely linked food protection protocols directly to economic efficiency, Kirezieva et al. (2015a) highlight its influence on operational effectiveness and financial outcomes. The systematic enforcement of safety measures and the use of SFSMS tools optimise resource allocation and reduce waste, yielding cost savings and increased profitability.

Moreover, SFSMS enables firms to adapt to sustainable growth challenges, a critical factor in achieving economic resilience. As businesses face increasing pressure from stakeholders to align competitiveness with sustainability, SFSMS provides the technological and integration-enabling organisational resources to balance efficiency with environmental and social responsibilities (Giannetti et al., 2020). This approach shifts the focus from physical assets to leveraging both tangible and intangible resources, safeguarding long-term economic growth while addressing the broader sustainability demands from the value chain (Ishaq et al., 2024; Zou et al., 2017). In this context, SFSMS serves as a strategic enabler, not only ensuring compliance and safety but also driving economic efficiency through innovation, efficiency, and sustainability.

Hypothesis development

SFSMS's Critical Success Factors leading to Decarbonisation

To comprehend the integration mechanisms that support the achievement of decarbonisation and, subsequently, economic efficiency, three foundational perspectives are widely recognised: *organisation, market,* and *administration*, as examined by relevant prior studies such as Kafetzopoulos and Gotzamani (2014) and Duong et al. (2024). Following this logic, our hypotheses are developed below.

<u>At the organisational level</u>

Extensive regulatory frameworks, standards, and empirical research underscore the necessity of strategic leadership involvement as a central component of supply chain sustainability coordination, given that senior leadership is responsible for formulating, executing, and continuously improving operational strategies. Strategic leadership thus becomes a coordination hub linking internal and external partners around food safety and carbon goals (Kafetzopoulos and Gotzamani, 2014; Nguyen and Li, 2021; Duong et al., 2023), contributing to the assurance of resource availability and the systematic training of the workforce (Kafetzopoulos and Gotzamani, 2014), nurturing a company-wide culture of safety and driving the ongoing enhancement of food safety systems (Nguyen and Li, 2021; Nyarugwe et al., 2018). The successful operation and maintenance of the FSMS are contingent upon the delegation of responsibilities and authority by leadership to designated food safety and handling staff (ISO, 2005).

The realisation of food safety goals is contingent upon the availability of sufficient resources, such as human capital, organisational resources, and conducive working environments, to facilitate the effective operation and ongoing enhancement of the SFSMS (ISO, 2005). Fundamentally, personnel administration, encompassing employee engagement, technical competence, and behavioural compliance, remains vital for sustaining cross-functional safety performance and facilitating inter-departmental coordination for carbon-conscious operations (Duong et al., 2024). According to Nyarugwe et al. (2016), employee attributes serve as indicators of individual behaviours, knowledge, and perceptions related to food safety and sanitation control. Complementary perspectives in the literature suggest that personnel administration is reflected in employee engagement (Nguyen & Li, 2021; Duong et al., 2023), technical competence in ensuring food safety (Kafetzopoulos & Gotzamani, 2014), and the

acknowledgement of employees' contributory part in influencing food safety performance outcomes (Nyarugwe et al., 2018).

Moreover, the advancement of organisational resources is crucial not only for operational excellence but also for connecting local producers and supply chain partners in emerging markets to international safety and sustainability standards. Several scholars, including Kafetzopoulos and Gotzamani (2014) and Duong et al. (2024), emphasise that workplace conditions and available amenities are pivotal in shaping organisational performance. Their implications for decarbonisation efforts are also explored. Notably, ISO 22000:2005 omits consideration of an organisation's financial and technical capabilities, despite prior studies identifying these elements as significant barriers to the implementation of SFSMS, given the serious consequences that may arise from their inadequacy (Duong et al., 2024).

At the market level

Supply chain alignment

Organisational network structures within emerging market supply chains significantly affect the integration and coordination of SFSMS (Nguyen & Li, 2021; Duong et al., 2023; Nguyen, 2023). Notably, food enterprises with higher levels of operational sophistication and system reliability were proven to benefit from cooperative and supportive supply chains (Luning et al., 2015), lending credence to this notion. In this sense, supply chain alignment represents a coordination mechanism through which firms synchronise safety protocols, data sharing, and environmental objectives. Researchers in other fields define supply chain characteristics as a set of variables (including commodity, production, organisation, and chain qualities) that influence the strategic formulation and operational implementation phases within the supply chain (Ngo et al., 2023). Supply chain corruption can be avoided by circumventing the development and promotion of collaboration among the concerned entities. However, there needs to be more information on cooperative supply chain links across research, such as how these organisations interact and contribute to decarbonisation (Duong et al., 2024).

The alignment of supply chain processes is expected to yield significant improvements in quality-related outcomes for businesses. As noted by Nguyen and Li (2021), in emerging markets, this alignment enables small and medium-sized suppliers to integrate into carbon-conscious networks, strengthening both compliance and competitiveness. According to Kirezieva et al. (2015b), a cooperative supply chain operates through the alignment of stakeholder expectations, the cultivation of strong supplier alliances, and the facilitation of transparent and continuous information flows. Furthermore, Despoudi et al. (2018) reveal that considerable levels of collaboration between manufacturers and organisations are related to fewer postharvest food losses and a lower proportion of damaged peaches from Greece. Hence, supply chain alignment is conceptualised here as a structural integration mechanism, allowing shared food safety responsibility and coordinated decarbonisation initiatives (Ishaq et al., 2024; Ngo et al., 2023).

External support

Driven by escalating statutory requirements and consumer expectations, the responsibilities and costs of food safety and sustainability assurance have shifted upstream across integrated supply chain tiers, from retailers to suppliers and from industrialised to emerging economies (Nguyen, 2023). Irrespective of deficiencies in essential facilities, equipment, and experienced labour in poverty-stricken nations, retailers often underscore their suppliers' adherence to new requirements without providing solutions for the additional costs. Therefore, food enterprises in emerging countries seek external support (i.e., financial investment) to modernise their organisational resources, equipment, and staff training; details to expand their market; and private adherence to regulatory requirements/certification to enhance their SFSMS in line with consumers' evolving demands (Nguyen & Li, 2021; Duong et al., 2024). External support thus acts as a facilitator of integration, allowing firms to bridge financial and technological gaps and engage more effectively in coordinated sustainability initiatives. Such support enhances the diffusion of information, regulatory knowledge, and innovation across actors, enabling synchronised responses to carbon and food safety pressures (Xiong et al., 2017; Qijun and Batt, 2016). Alternatively, technology is recognised as a fundamental enabler of communication, offering enhanced visibility across operations and promoting superior performance outcomes for firms. Despite these advantages, empirical work remains limited

on how external institutional coordination shapes SFSMS adoption and decarbonisation success, particularly in emerging markets.

Food protection protocols

Regulatory oversight and food protection protocols play a key role in structuring cross-tier governance for food safety integration (Duong et al., 2023). Administrative mechanisms such as audits, inspections, and third-party certifications may serve as coordination tools that link public agencies, private actors, and suppliers across jurisdictions (Rouvière and Caswell, 2012). Several methods are employed to guarantee the quality and security of food. This includes a range of instruments such as audits and inspections, coercive and incentivising measures, knowledge dissemination efforts, and mechanisms for sampling and regulatory oversight (Nguyen, 2023; Duong et al., 2024). However, limited evidence exists on how these governance mechanisms contribute to decarbonisation. By enforcing integrated oversight, these protocols establish accountability chains that align operational, environmental, and safety targets.

The implementation of food safety administrative measures serves to ensure that firms operate in accordance with the expectations of food safety authorities and associated stakeholders. As outlined by Rouvière and Caswell (2012), administrative duties in food safety governance are typically categorised as either direct or indirect. Direct oversight involves physical evaluations of operational sites, whether scheduled or unannounced, while indirect oversight encompasses the examination of documentation and reliance on third-party audit processes. The development of a globally integrated food safety management system has been largely shaped by the engagement of numerous governmental agencies operating across national and international jurisdictions. Rouvière and Caswell (2012), along with Kirezieva et al. (2015a), highlight that audits and inspections, whether conducted on a scheduled or ad hoc basis, are implemented at various stages, including prior to and following the distribution of goods at business premises, retailers and export locations. Mandatory inspections, examinations, and sampling procedures serve as enforcement mechanisms to assess whether firms are subject to penalties, legal action, sanctions, or potential license revocation due to non-compliance with statutory regulations or policy mandates. In response to breaches of food safety requirements, regulatory authorities may impose a spectrum of disciplinary actions on food firms, ranging from regulatory penalties, suspension of operations, seizure of products, and prohibition from participating in commercial trade, contingent upon the gravity of the non-compliance (Nguyen, 2023).

In contrast, informative approaches are primarily characterised by corrective measures and public disclosure, often referred to as 'naming and shaming', which involve transparently communicating relevant information to consumers (Rouvière & Caswell, 2012). Beyond symbolic rewards such as recognition or awards, tangible incentives like tax benefits may also be employed to promote compliance with regulatory standards (Kirezieva et al., 2015b). Moreover, a multitude of small and medium-sized enterprises yield the most benefits out of knowledge and education (such as regulations, instruction, and assistance) (Tsang et al., 2023). The efficacy of the SFSMS and the performance of the organisations may be significantly affected by these administrations.

Following that, the hypotheses $H_{1a\text{-}f}$ are proposed below:

H_1: SFSMS's Critical success factors, including Personnel administration, Strategic leadership involvement, Organisational resources, Supply chain alignment, Food protection protocols, and External support, directly and positively drive Decarbonisation through enhanced integration and coordination mechanisms in food supply chains.

The mediating effect of SFSMS practices between CSFs and Decarbonisation

From an environmental standpoint, the role of SFSMS practices in achieving decarbonisation has been widely acknowledged. Smart integration practices serve as mechanisms for linking firm-level CSFs with sustainability outcomes across supply chains such as interconnected quality control, ecosystem resilience, and system robustness. Wang et al. (2021) describe how integrating advanced SFSMS technologies in controlled environments, such as closed-loop indoor farming systems, can simultaneously enhance productivity and significantly reduce carbon emissions. This highlights the potential of SFSMS ecosystems to minimise environmental impacts while meeting food safety standards. Furthermore, more studies have

demonstrated that adopting intelligent food safety measures - such as IoT, artificial intelligence, and machine learning - improves product quality and strengthens firms' competitive positions by aligning with sustainability goals (Duong et al., 2024).

Building on these findings, our study hypothesises that SFSMS practices, including Quality Standards, Ecosystem, and Robustness, mediate the relationship between critical success factors (CSFs) and decarbonisation (H2a-c, H3a-c). Each dimension of SFSMS practices provides a pathway for operationalising the enabling factors to achieve sustainability outcomes. For example, Quality Standards coordinate hazard control and efficiency across organisational boundaries, Ecosystem promotes energy-efficient design and waste minimisation, and Robustness supports real-time information exchange that enables cross-tier environmental monitoring (Nguyen and Li, 2021). Research from Mukherjee et al. (2024) further supports this argument, indicating that achieving decarbonisation through decarbonisation strategies, digitalisation, and resource optimisation improves not only environmental outcomes but also business performance. Thus, SFSMS practices represent integration mechanisms that bridge organisational structures and sustainability goals (Hajer, 1995), which advocate for integrating technological and institutional advancements to address environmental challenges while fostering economic growth. The critical role of governance and stakeholder collaboration (i.e., the CSFs) in enabling such transitions underscores the importance of embedding SFSMS practices within broader organisational and institutional frameworks. In the context of emerging economies like China and Vietnam, where regulatory frameworks and organisational resources are rapidly evolving, the mediating role of SFSMS practices becomes even more critical.

Such claims support our hypotheses as follows:

$H_{2a\text{-}c}$ and $H_{3a\text{-}c}$: SFSMS practices (e.g., Quality standards, Ecosystem, Robustness) mediate the driving effects of SFSMS's CSFs toward higher Decarbonisation through integrated coordination across supply chain partners.

Decarbonisation and Economic Efficiency

Decarbonisation increasingly represents a coordinated outcome of cross-supply chain sustainability efforts, where emission reductions and process optimisation contribute to financial efficiency. Firms that integrate carbon management across supply chain tiers not only meet environmental regulations but also achieve long-term cost savings and market differentiation (Feng et al., 2024; Zhang et al., 2023). Consequently, food firms, among others, must prioritise profitability alongside the integration of more comprehensive sustainable performance. Several investigations have explored whether meeting decarbonisation goals can enhance the economic efficiency of businesses over the long term, considering the significant initial investments needed (Zhang et al., 2023). Okereke (2007) has raised concerns regarding a company's profitability when it seeks to reduce emissions, while empirical evidence presented by Jacobs et al. (2010) suggests that voluntary emissions reduction efforts correlate negatively with financial performance among publicly listed firms in the US and European markets. Nevertheless, the commitment and efforts of early adopters to achieve decarbonisation resulted in enhanced economic efficiency, as demonstrated by Zhang et al. (2023). Findings such as these highlight the advantages of embracing new developments ahead of the curve.

In emerging markets, this coordination allows smaller firms to share technology, logistics, and knowledge resources with larger partners, thereby improving both emission outcomes and operational efficiency. These synergies underscore the systemic nature of decarbonisation, linking it directly to improved financial resilience and competitiveness (Goh, 2019).

We thereby propose:

H_4: Achieving Decarbonisation through coordinated and integrated supply chain mechanisms enhances Economic Efficiency in food firms.

The overall research model is presented in Figure 1 as follows:

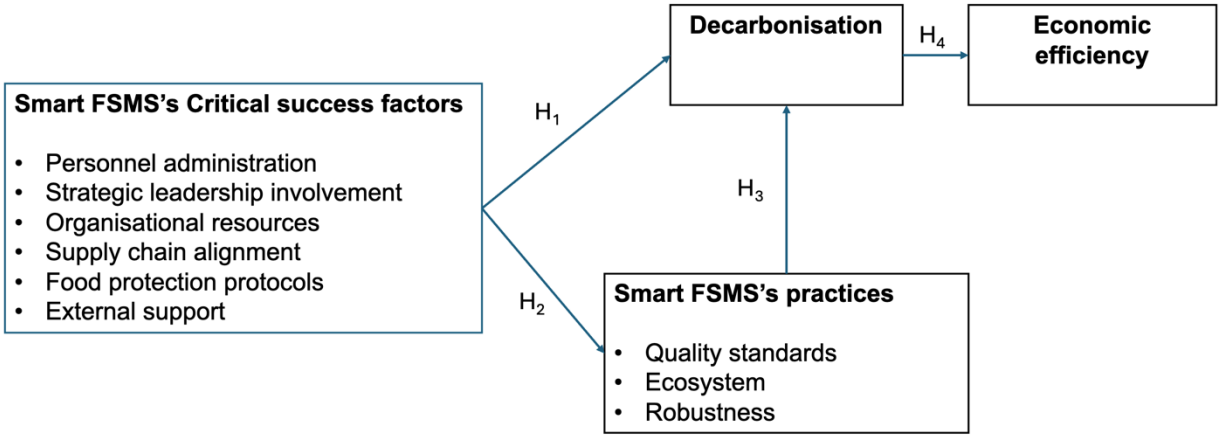


Figure 1: Research Model

Methods

Research Methodology

Sampling design

Our study focuses on food-producing and exporting businesses in Asia, with a particular emphasis on China and Vietnam. As two of the world's leading food producers and exporters, these nations have been instrumental in establishing Asia as a global powerhouse in the food industry (FAO, 2020). Both countries are experiencing rapid growth in their food industries, driven by expanding production and increasing adoption of advanced technologies (Khan et al., 2020). This makes them ideal contexts for examining the impacts of SFSMS. At the same time, China and Vietnam face significant challenges, including high greenhouse gas emissions from food production, which underscores the importance of exploring how SFSMS can support decarbonisation and broader sustainability goals (Qijun and Batt, 2016; Xiong et al., 2017; Nguyen and Li, 2021). In this context, building operational robustness through ESG-orientated strategies is essential for firms navigating the complex and volatile environments typical of emerging markets (Tsang et al., 2024). Given that many businesses in our sample are actively engaged in international trade (Appendix 1), the findings from this study offer practical insights not only for China and Vietnam but also for other developing and transitional economies facing similar sustainability and compliance challenges.

The professionals and companies invited to participate in the survey were selected based on several criteria to ensure the relevance and depth of responses. Eligible companies included food-producing and -exporting firms from key subsectors such as fisheries, fresh fruits and vegetables, dairy, poultry, drinks and beverages, and rice and grains. Firms were chosen to represent a range of operational scales, including micro, small and medium enterprises (SMEs) and large firms, to capture diverse organisational perspectives and practices. Participants were required to hold senior roles including quality control managers, supply chain managers, CEOs, directors, or trading managers to ensure that respondents had direct knowledge of their company's food safety management practices, technological adoption, and sustainability strategies. Additionally, companies were prioritised if they demonstrated measurable involvement in international markets, reflecting their exposure to global regulatory standards and competitive pressures.

To obtain empirical data, 1,000 managers from the food industry were surveyed through both digital and in-person channels, employing structured questions formulated in Chinese and Vietnamese. Details of the questionnaire design and statistical validation are provided in Appendix 1. The survey achieved a 24.3% response rate, with 243 food enterprises participating. The distribution across sub-sectors was as follows: fishery (44.4%), poultry (9.1%), dairy (9.5%), fresh produce (22.2%), beverages (8.6%), and miscellaneous sectors (6.2%). Most respondents represented SMEs (71.2%), while 15.2% were large-scale enterprises and 13.6% were classified as micro firms. Export volumes varied, with 10.7% of firms exporting over 3,000 tonnes annually, 50.2% exporting under 500 tonnes, and the remainder falling between these thresholds. The roles of respondents included quality control managers (29.2%), supply chain managers (32.1%), and executive-level personnel (38.7%).

Development of the instrument and metrics

Drawing on the previously discussed theoretical framework, tests for reliability and validity are used to define and constrain measurement variables to those that accurately reflect the underlying constructs. All measurement items were initially developed in English and back-translated into Chinese and Vietnamese. Four academics, three business executives, and two advisors reviewed and revised the five-point Likert scale questionnaire (from unlikely to extremely significant) used in an online pilot survey of fifty food businesses to guarantee content validity and check for illogical sequences and unclear terms. During this pilot test, the scale's reliability was evaluated using Cronbach's alpha and exploratory factor analysis (EFA). The eleven scales constituting the composite structures, including sixty-three different variables, were deemed valid. The subsequent official survey relied on the aforementioned factors (see *Appendix*).

Data analysis

The underlying structures of the variables, particularly the market and governance-based critical factors, were analysed using Confirmatory Factor Analysis (CFA) to ensure alignment between the number of factors, variable loadings, and theoretical expectations. Key statistical assumptions were carefully evaluated to validate the model's appropriateness, including checks for multicollinearity, unidimensionality, scale precision, and construct validity (Hair et al., 2019a). Structural Equation Modelling (SEM), performed using route analysis and the bootstrapping method with IBM SPSS and AMOS (25th iteration), was selected for its ability to examine multilevel relationships and latent variables. CFA established construct validity, while SEM captured the direct and indirect relationships crucial to understanding the dynamics of our complex model (Hair et al., 2019a).

To confirm the robustness of SEM, we assessed statistical assumptions such as normality, homoscedasticity, and the presence of outliers. Goodness-of-fit indices, including CFI, TLI, RMSEA, and SRMR, were applied, with results meeting the recommended thresholds for model adequacy. Recognising potential challenges such as overfitting due to a high number of parameters relative to the sample size and common method bias associated with cross-sectional data (Lowry and Gaskin, 2014), several precautions were taken. These included maintaining an appropriate sample size, employing bootstrapping techniques to enhance estimate reliability, and using Harman's single-factor test to address common method variance. Multicollinearity was also checked, with variance inflation factor (VIF) scores confirming acceptable levels, ensuring the stability of the findings (Lowry and Gaskin, 2014; Hair et al., 2019a).

Results

Construct reliability and validity

The study employed traditional psychometric methods to evaluate the reliability and validity of the measurement instruments (Hair et al., 1995). Variables that failed to meet the specified thresholds, such as environmental performance, were excluded from further analysis. The remaining indicators loaded significantly on their respective constructs, with standardised regression coefficients exceeding 0.521 (> 2 x standard error) and R^2 values of at least 0.311, indicating compliance with accepted criteria for convergent validity. Moreover, Average Variance Extracted was equal to or surpassed 51.1% and composite reliability values were no less than 0.752, proving to construct reliability (Table 2). The chosen constructs were also proven to be unaffected by multicollinearity issues, as all VIF values were below the suggested threshold of 10 (Hair et al., 2019a).

EFA			CFA		
Measurement items	Factor loadings	Item – total correlation	Standardised Regression Weights	Standard errors	R^2
Personnel administration: Eigenvalue = 2.616, Variance Extracted = 65.391%, Cronbach's Alpha = 0.823, Composite Reliability (CFA) = 0.813, Variance Extracted (CFA) = 0.524					
Employees' knowledge and skills	0.829	0.677	0.799	0.071	0.638
Awareness of the personnel	0.813	0.652	0.776	0.075	0.601
Training programs for employee	0.767	0.593	0.607	0.076	0.368
Employees' involvement	0.823	0.667	0.698	0.072	0.487
Strategic leadership involvement: Eigenvalue = 2.823, Variance Extracted = 70.584%, Cronbach's Alpha = 0.859, Composite Reliability (CFA) = 0.863, Variance Extracted (CFA) = 0.613					
Managers commitments	0.884	0.773	0.867	0.045	0.751
Food safety policy	0.866	0.742	0.833	0.054	0.694
Responsibilities and authorities	0.835	0.698	0.755	0.046	0.57
Food safety culture	0.772	0.616	0.661	0.064	0.436
Organisational resources: Eigenvalue = 2.206, Variance Extracted = 73.524%, Cronbach's Alpha = 0.817, Composite Reliability (CFA) = 0.821, Variance Extracted (CFA) = 0.604					
Qualified facilities and equipment	0.873	0.7	0.822	0.054	0.676
Financial condition	0.845	0.654	0.744	0.039	0.553
Technological condition	0.853	0.669	0.764	0.055	0.584
External support: Eigenvalue = 2.575, Variance Extracted = 51.492%, Cronbach's Alpha = 0.758, Composite Reliability (CFA) = 0.752, Variance Extracted (CFA) = 0.511					
Supports from financial institutions	0.66	0.468	Deleted		
Supports from business associations	0.81	0.638	0.793	0.072	0.629
Supports from stakeholders in supply chains	0.81	0.639	0.795	0.068	0.632
Supports from the government and authorities	0.684	0.488	0.521	0.052	0.311
Supports from non-governmental organizations	0.6	0.416	Deleted		
Supply chain alignment: Eigenvalue = 2.532, Variance Extracted = 63.292%, Cronbach's Alpha = 0.806, Composite Reliability (CFA) = 0.808, Variance Extracted (CFA) = 0.515					
Information exchange	0.791	0.614	0.7	0.039	0.49
Emerging problems	0.849	0.697	0.822	0.039	0.676
Planning and goal-setting activities	0.775	0.593	0.676	0.044	0.457
Continuous improvement programs	0.765	0.581	0.661	0.045	0.437
Food protection protocols: Eigenvalue = 2.637, Variance Extracted = 65.930%, Cronbach's Alpha = 0.824, Composite Reliability (CFA) = 0.829, Variance Extracted (CFA) = 0.550					

Food safety audits and inspections	0.81	0.646	0.735	0.061	0.54
Regulatory sanctions	0.838	0.686	0.785	0.052	0.616
Regulatory stimulus	0.848	0.704	0.802	0.042	0.643
Regulatory information and education	0.747	0.569	0.634	0.068	0.402
Quality standards: Eigenvalue = 5.153, Variance Extracted = 73.620%, Cronbach's Alpha = 0.940, Composite Reliability (CFA) = 0.940, Variance Extracted (CFA) = 0.692					
Hazards identified at each step	0.88	0.831	0.864	0.031	0.746
The points of which control are taken by a quality standard team	0.867	0.814	0.846	0.037	0.715
The scale of effectiveness in determining quality standard critical limits	0.837	0.775	0.803	0.046	0.645
Monitoring procedures and systems at quality standards	0.871	0.819	0.85	0.035	0.723
Installed corrective actions at quality standards.	0.847	0.788	0.818	0.043	0.67
Validation procedures	0.844	0.785	0.813	0.041	0.661
The provision of efficient records and paperwork	0.859	0.804	0.829	0.037	0.687
Ecosystem: Eigenvalue = 5.352, Variance Extracted = 66.895%, Cronbach's Alpha = 0.929, Composite Reliability (CFA) = 0.915, Variance Extracted (CFA) = 0.608					
Building and infrastructure construction and planning	0.767	0.696	0.676	0.049	0.457
Building design and layout	0.842	0.784	Deleted		
The provision of air, water, energy and other utilities	0.796	0.73	0.729	0.05	0.531
Waste and sewage disposal among other auxiliary services	0.792	0.726	0.733	0.047	0.537
Properness of equipment	0.84	0.784	0.823	0.041	0.678
Material procurement administration	0.849	0.795	0.828	0.044	0.685
Strategies for limiting the spread of diseases	0.836	0.78	0.851	0.041	0.724
Systematic cleaning and disinfection	0.815	0.755	0.804	0.048	0.646
Robustness: Eigenvalue = 7.551, Variance Extracted = 68.648%, Cronbach's Alpha = 0.954, Composite Reliability (CFA) = 0.954, Variance Extracted (CFA) = 0.656					
Traceability system	0.85	0.813	0.836	0.034	0.698
Corrective actions	0.842	0.805	0.824	0.036	0.679
Techniques for safely processing potentially harmful products	0.762	0.715	0.73	0.045	0.533
Control measurements	0.859	0.825	0.844	0.036	0.713

The ability to provide sufficient evidence	0.851	0.814	0.839	0.034	0.704
Internal audits	0.829	0.789	0.807	0.037	0.651
All required records and documents are properly controlled	0.838	0.799	0.821	0.031	0.674
Internal communication	0.779	0.733	0.75	0.045	0.563
External communication	0.808	0.765	0.786	0.037	0.618
Enhancing and constantly upgrading the food safety management system	0.855	0.819	0.841	0.034	0.708
Activeness in pursuing accreditation or registration	0.837	0.798	0.819	0.034	0.671
Economic efficiency: Eigenvalue = 1.003, Variance Extracted = 74.754%, Cronbach's Alpha = 0.889, Composite Reliability (CFA) = 0.889, Variance Extracted (CFA) = 0.616					
Company's operational costs of the previous year	Deleted		Deleted		
Enhanced product and process	0.85	0.749	0.853	0.037	0.728
Market expansion	0.841	0.741	0.8	0.034	0.64
Net profit margin of the previous year	0.834	0.735	0.798	0.032	0.637
Sales growth during the last year	0.821	0.716	0.749	0.056	0.561
Cash flow of the previous year	0.822	0.721	0.717	0.045	0.514
Decarbonisation: Eigenvalue = 4.436, Variance Extracted = 73.926%, Cronbach's Alpha = 0.929, Composite Reliability (CFA) = 0.917, Variance Extracted (CFA) = 0.689					
Reduction of using natural resources	0.856	0.789	Deleted		
Reduction of carbon emissions	0.893	0.836	0.862	0.032	0.743
Reduction of energy consumption	0.839	0.767	0.809	0.038	0.655
Increase of using renewable energy in distribution	0.845	0.773	0.829	0.034	0.688
Effectiveness in input management	0.885	0.828	0.848	0.044	0.72
Effectiveness in waste disposal, packaging, recycling,…	0.839	0.768	0.801	0.047	0.642

Table 2. Construct reliability and validity results

Structural model

The SEM results are visually represented in Figure 2. The model fit indices Chi-square (χ^2 = 5.135, df = 2, p = 0.077), Chi-square/df = 2.568, GFI = 0.990, TLI = 0.984, CFI = 0.995, and RMSEA = 0.080, indicate that the model provides a good fit to the data.

To examine the relationships and mediation effects, we employed the bootstrapping approach (Hair et al., 2019). The results, illustrated in Figure 2, confirm that all relationships are statistically significant at the $p < 0.1$ level.

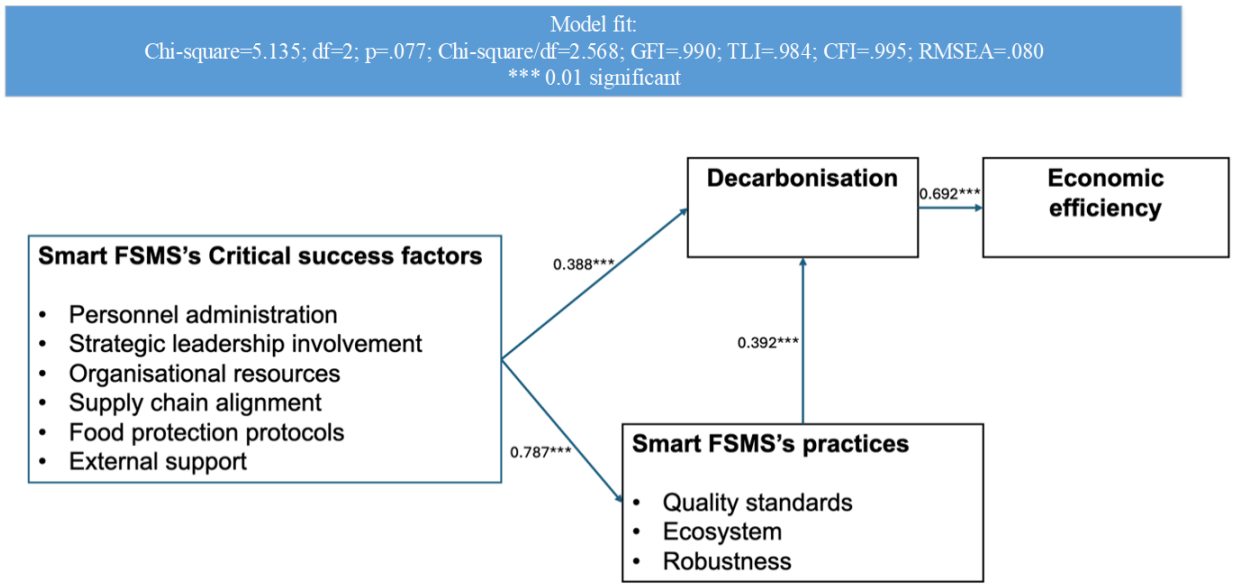


Figure 2: Relationship testing results

The mediation analysis demonstrates the critical role of "SFSMS practices" in bridging the influence of critical success factors on Decarbonisation, supported by robust testing of direct, indirect, and total effects (see *Table 3*). The direct effect of 0.388 indicates a significant positive relationship between CSFs and Decarbonisation, reflecting the foundational role of governance, market readiness, and technological adoption. However, the indirect effect of 0.309 through SFSMS Practices highlights a complementary pathway, where the operationalisation of these critical factors into specific practices amplifies their impact, with a Variance Accounted For (VAF) of 44.3%, confirming partial mediation. The mediation testing results show that SFSMS Practices translate strategic enablers into actionable outcomes by leveraging Industry 4.0 technologies such as IoT, AI, and blockchain for advanced traceability, real-time risk management, and operational efficiency. This alignment is evident in the significant path coefficient of 0.787 between CSFs and SFSMS Practices, emphasising the reliance of these practices on strong foundational enablers. The further impact of SFSMS Practices on Decarbonisation, with a significant coefficient of 0.392, demonstrates their ability to reduce resource waste, optimise energy use, and minimise emissions, substantiating their role as key mechanisms driving sustainability. The broader implications of these findings are underscored by the strong link between Decarbonisation and Economic Efficiency (0.692), suggesting that sustainability efforts through SFSMS not only address environmental goals but also yield economic benefits.

Relationships	Direct effect (t-value)	Indirect effect (t-value)	Total effect	VAF(%)	Interpretation	Conclusion
Critical Factors -->SFSMS's Practices --> Decarbonisation	0.388	0.309	0.697	44.3	Partial mediation	Supported

Table 3. The mediation analysis

Discussion

Key findings

Impact of the SFSMS critical factors on Decarbonisation, leading to firms' economic efficiency

This study analysed the impact of critical success factors (CSFs) on food safety management in 243 food manufacturing firms, considering 24 CSF indicators across organisational, market, and governance levels. The findings demonstrate that the CSFs of Smart Food Safety Management Systems (SFSMS) exert a significant and positive effect ($\beta = 0.388^{***}$) on the decarbonisation of food organisations. These results highlight the importance of integrating SFSMS elements within a coordinated system, where actors across internal departments and external supply chain partners collectively support sustainability goals. At the organisational level, key drivers include personnel administration, strategic leadership involvement, and robust organisational resources, which collectively enable the effective implementation of SFSMS practices. The market level highlights the critical role of supply chain alignment and external support in fostering collaborative supply chain efforts and resource accessibility for sustainability initiatives. At the administrative level, food protection protocols ensure compliance with regulatory requirements, strengthen inter-organisational trust, and bolster the credibility of carbon-neutral strategies. These findings build upon and extend prior research by highlighting the multi-layered coordination mechanisms through which CSFs contribute to advancing global food safety and sustainability objectives (e.g., Kafetzopoulos & Gotzamani, 2014; Kirezieva et al., 2015; Nguyen & Li, 2021; Duong et al., 2023; Nguyen, 2023; Duong et al., 2024).

The results underscore the transformative potential of SFSMS in achieving decarbonisation while maintaining food safety and operational efficiency. This aligns with the theoretical foundations of the Technology-Organisation-Environment (TOE) framework, which emphasises the integration of internal and external factors for technological adoption, and the Ecological Modernisation Theory (EMT), which posits that technological innovation can harmonise economic and environmental objectives through system-wide coordination and innovation.

Additionally, the findings confirm that achieving decarbonisation positively influences economic efficiency, aligning with prior studies highlighting sustainability initiatives' financial benefits. Zhang et al. (2023) demonstrate that early adopters of carbon-neutral practices experience enhanced profitability, driven by improved operational efficiency, reduced resource consumption, and increased market appeal. Similarly, Goh (2019) finds that transitioning towards carbon-neutral operations expands customer bases and strengthens brand loyalty, particularly among environmentally conscious consumers. These findings support the notion that sustainability strategies are not only aligned with environmental goals but also create competitive advantages and long-term economic gains. While earlier research, such as Jacobs et al. (2010), raises concerns about the potential financial drawbacks of voluntary emissions reduction, our results suggest that integrating advanced SFSMS practices helps mitigate these risks by optimising resource use and aligning with regulatory incentives. This underscores the dual value of decarbonisation, enhancing both environmental sustainability and business outcomes, particularly for firms in emerging markets like China and Vietnam.

The mediating role of SFSMS practices on the correlation between SFSMS's critical factors and Decarbonisation

The findings demonstrate that practices within the smart system play a crucial mediating role between the examined CSFs and Decarbonisation, offering significant insights into the challenges and opportunities faced by modern Chinese and Vietnamese food firms. Within the framework of the TOE model, the study highlights how technological readiness (e.g., access to IoT and blockchain), organisational resources (e.g., strategic leadership involvement and organisational resources), and external pressures (e.g., regulatory compliance and global market demands) drive the implementation of these practices, similar to Li and Nguyen (2021).

More importantly, this mediation process reflects the coordinated integration of digital, operational, and regulatory mechanisms, which collectively enable firms to convert strategic intent into sustainability outcomes. For food firms in China and Vietnam, where rapid industrialisation and global trade participation have intensified regulatory and sustainability pressures (Li et al., 2023), operationalising CSFs through smart practices is essential for achieving both environmental and economic goals. The significant indirect effect observed emphasises that while CSFs provide a strategic foundation for sustainability, their impact is amplified through operational actions such as real-time monitoring, traceability, and resource

optimisation. This finding builds on prior research (e.g., Hassoun et al., 2022) by quantifying the mediating role of these practices in the context of emerging economies.

From the ecological modernisation perspective, the results illustrate how integrating advanced technologies into operational practices allows Chinese and Vietnamese food firms to achieve Decarbonisation without compromising economic efficiency. In these rapidly industrialising economies, where food safety is both a regulatory mandate and a competitive necessity in global markets (Macheka et al., 2013), the coordination of smart safety protocols and supply chain systems enables alignment with local and international sustainability standards. The partial mediation observed suggests that while CSFs such as governance and technological organisational resources independently influence Decarbonisation, their effectiveness depends on well-coordinated execution through integrated safety mechanisms. This layered understanding contrasts with studies focusing solely on direct relationships between sustainability strategies and outcomes (such as Kafetzopoulos and Gotzamani, 2014), highlighting the complexity of achieving sustainability in transitional economies.

Third, our findings empirically verify the hypothesis that achieving decarbonisation positively impacts economic efficiency, aligning with prior research emphasising the long-term benefits of sustainable practices. Consistent with Zhang et al. (2023), our results demonstrate that firms prioritising decarbonisation not only enhance their environmental outcomes but also improve profitability by expanding their customer base and appealing to environmentally conscious clients. This aligns with Goh (2019), who highlighted the competitive advantages gained by early adopters of sustainability initiatives. However, our findings diverge from studies like Jacobs et al. (2010), which reported negative financial impacts of voluntary emissions reduction, particularly among publicly listed US and European firms. These differences may stem from contextual variations, such as regulatory environments or market conditions, underscoring the importance of considering geographic and industrial settings in such analyses (Mukherjee et al., 2024). Additionally, our study offers a counterpoint to Okereke's (2007) concerns about profitability challenges in emissions reduction, demonstrating that strategic integration of sustainability initiatives can yield both environmental and economic gains when supported by robust organisational practices, particularly in the context of emerging markets like China and Vietnam.

In conclusion, building smart food safety integration mechanisms, grounded in coordination, trust, and data-sharing, will significantly enhance firms' capacity to deliver on carbon mitigation while sustaining performance in emerging market contexts.

Research implications

Theoretical implications

This study makes significant theoretical contributions by integrating the TOE framework and EMT model to examine the dynamics of SFSMS adoption and its outcomes. It advances the understanding of how critical factors at organisational, market, and governance levels interact to enable sustainability goals. Unlike earlier research that often considers critical factors as homogeneous (Nguyen & Li, 2021; Duong et al., 2023), this study disentangles their distinct influences and demonstrates how they collectively support the operationalisation of SFSMS practices. Importantly, the study frames SFSMS not as an isolated tool but as part of a broader integration mechanism that coordinates internal and external resources across the supply chain.

By focusing on the multi-level nature of these factors, the research also extends the application of CSF literature within the context of smart systems for food safety management. More specifically, the TOE framework is expanded through this study by showing how technological readiness, organisational capacity, and external governance pressures jointly shape the adoption of SFSMS practices. This multidimensional approach highlights the importance of aligning internal capabilities, such as organisational resources, readiness, and strategic leadership involvement, with external forces, such as regulatory and market demands, to drive sustainable transformations (Shang et al., 2022). By embedding these elements within the broader sustainability landscape, the research enriches TOE by providing a deeper understanding of the mechanisms through which firms in emerging economies, like those in China and Vietnam, navigate the complexities of SFSMS adoption to achieve both environmental and economic outcomes. Incorporating EMT, this study validates the role of

technological advancements in achieving dual objectives of environmental sustainability and economic efficiency. It empirically demonstrates how the integration of SFSMS practices, such as real-time monitoring, IoT-enabled traceability, and data-driven decision-making, reduces greenhouse gas emissions while enhancing resource efficiency and productivity (Wang et al., 2021; Zhang et al., 2023). These findings provide critical insights into the operational mechanisms through which decarbonisation initiatives can align with profitability goals (Feng et al., 2024), addressing concerns raised in earlier literature about the financial feasibility of such transitions (Okereke, 2007; Jacobs et al., 2010). In this way, the study positions SFSMS as an embedded coordination system that links strategic enablers with measurable sustainability and business outcomes.

Overall, by linking critical success factors, SFSMS practices, decarbonisation, and economic efficiency, this study contributes to a more comprehensive understanding of sustainability transitions within the food industry. It advances a systems-based view of smart food safety integration mechanisms, especially suited for emerging market supply chains, where alignment between policy, technology, and inter-firm collaboration is essential.

Managerial implications

The findings above are exceedingly important for SFSMS practitioners. The conclusion encourages food safety practices to zero in on organisational initiatives, particularly strategic leadership involvement, to strengthen Decarbonisation. Moreover, this study postulates that food companies should cooperate with supply chain members and stakeholders to resolve food safety threats in lieu of working unilaterally. Government, authorities, and business associations should aid enterprises in implementing SFSMS, primarily in China and Vietnam. Specifically, this study foregrounds the merit of organisations' proactive SFSMS participation in dynamic and competitive food supply chains. In this context, smart food safety systems function as integration mechanisms that promote alignment between internal processes and external coordination across supply chain actors. Unceasing updates and improvements of the SFSMS will strengthen international food trade operations.

In more detail, food industry stakeholders can adopt several specific strategies to enhance SFSMS implementation and align with sustainability goals. First, firms should invest in advanced technologies such as IoT-based monitoring systems, AI-driven analytics, and blockchain for traceability to optimise operational efficiency and reduce greenhouse gas emissions (Wang et al., 2021; Zhang et al., 2023). These technologies enable real-time data collection and analysis, facilitating proactive risk management and compliance with decarbonisation goals (Khan et al., 2020). Second, fostering cross-functional collaboration within organisations is essential to ensure that strategic leadership involvement translates into actionable practices (Sharma et al., 2022). This can be achieved through targeted training programmes that enhance employee skills in using smart systems and foster a culture of accountability.

Third, companies should work closely with supply chain partners and regulatory bodies to create collaborative frameworks for adopting uniform quality standards and sustainability practices across the value chain (Hassoun et al., 2023; Shang et al., 2022). For instance, joint investments in shared organisational resources or co-developing sustainable practices can amplify the impact of SFSMS. This type of coordinated action is particularly crucial in emerging markets, where fragmented governance and uneven access to technological resources can limit consistent safety and sustainability outcomes. Lastly, policymakers can incentivise the adoption of SFSMS through subsidies or tax benefits for technology investments and guide to ensure regulatory alignment (Nguyen and Li, 2021).

Finally, our study responds to the recent call for further exploration of the development of the application of Industry 4.0 technologies and principles to FSMS in the context of developing countries, including Vietnam and China (Xiong et al., 2017; Nguyen and Li, 2021; Duong et al., 2024). Ensuring the safety and quality of food products is crucial to protecting public health and promoting consumer confidence, but food safety remains a significant challenge in these developing countries (Qijun and Batt, 2016). Industry 4.0 technologies can help to improve the efficiency and effectiveness of FSMS (Sinha et al., 2022). Vietnam and China are major food producers and exporters, and therefore, ensuring the safety and quality of food products and sustainability in the food industry from these countries is critical for international trade and commerce. Positioning SFSMS as a cross-functional integration mechanism allows

food firms in these markets to move beyond compliance, building more resilient and sustainable supply chains through structured coordination and digital intelligence. By adopting these strategies, food firms in emerging markets can achieve both environmental sustainability and economic efficiency, as demonstrated by the study's findings.

Limitations of the study and future research

This study provides important insights but is not without limitations. First, the reliance on cross-sectional survey data raises the possibility of response bias, as managerial self-reports may overestimate the effectiveness of practices or reflect socially desirable responses. Future research could address this limitation by incorporating diverse data sources, such as operational metrics or third-party assessments, to provide a more balanced perspective. We also encourage future longitudinal studies or experimental designs to test the effectiveness of our suggested interventions.

Second, while offering valuable context, the focus on China and Vietnam limits the generalisability of the findings. Cultural and regulatory differences likely influence the adoption and effectiveness of SFSMS practices. Cross-national comparisons could shed light on how local factors shape these systems, offering lessons for broader implementation. Comparative research across other emerging markets in Asia, Africa, or Latin America could reveal how smart integration mechanisms evolve under different institutional and infrastructure conditions.

Additionally, although this study emphasises decarbonisation, SFSMS adoption likely impacts other environmental dimensions, such as resource efficiency, waste reduction, and water conservation (Sharma et al., 2022), which remain underexplored. Future studies should consider these additional sustainability factors to provide a more comprehensive understanding of SFSMS's role. There is also a growing need to investigate how smart food safety integration supports circular economy practices, such as closed-loop recycling, waste valorisation, or reuse of by-products across supply chain partners. Whether there is a link between SFSMS and the social performance of food firms is also worth a deeper look into.

Lastly, external influences such as supply chain collaboration, adoption barriers, and consumer perceptions deserve further investigation, alongside the development of robust evaluation tools for SFSMS practices (Ansari et al., 2020). Future research could examine how smart integration mechanisms influence inter-organisational trust, data sharing behaviour, and collaborative innovation in food supply chains. These areas of inquiry would deepen the understanding of how smart food safety systems drive safer, more sustainable, and effective global food supply chains.

CONCLUSION

This study provides empirical insights into how multi-level critical success factors, spanning organisational capabilities, supply chain alignment, governance mechanisms, and external support, drive the adoption of Smart Food Safety Management Systems and support both decarbonisation and economic efficiency in food firms. Using a multi-level mediating framework, we show how SFSMS practices related to quality standards, ecosystem design, and operational robustness transform strategic enablers into tangible environmental and financial outcomes.

Our findings reinforce the value of integrating the TOE framework and EMT. Together, these frameworks explain how technological readiness, institutional alignment, and external pressures enable firms to meet emissions reduction goals while preserving competitiveness. The observed indirect effects highlight that SFSMS should not be seen merely as a compliance tool, but as a strategic resource for sustainable transformation.

For fast-growing food sectors in countries like China and Vietnam, the results point to a feasible path: by investing in IoT traceability, AI-driven risk analytics, and blockchain-enabled transparency, firms can align with evolving regulatory demands and international sustainability standards without sacrificing economic outcomes. At the same time, cross-organisational collaboration remains essential for eliminating inefficiencies and improving trust across supply chains. These insights offer concrete implications for both industry leaders and policymakers. Progress will rely not only on strengthening internal capacities but also on fostering supportive ecosystems through innovation incentives, targeted training, and

adaptive regulations. Future research should continue to explore how SFSMS impacts social sustainability and examine the role of collaboration, perception, and structural barriers in shaping broader system outcomes.

REFERENCES

Agya, B. A. (2025). Technological solutions and consumer behaviour in mitigating food waste: A global assessment across income levels. Sustainable Production and Consumption.

Almeida, C., Agostinho, F., Giannetti, B. and Huisingh, D. (2015), "Integrating cleaner production into sustainability strategies: an introduction to this special volume", *Journal of Cleaner Production,* Vol. 96, pp. 1-9.

Anand, R. and Saxena, K. (2022), "A Model for Secure Food through smart technologies-IOT", in *2022 International Mobile and Embedded Technology Conference (MECON)*, pp. 189-192.

Anthony Jr, B., Abdul Majid, M. and Romli, A. (2018), "A collaborative agent based green IS practice assessment tool for environmental sustainability attainment in enterprise data centers", *Journal of Enterprise Information Management,* Vol. 31 No. 5, pp. 771-795.

Ansari, M. A., Haider, S., & Khan, N. A. (2020). Does trade openness affects global carbon dioxide emissions: evidence from the top CO2 emitters. *Management of Environmental Quality: An International Journal*, *31*(1), 32-53.

Arvanitoyiannis, S. I., Varzakas, H. T. and Koukaliaroglou, M. v. H. (2009), *Implementing HACCP and ISO 22000 for foods of animal origin - Dairy products. In HACCP and ISO 22000 - Application to foods of animal origin*.

Babich, V. and Tang, C. S. (2012), "Managing Opportunistic Supplier Product Adulteration: Deferred Payments, Inspection, and Combined Mechanisms", *Manufacturing & Service Operations Management,* Vol. 14 No. 2, pp. 301-314.

Ball, G., Siemsen, E. and Shah, R. (2017), "Do Plant Inspections Predict Future Quality? The Role of Investigator Experience", *Manufacturing & Service Operations Management,* Vol. 19 No. 4, pp. 534-550.

Bui, L. T. C., Carvalho, M., Pham, H. T., Nguyen, T. T. B., Duong, A. T. B. and Quang, H. T. (2022), "Supply chain quality management 4.0: conceptual and maturity frameworks", *International Journal of Quality & Reliability Management,* No. ahead-of-print.

CAC (2009), "Foods derived from modern biotechnology", *Codex Alimentarius Commission, Joint FAO/WHO Food Standards Programme, Rome, Italy*.

Chardine-Baumann, E. and Botta-Genoulaz, V. (2014), "A framework for economic performance assessment of supply chain management practices", *Computers & Industrial Engineering,* Vol. 76, pp. 138-147.

Clarke, R. (2010), "Private Food Safety Standards : Their Role in Food Safety Regulation and their Impact", *33rd Session of the Codex Alimentarius Commission*, pp. 1-36.

Clegg, B., Gholami, R. and Omurgonulsen, M. (2013), "Quality management and performance: a comparison between the UK and Turkey", *Production Planning & Control,* Vol. 24 No. 12, pp. 1015-1031.

Cohen, P., West, S. G. and Aiken, L. S. (2014), *Applied multiple regression/correlation analysis for the behavioral sciences,* Psychology press.

De Boeck, E., Jacxsens, L., Mortier, A. V. and Vlerick, P. (2018), "Quantitative study of food safety climate in Belgian food processing companies in view of their organizational characteristics", *Food Control,* Vol. 88, pp. 15-27.

Despoudi, S., Papaioannou, G., Saridakis, G. and Dani, S. (2018), "Does collaboration pay in agricultural supply chain? An empirical approach", *International Journal of Production Research,* Vol. 56 No. 13, pp. 4396-4417.

DiMaggio, P. J. and Powell, W. W. (1983), "The iron cage revisited: Institutional isomorphism and collective rationality in organizational fields", *American sociological review*, pp. 147-160.

Dora, M., Kumar, A., Mangla, S. K., Pant, A. and Kamal, M. M. (2021), "Critical success factors influencing artificial intelligence adoption in food supply chains", *International Journal of Production Research,* Vol. 59, pp. 1-20.

Duong, B. A. T., Truong, H. Q., Sameiro, M., Sampaio, P., Fernandes, A. C., Vilhena, E., Bui, L. T. C. and Yadohisa, H. (2019), "Supply chain management and organizational performance: the resonant influence", *International Journal of Quality & Reliability Management,* Vol. 36 No. 7, pp. 1053-1077.

EC (2002), "Regulation (EC) No 178/2002 of the European Parliament and of the Council of 28 January 2002 laying down the general principles and requirements of food law,

establishing the European Food Safety Authority and laying down procedures in matters of food safety", *OJ L*.
Eves, A., Kim, B., Hodgkins, C., Raats, M., & Timotijevic, L. (2025). Is it food or is it waste? Determinants of decisions to throw food away. Sustainable Production and Consumption, 54, 43-51.
FDA, U. (2001), "Secondary direct food additives permitted in food for human consumption", *Federal Register*, pp. 33829-33830.
Feng, Y., Chen, J., & Luo, J. (2024). Life cycle cost analysis of power generation from underground coal gasification with carbon capture and storage (CCS) to measure the economic feasibility. *Resources Policy*, 92, 104996.
Fernandes, A. C., Sampaio, P., Sameiro, M. and Truong, H. Q. (2017), "Supply chain management and quality management integration: A conceptual model proposal", *International Journal of quality & reliability management,* Vol. 34 No. 1, pp. 53-67.
Flynn, B. B., Huo, B. and Zhao, X. (2010), "The impact of supply chain integration on performance: A contingency and configuration approach", *Journal of operations management,* Vol. 28 No. 1, pp. 58-71.
Fotopoulos, C., Kafetzopoulos, D. and Gotzamani, K. (2011), "Critical factors for effective implementation of the HACCP system: a Pareto analysis", *British Food Journal,* Vol. 113 No. 5, pp. 578-597.
Fotopoulos, C. V., Kafetzopoulos, D. P. and Psomas, E. L. (2009), "Assessing the critical factors and their impact on the effective implementation of a food safety management system", *International Journal of Quality & Reliability Management,* Vol. 26 No. 9, pp. 894-910.
Freeman, R. E. and Reed, D. L. (1983), "Stockholders and stakeholders: A new perspective on corporate governance", *California management review,* Vol. 25 No. 3, pp. 88-106.
Glenisson, L., Hallez, L., & Smits, T. (2025). "Thought for food": A systematic review of how psychological state factors affect sustainable food outcomes. Sustainable Production and Consumption.
Giannetti, B., Agostinho, F., Eras, J. C., Yang, Z. and Almeida, C. (2020), "Cleaner production for achieving the sustainable development goals", *Journal of Cleaner Production,* Vol. 271, p. 122127.
Guidani, B., Ronzoni, M., & Accorsi, R. (2024). Virtual agri-food supply chains: A holistic digital twin for sustainable food ecosystem design, control and transparency. Sustainable Production and Consumption, 46, 161-179.
Gong, Y., Jia, F., Brown, S. and Koh, L. (2018), "Supply chain learning of sustainability in multi-tier supply chains: A resource orchestration perspective", *International Journal of Operations & Production Management,* Vol. 38 No. 4, pp. 1061-1090.
Hair, J. F., Anderson, R. E., Tatham, R. L. and Black, W. C. (1995), "Multivariate data analysis withreadings", *NewYork, NY: PrenticeHall*.
Hair, J. F., Risher, J. J., Sarstedt, M. and Ringle, C. M. (2019a), "When to use and how to report the results of PLS-SEM", *European business review,* Vol. 31 No. 1, pp. 2-24.
Hair, J. F., Sarstedt, M. and Ringle, C. M. (2019b), "Rethinking some of the rethinking of partial least squares", *European Journal of Marketing*.
Haque, F. and Ntim, C. G. (2022), "Do corporate sustainability initiatives improve corporate carbon performance? Evidence from European firms", *Business Strategy and the Environment,* Vol. 31 No. 7, pp. 3318-3334.
Hassoun, A., Alhaj Abdullah, N., Aït-Kaddour, A., Ghellam, M., Beşir, A., Zannou, O., Önal, B., Aadil, R. M., Lorenzo, J. M. and Mousavi Khaneghah, A. (2022), "Food traceability 4.0 as part of the fourth industrial revolution: key enabling technologies", *Critical Reviews in Food Science and Nutrition*, pp. 1-17.
Ishaq, S., Hoang, T. G., Tanveer, U., Hoang, T.-H. and Truong, H. Q. (2024), "Transformative capabilities of MedTech organizations in driving circularity in the healthcare industry: Insights from multiple cases", *Journal of Cleaner Production*, p. 141370.
ISO (2005), "22000: 2005", *Sistema de Gestión de Inocuidad de los Alimentos: Requisitos para cualquier organización en la cadena alimentaria*.
ISO (2009), "Prerequisite programmes on food safety. Part 1: Food manufacturing, ISO 22002-1".
Jaccard, J., Turrisi, R. and Jaccard, J. (2003), *Interaction effects in multiple regression,* Sage.
Jacobs, B. W., Singhal, V. R., & Subramanian, R. (2010). An empirical investigation of environmental performance and the market value of the firm. *Journal of Operations Management,* 28(5), 430-441. https://doi. org/10.1016/j.jom.2010.01.001

Jacxsens, L., Luning, P. A., Marcelis, W. J., van Boekel, T., Rovira, J., Oses, S., Kousta, M., Drosinos, E., Jasson, V. and Uyttendaele, M. (2011), "Tools for the performance assessment and improvement of food safety management systems", *Trends in Food Science & Technology,* Vol. 22 No. SUPPL. 1, pp. S80-S89.

Kafetzopoulos, D. P. and Gotzamani, K. D. (2014), "Critical factors, food quality management and organizational performance", *Food Control,* Vol. 40 No. 1, pp. 1-11.

Kafetzopoulos, D. P., Psomas, E. L. and Kafetzopoulos, P. D. (2013), "Measuring the effectiveness of the HACCP Food Safety Management System", *Food Control,* Vol. 33 No. 2, pp. 505-513.

Khan, P. W., Byun, Y.-C. and Park, N. (2020), "IoT-blockchain enabled optimized provenance system for food industry 4.0 using advanced deep learning", *Sensors,* Vol. 20 No. 10, p. 2990.

Kirezieva, K., Jacxsens, L., Hagelaar, G. J. L. F., van Boekel, M. A. J. S., Uyttendaele, M. and Luning, P. A. (2015a), "Exploring the influence of context on food safety management: Case studies of leafy greens production in Europe", *Food Policy,* Vol. 51, pp. 158-170.

Kirezieva, K., Jacxsens, L., Uyttendaele, M., Van Boekel, M. A. J. S. and Luning, P. A. (2013a), "Assessment of Food Safety Management Systems in the global fresh produce chain", *Food Research International,* Vol. 52 No. 1, pp. 230-242.

Kirezieva, K., Luning, P. A., Jacxsens, L., Allende, A., Johannessen, G. S., Tondo, E. C., Rajkovic, A., Uyttendaele, M. and van Boekel, M. A. J. S. (2015b), "Factors affecting the status of food safety management systems in the global fresh produce chain", *Food Control,* Vol. 52, pp. 85-97.

Kirezieva, K., Nanyunja, J., Jacxsens, L., van der Vorst, J. G. A. J., Uyttendaele, M. and Luning, P. A. (2013b), "Context factors affecting design and operation of food safety management systems in the fresh produce chain", *Trends in Food Science & Technology,* Vol. 32 No. 2, pp. 108-127.

Lee, P. T.-W., Kwon, O. K. and Ruan, X. (2019), "Sustainability challenges in maritime transport and logistics industry and its way ahead", MDPI p. 1331.

Lewis, M. (2003), "Cause, consequence and control: towards a theoretical and practical model of operational risk", *Journal of Operations Management,* Vol. 21 No. 2, pp. 205-224.

Li, B., Wang, J., Nassani, A. A., Binsaeed, R. H., & Li, Z. (2023). The future of Green energy: A panel study on the role of renewable resources in the transition to a Green economy. *Energy Economics*, 127, 107026.

Liu, W., Zhang, J. and Wang, S. (2021), "Factors influencing the smart supply chain innovation performance of commodity distribution enterprises: an investigation from China", *Industrial Management & Data Systems,* Vol. 121 No. 10, pp. 2073-2099.

Liu, Z., Xie, K., Li, L. and Chen, Y. (2020), "A paradigm of safety management in industry 4.0", *Systems Research and Behavioral Science,* Vol. 37 No. 4, pp. 632-645.

Liu, A., Zhu, Q., Xu, L., Lu, Q., & Fan, Y. (2021). Sustainable supply chain management for perishable products in emerging markets: An integrated location-inventory-routing model. Transportation Research Part E: Logistics and Transportation Review, 150, 102319.

Long, Y., Feng, T., Fan, Y., & Liu, L. (2023). Adopting blockchain technology to enhance green supply chain integration: The moderating role of organizational culture. Business Strategy and the Environment, 32(6), 3326-3343.

Lu, H., Mangla, S. K., Hernandez, J. E., Elgueta, S., Zhao, G., Liu, S. and Hunter, L. (2021), "Key operational and institutional factors for improving food safety: a case study from Chile", *Production Planning & Control,* Vol. 32 No. 14, pp. 1248-1264.

Luning, P. A., Bango, L., Kussaga, J., Rovira, J. and Marcelis, W. J. (2008), "Comprehensive analysis and differentiated assessment of food safety control systems: a diagnostic instrument", *Trends in Food Science and Technology,* Vol. 19 No. 10, pp. 522-534.

Luning, P. A., Kirezieva, K., Hagelaar, G., Rovira, J., Uyttendaele, M. and Jacxsens, L. (2015), "Performance assessment of food safety management systems in animal-based food companies in view of their context characteristics: A European study", *Food Control,* Vol. 49, pp. 11-22.

Luning, P. A., Marcelis, W. J., Rovira, J., van Boekel, M. A. J. S., Uyttendaele, M. and Jacxsens, L. (2011), "A tool to diagnose context riskiness in view of food safety activities and microbiological safety output", *Trends in Food Science and Technology,* Vol. 22 No. SUPPL. 1, pp. S67-S79.

Luu, P. H., Davies, B. and Dunne, M. P. (2017), "The association between factors which affect the food safety practices of seafood distributors within the southern domestic distribution chains in Vietnam", *Food Control,* Vol. 73, pp. 332-340.
Lyng, K. A., Møller, H., Mittenzwei, K., Pettersen, I., Olsen, J. V., & Olsen, H. F. (2024). Transforming the food system with a biomass value hierarchy: Sustainability and policy insights. Sustainable Production and Consumption, 52, 602-612.
Macheka, L., Manditsera, F. A., Ngadze, R. T., Mubaiwa, J. and Nyanga, L. K. (2013), "Barriers, benefits and motivation factors for the implementation of food safety management system in the food sector in Harare Province, Zimbabwe", *Food Control,* Vol. 34 No. 1, pp. 126-131.
Macheka, L., Spelt, E., van der Vorst, J. G. A. J. and Luning, P. A. (2017), "Exploration of logistics and quality control activities in view of context characteristics and postharvest losses in fresh produce chains: A case study for tomatoes", *Food Control,* Vol. 77, pp. 221-234.
Marucheck, A., Greis, N., Mena, C. and Cai, L. (2011), "Product safety and security in the global supply chain: Issues, challenges and research opportunities", *Journal of Operations Management,* Vol. 29 No. 7-8, pp. 707-720.
Mensah, L. D. and Julien, D. (2011), "Implementation of food safety management systems in the UK", *Food Control,* Vol. 22 No. 8, pp. 1216-1225.
Mukherjee, S., Baral, M. M., Singh, R. K., Chittipaka, V., & Kamble, S. S. (2024). Achieving carbon neutrality for the improvement of the business performance: a systematic literature review and future research directions. *International Journal of Productivity and Performance Management*, *73*(8), 2385-2413.
Nanyunja, J., Jacxsens, L., Kirezieva, K., Kaaya, A. N., Uyttendaele, M. and Luning, P. A. (2016), "Shift in performance of food safety management systems in supply chains: case of green bean chain in Kenya versus hot pepper chain in Uganda", *Journal of the Science of Food and Agriculture,* Vol. 96 No. 10, pp. 3380-3392.
Ngo, V. M., Quang, H. T., Hoang, T. G. and Binh, A. D. T. (2023), "Sustainability-related supply chain risks and supply chain performances: The moderating effects of dynamic supply chain management practices", *Business Strategy and the Environment*.
Nguyen, T. T. B. and Li, D. (2021), "A systematic literature review of food safety management system implementation in global supply chains", *British Food Journal*.
Nyarugwe, S. P., Linnemann, A., Hofstede, G. J., Fogliano, V. and Luning, P. A. (2016), "Critical factors for conducting food safety culture research", *Trends in Food Science & Technology,* Vol. 56, pp. 77-87.
Nyarugwe, S. P., Linnemann, A., Nyanga, L. K., Fogliano, V. and Luning, P. A. (2018), "Food safety culture assessment using a comprehensive mixed-methods approach: A comparative study in dairy processing organisations in an emerging economy", *Food Control,* Vol. 84, pp. 186-196.
Okereke, C. (2007). An exploration of motivations, drivers and barriers to carbon management: The UK FTSE 100. *European Management Journal*, 25(6), 475-486. https://doi.org/10.1016/j.emj.2007.08.002
Pakseresht, A., Yavari, A., Kaliji, S. A., & Hakelius, K. (2023). The intersection of blockchain technology and circular economy in the agri-food sector. Sustainable Production and Consumption, 35, 260-274.
Pinkse, J. and Busch, T. (2013), "The emergence of corporate carbon norms: Strategic directions and managerial implications", *Thunderbird International Business Review,* Vol. 55 No. 6, pp. 633-645.
Qijun, J. and Batt, P. J. (2016), "Barriers and benefits to the adoption of a third party certified food safety management system in the food processing sector in Shanghai, China", *Food Control,* Vol. 62, pp. 89-96.
Quang, H. T., Sampaio, P., Carvalho, M. S., Fernandes, A. C., An, D. T. B. and Vilhenac, E. (2016), "An extensive structural model of supply chain quality management and firm performance", *International Journal of Quality & Reliability Management,* Vol. 33 No. 4, pp. 444-464.
Rahim, R. and Raman, A. A. A. (2017), "Carbon dioxide emission reduction through cleaner production strategies in a recycled plastic resins producing plant", *Journal of Cleaner Production,* Vol. 141, pp. 1067-1073.
Rouvière, E. and Caswell, J. A. (2012), "From punishment to prevention: A French case study of the introduction of co-regulation in enforcing food safety", *Food Policy,* Vol. 37 No. 3, pp. 246-254.

Shang, C., Saeidi, P. and Goh, C. F. (2022), "Evaluation of circular supply chains barriers in the era of Industry 4.0 transition using an extended decision-making approach", *Journal of Enterprise Information Management,* Vol. 35 No. 4/5, pp. 1100-1128.
Shang, M. and Luo, J. (2021), "The tapio decoupling principle and key strategies for changing factors of Chinese urban carbon footprint based on cloud computing", International Journal of Environmental Research and Public Health, Vol. 18 No. 4, p. 2101.
Sharma, R., Jabbour, C. J. C. and Lopes de Sousa Jabbour, A. B. (2021), "Sustainable manufacturing and industry 4.0: what we know and what we don't", *Journal of Enterprise Information Management,* Vol. 34 No. 1, pp. 230-266.
Sharma, R., Lopes de Sousa Jabbour, A. B., Jain, V. and Shishodia, A. (2022), "The role of digital technologies to unleash a green recovery: Pathways and pitfalls to achieve the European Green Deal", *Journal of Enterprise Information Management,* Vol. 35 No. 1, pp. 266-294.
Sinha, A., Adhikari, A. and Jha, A. K. (2022), "Innovational duality and sustainable development: finding optima amidst socio-ecological policy trade-off in post-COVID-19 era", *Journal of Enterprise Information Management*.
Song, H., Turson, R., Ganguly, A. and Yu, K. (2017), "Evaluating the effects of supply chain quality management on food firms' performance", *International Journal of Operations & Production Management,* Vol. 37 No. 10, pp. 1541-1562.
Talib, M. S. A., Bakar, A. H. A. and Too, A. C. (2019), "Conceptualizing the implementation of halal food certification: An institutional theory perspective", in *Contemporary Management and Science Issues in the Halal Industry: Proceedings of the International Malaysia Halal Conference (IMHALAL)*, pp. 385-393.
Taylor, E. and Taylor, J. (2015), "Improving food safety - replicating the Abu Dhabi success story", *Worldwide Hospitality and Tourism Themes,* Vol. 7 No. 1, pp. 90-96.
Tran, N., Bailey, C., Wilson, N. and Phillips, M. (2013), "Governance of Global Value Chains in Response to Food Safety and Certification Standards: The Case of Shrimp from Vietnam", *World Development,* Vol. 45 No. 202374, pp. 325-336.
Tran, T. H. (2018), "Critical Factors and Enablers of Food Quality And Safety Compliance Risk Management in the Vietnamese Seafood Supply Chain", *International Journal of Managing Value and Supply Chains,* Vol. 9 No. 1, pp. 01-20.
Truong, H. Q., Sameiro, M., Fernandes, A. C., Sampaio, P. and Duong, B. A. T. (2017), "Supply chain management practices and firms' operational performance", *International Journal of Quality & Reliability Management,* Vol. 34 No. 2, pp. 176-193.
Tsang, Y. P., Fan, Y., & Feng, Z. P. (2023). Bridging the gap: Building environmental, social and governance capabilities in small and medium logistics companies. Journal of Environmental Management, 338, 117758.
Tsang, Y. P., Fan, Y., Feng, Z. P., & Li, Y. (2024). Examining supply chain vulnerability via an analysis of ESG-Prioritized firms amid the Russian-Ukrainian conflict. Journal of Cleaner Production, 434, 139754.
van Asselt, E. D., Meuwissen, M. P. M., van Asseldonk, M. A. P. M., Teeuw, J. and van der Fels-Klerx, H. J. (2010), "Selection of critical factors for identifying emerging food safety risks in dynamic food production chains", *Food Control,* Vol. 21 No. 6, pp. 919-926.
Walsh, C. and Leva, M. C. (2019), "A review of human factors and food safety in Ireland", *Safety Science,* Vol. 119, pp. 399-411.
Wang, F., Harindintwali, J. D., Yuan, Z., Wang, M., Wang, F., Li, S., Yin, Z., Huang, L., Fu, Y. and Li, L. (2021), "Technologies and perspectives for achieving carbon neutrality", *The Innovation,* Vol. 2 No. 4, p. 100180.
Xiong, C., Liu, C., Chen, F. and Zheng, L. (2017), "Performance assessment of food safety management system in the pork slaughter plants of China", *Food Control,* Vol. 71, pp. 264-272.
Zhang, A., Tay, H. L., Alvi, M. F., Wang, J. X. and Gong, Y. (2023), "Carbon neutrality drivers and implications for firm performance and supply chain management", *Business Strategy and the Environment*.
Zheng, Q., Ieromonachou, P., Fan, T. and Zhou, L. (2017), "Supply chain contracting coordination for fresh products with fresh-keeping effort", *Industrial Management & Data Systems*.
Zou, H., Du, H., Wang, Y., Zhao, L., Mao, G., Zuo, J., Liu, Y., Liu, X. and Huisingh, D. (2017), "A review of the first twenty-three years of articles published in the Journal of Cleaner Production: With a focus on trends, themes, collaboration networks, low/no-fossil

carbon transformations and the future", *Journal of Cleaner Production,* Vol. 163, pp. 1-14.

SMART FOOD SAFETY SYSTEMS AS MULTI-LEVEL ENABLERS OF DECARBONISATION AND ECONOMIC EFFICIENCY IN EMERGING MARKETS

Appendix: Questionnaire and statistical results

We sincerely thank you for taking part in this research, which aims to advance smart food safety management by gaining a better understanding of current practices. All information you provide will remain strictly confidential. Please read the instructions carefully and select the options that best represent your company's profile and food safety management activities.

Part 1: Demographic characteristics

Question	Answer	%
Please choose the number of existing employees of your company	1 - 10 staff	13.6
	11- 50 staff	37.4
	51 - 250 staff	33.7
	More than 250 staff	15.2
What is your current position at the firm?	Supply chain manager	32.1
	Quality control manager	29.2
	Director/CEO	7.8
	Food safety team	28.8
	Other. (Please specify)	2.1
What kind of food is your company exporting?	Fishery	44.4
	Poultry	9.1
	Dairy	9.5
	Fresh fruit and vegetables	22.2
	Drinks and beverage	8.6
	Other. (Please specify)	6.2
How many tons does your company export per year?	Less than 500	50.2
	500 – 1000	25.1
	1000 – 2000	9.9
	2000 – 3000	4.1
	More than 3000	10.7
What certificates is your company complying? (As many as apply)	HACCP	81.5
	ISO9001	47.3
	ISO22000	19.8
	BRC	12.8
	GlobalGAP	15.2
	SQF	7.8
	IFS	7.4

Part 2: Smart Food Safety Management System's Critical Factors

(Adapt from Kafetzopoulos & Gotzamani, 2014; Kirezieva et al., 2015; Nguyen & Li, 2021; Duong et al., 2023; Nguyen, 2023; Duong et al., 2024)

To what extent do you think these factors are important to your food safety management system within the organization:

High	Above average	Average	Below average	Low
5	4	3	2	1

***Personnel administration*:** Eigenvalue = 2.616, Variance Extracted = 65.391%, Cronbach's Alpha = 0.823, Composite Reliability $_{(CFA)}$ = 0.813, Variance Extracted $_{(CFA)}$ = 0.524

Measurement items	EFA		CFA		
	Factor loadings	Item – total correlation	Standardised Regression Weights	Standard errors	R^2
What is the level of knowledge and skills among employees in terms of ensuring smart food safety practices?	0.829	0.677	0.799	0.071	0.638
How aware are employees of the relevance and importance of their activities in contributing to smart food safety management?	0.813	0.652	0.776	0.075	0.601
What types of training programs related to food safety are available to employees, and how effective are they in equipping them with the necessary skills for smart food safety management?	0.767	0.593	0.607	0.076	0.368
To what extent are employees actively involved in smart food safety management activities?	0.823	0.667	0.698	0.072	0.487

***Strategic leadership involvement*:** Eigenvalue = 2.823, Variance Extracted = 70.584%, Cronbach's Alpha = 0.859, Composite Reliability $_{(CFA)}$ = 0.863, Variance Extracted $_{(CFA)}$ = 0.613

Measurement items	EFA		CFA		
	Factor loadings	Item – total correlation	Standardised Regression Weights	Standard errors	R^2
How do managers demonstrate their commitment to implementing and maintaining smart food safety management practices?	0.884	0.773	0.867	0.045	0.751

To what extent does your company's food safety policy serve as a foundation for guiding the implementation of smart food safety practices?	0.866	0.742	0.833	0.054	0.694
How clearly are responsibilities and authorities defined within your organization for key personnel, such as food safety teams, team leaders, and direct workers, to ensure effective operation and maintenance of the smart food safety management system?	0.835	0.698	0.755	0.046	0.570
How would you describe the established food safety culture within your organization?	0.772	0.616	0.661	0.064	0.436

***Organisational resources*:** Eigenvalue = 2.206, Variance Extracted = 73.524%, Cronbach's Alpha = 0.817, Composite Reliability $_{(CFA)}$ = 0.821, Variance Extracted $_{(CFA)}$ = 0.604

Measurement items	**EFA**		**CFA**		
	Factor loadings	**Item – total correlation**	**Standardised Regression Weights**	**Standard errors**	**R^2**
Are your company's facilities and equipment adequately equipped to implement and sustain smart food safety management systems?	0.873	0.700	0.822	0.054	0.676
How does your company's financial condition support the implementation of smart food safety management systems?	0.845	0.654	0.744	0.039	0.553
How capable is your company in terms of adopting and utilizing advanced technologies for smart food safety management?	0.853	0.669	0.764	0.055	0.584

***External support*:** Eigenvalue = 2.575, Variance Extracted = 51.492%, Cronbach's Alpha = 0.758, Composite Reliability $_{(CFA)}$ = 0.752, Variance Extracted $_{(CFA)}$ = 0.511

How useful are the following stakeholders in enhancing your company's smart food safety management practices?

Measurement items	**EFA**		**CFA**		
	Factor loadings	**Item – total correlation**	**Standardised Regression Weights**	**Standard errors**	**R^2**
To what extent do financial institutions (e.g., banks, investors) provide funding, financial products, or incentives	0.660	0.468	Deleted		

that support the implementation of Smart Food Safety Management Systems in your organization?					
How would you rate the contribution of business associations (e.g., industry groups, chambers of commerce) in promoting and facilitating Smart Food Safety Management Systems in your sector?	0.810	0.638	0.793	0.072	0.629
To what extent do your supply chain partners (e.g., suppliers, distributors, logistics providers) collaborate or contribute to the development and operation of Smart Food Safety Management Systems?	0.810	0.639	0.795	0.068	0.632
How would you assess the role of government agencies and regulatory authorities in encouraging and enabling the adoption of Smart Food Safety Management Systems (e.g., through regulations, funding, training programs)?	0.684	0.488	0.521	0.052	0.311
o what degree have non-governmental organizations (NGOs) assisted your organization in the adoption, training, or monitoring of Smart Food Safety Management Systems?	0.600	0.416	Deleted		

***Supply chain alignment*:** Eigenvalue = 2.532, Variance Extracted = 63.292%, Cronbach's Alpha = 0.806, Composite Reliability $_{(CFA)}$ = 0.808, Variance Extracted $_{(CFA)}$ = 0.515

Measurement items	EFA		CFA		
	Factor loadings	**Item – total correlation**	**Standardised Regression Weights**	**Standard errors**	**R^2**
How does the level of information exchange among supply chain stakeholders influence the effectiveness of Smart Food Safety Management Systems (SFSMS)?	0.791	0.614	0.700	0.039	0.490
How do smart food safety management systems help businesses detect and respond to emerging food safety challenges?	0.849	0.697	0.822	0.039	0.676
How do structured planning and goal-setting activities contribute to the successful integration of carbon neutrality initiatives within food safety management systems?	0.775	0.593	0.676	0.044	0.457
How do continuous improvement programs in food safety management contribute to long-term economic performance and environmental sustainability?	0.765	0.581	0.661	0.045	0.437

***Food protection protocols*:** Eigenvalue = 2.637, Variance Extracted = 65.930%, Cronbach's Alpha = 0.824, Composite Reliability $_{(CFA)}$ = 0.829, Variance Extracted $_{(CFA)}$ = 0.550

Measurement items	EFA		CFA		
	Factor loadings	Item – total correlation	Standardised Regression Weights	Standard errors	R^2
How do food safety audits and inspections by regulatory agencies influence compliance and the implementation of smart food safety management practices?	0.810	0.646	0.735	0.061	0.540
How do regulatory sanctions, such as penalties, prosecutions, or recalls, impact your company's adherence to smart food safety management practices?	0.838	0.686	0.785	0.052	0.616
What role do stimuli such as awards, certification labels, or tax reductions from regulatory agencies play in encouraging your company's compliance with smart food safety management standards?	0.848	0.704	0.802	0.042	0.643
How effective are the guidelines, training, and advice provided by regulatory agencies in supporting your company's smart food safety management efforts?	0.747	0.569	0.634	0.068	0.402

Part 3: Smart Food Safety Management System practices

On a scale from 1 (poor) to 5 (good), please rate the condition of the following within your food safety management activities: *(Adapt from Duong et al., 2024)*

***Quality standard*:** Eigenvalue = 5.153, Variance Extracted = 73.620%, Cronbach's Alpha = 0.940, Composite Reliability $_{(CFA)}$ = 0.940, Variance Extracted $_{(CFA)}$ = 0.692

Measurement items	EFA		CFA		
	Factor loadings	Item – total correlation	Standardised Regression Weights	Standard errors	R^2
How effectively are hazards identified and addressed at each step, from raw materials to the finished product, using smart food safety approaches?	0.880	0.831	0.864	0.031	0.746

To what extent are critical control points established and managed by the quality team for assuring product safety in a smart food safety system?	0.867	0.814	0.846	0.037	0.715
How efficient is the establishment of critical limits at control points for the prevention, elimination, or reduction of identified hazards?	0.837	0.775	0.803	0.046	0.645
How well are monitoring procedures and systems at critical control points implemented in your smart food safety practices?	0.871	0.819	0.850	0.035	0.723
Are corrective actions efficiently implemented when monitoring indicates that a critical control point is not under control?	0.847	0.788	0.818	0.043	0.670
How thorough are your validation procedures in confirming that critical control points effectively control identified hazards and that the system operates as planned daily?	0.844	0.785	0.813	0.041	0.661
How well does your quality documentation demonstrate that the system is under control and that corrective actions are taken for deviations from critical limits?	0.859	0.804	0.829	0.037	0.687

***Ecosystem*:** Eigenvalue = 5.352, Variance Extracted = 66.895%, Cronbach's Alpha = 0.929, Composite Reliability $_{(CFA)}$ = 0.915, Variance Extracted $_{(CFA)}$ = 0.608

Measurement items	**EFA**		**CFA**		
	Factor loadings	**Item – total correlation**	**Standardised Regression Weights**	**Standard errors**	**R^2**
How does your organization ensure that the construction and layout of buildings and utilities are suitable for supporting smart food safety management?	0.767	0.696	0.676	0.049	0.457
To what extent does the layout of premises, including workspaces, employee facilities, laboratories, and storage areas, align with smart food safety principles?	0.842	0.784	Deleted		
How are air, water, energy, and other utility supplies managed to support a smart food safety management system?	0.796	0.730	0.729	0.050	0.531

How effective are your supporting services, such as waste and sewage disposal, in maintaining hygiene and compliance with smart food safety standards?	0.792	0.726	0.733	0.047	0.537
Are equipment and tools suitable for smart food safety operations, and are they easily accessible for cleaning, maintenance, and preventive maintenance?	0.840	0.784	0.823	0.041	0.678
What measures are in place to ensure the management of purchased materials aligns with smart food safety standards?	0.849	0.795	0.828	0.044	0.685
How effective are your preventive measures against physical, allergen, and microbiological cross-contamination in a smart food safety context?	0.836	0.780	0.851	0.041	0.724
How well-established and effective are your cleaning and sanitizing programs in maintaining a hygienic food-processing environment?	0.815	0.755	0.804	0.048	0.646

Robustness: Eigenvalue = 7.551, Variance Extracted = 68.648%, Cronbach's Alpha = 0.954, Composite Reliability $_{(CFA)}$ = 0.954, Variance Extracted $_{(CFA)}$ = 0.656

Measurement items	**EFA**		**CFA**		
	Factor loadings	**Item – total correlation**	**Standardised Regression Weights**	**Standard errors**	**R^2**
How effective is your traceability system in identifying materials from suppliers and tracking the distribution routes of end products?	0.850	0.813	0.836	0.034	0.698
How reliably are corrective actions initiated when critical limits are exceeded or when there is a lack of conformity with operational prerequisite programs?	0.842	0.805	0.824	0.036	0.679
How robust are your procedures for handling potentially unsafe products in a smart food safety system?	0.762	0.715	0.730	0.045	0.533
Are your control measures effective in ensuring that identified food safety hazards are managed appropriately?	0.859	0.825	0.844	0.036	0.713
How capable is your system in providing evidence that monitoring and measuring methods and equipment are adequate for ensuring smart food safety practices?	0.851	0.814	0.839	0.034	0.704
How frequently and effectively are internal audits conducted to evaluate and update the food safety	0.829	0.789	0.807	0.037	0.651

management system based on the results of verification activities?					
Are all records and documents required by the smart food safety management system properly controlled and accessible?	0.838	0.799	0.821	0.031	0.674
How efficient is internal communication in exchanging critical food safety information throughout the organization?	0.779	0.733	0.750	0.045	0.563
How effective is external communication in exchanging food safety information with suppliers, contractors, customers, regulatory authorities, and other stakeholders in the food chain?	0.808	0.765	0.786	0.037	0.618
How proactive is your organization in improving and continuously updating its smart food safety management system?	0.855	0.819	0.841	0.034	0.708
To what extent is your organization active in seeking external certification, registration, or self-declaration of conformity for its food safety management system?	0.837	0.798	0.819	0.034	0.671

Part 4: Firm's Sustainable Performance

(Adapt from Nguyen & Li, 2021; Nguyen, 2023; Duong et al., 2024)

On a scale from 1 (low) to 5 (high), please rate the following, which reflect your company's economic performance and Carbon Neutrality.

***Economic efficiency*:** Eigenvalue = 1.003, Variance Extracted = 74.754%, Cronbach's Alpha = 0.889, Composite Reliability $_{(CFA)}$ = 0.889, Variance Extracted $_{(CFA)}$ = 0.616

Measurement items	EFA		CFA		
	Factor loadings	**Item – total correlation**	**Standardised Regression Weights**	**Standard errors**	**R^2**
How would you describe the trend in your company's operational costs over the past year?	Deleted		Deleted		
To what extent has your company improved its products and processes to enhance efficiency and sustainability over the past year?	0.850	0.749	0.853	0.037	0.728
Has your company entered new markets or expanded its market presence over the past year?	0.841	0.741	0.800	0.034	0.640

What was the trend of your company's net profit margin in the previous financial year?	0.834	0.735	0.798	0.032	0.637
How would you rate your company's sales growth during the last year?	0.821	0.716	0.749	0.056	0.561
How stable was your company’s cash flow during the previous financial year?	0.822	0.721	0.717	0.045	0.514

***Decarbonisation*:** Eigenvalue = 4.436, Variance Extracted = 73.926%, Cronbach’s Alpha = 0.929, Composite Reliability $_{(CFA)}$ = 0.917, Variance Extracted $_{(CFA)}$ = 0.689

Measurement items	**EFA**		**CFA**		
	Factor loadings	**Item – total correlation**	**Standardised Regression Weights**	**Standard errors**	**R^2**
To what extent has your company reduced the use of natural resources (e.g., water, raw materials) in operations?	0.856	0.789	Deleted		
How effective has your company been in reducing carbon emissions over the past year?	0.893	0.836	0.862	0.032	0.743
Has your company implemented measures to reduce overall energy consumption?	0.839	0.767	0.809	0.038	0.655
To what degree has your company adopted renewable energy sources (e.g., solar, biofuel) for distribution activities?	0.845	0.773	0.829	0.034	0.688
How would you evaluate the effectiveness of your company's input management (e.g., sourcing sustainable raw materials)?	0.885	0.828	0.848	0.044	0.720
How would you assess your company's effectiveness in waste disposal, eco-friendly packaging, and recycling practices?	0.839	0.768	0.801	0.047	0.642

The end of the questionnaire.
Thank you for your time.
Best wishes!

BUILDING RESILIENCE FOR SUPPLY CHAINS

The Nexus Between Resilience and Sustainability in the Maritime Industry: Toward an Exploratory Theoretical Framework

Minh B. Chu[1], Vinh V. Thai[1], Canh Lam Nguyen[2]

1: School of Accounting, Information Systems and Supply Chain, RMIT University, Australia; 2: The Business School, RMIT University, Vietnam

INTRODUCTION

Sustainability and resilience are listed as two major pillars for global economic growth, as highlighted in the Future of Growth Report (World Economic Forum, 2024). Beyond environmental preservation, sustainability has become a financial imperative as firms with strong Economic, Social, Governance (ESG) practices achieve 23% higher profitability, whereas a 'sustainability lag' poses a systemic risk to business continuity and global trade stability (World Economic Forum, 2025). Failure to adapt to these ecological and economic pressures not only undermines productivity but also exacerbates social and structural deficits within the global labour market, underscoring the importance of achieving sustainability performance (SP). Simultaneously, as today's businesses face continual economic and socio-political shocks alongside unforeseen catastrophic events, it underscores the need for organisational resilience. As noted by Herberg and Torgersen (2021), such high-impact unforeseen events in a globalised world accentuate the critical need for a deeper understanding of organisational resilience competence (ORC) to enhance firm performance. The necessity of integrating these domains lies in their functional interdependence, where resilience provides the adaptive capacity to safeguard long-term sustainability commitments against immediate systemic shocks, thereby transforming these dual imperatives into a unified driver for sustained competitive advantage (SCA). In an era of global volatility, a firm's superior performance is increasingly determined by its ability to maintain sustainability commitments while effectively navigating systemic disruptions. By integrating these two domains, organisations can develop unique, non-substitutable strategic capabilities that not only safeguard operational continuity but also enhance long-term market positioning and brand reputation.

The maritime industry provides a compelling context for this nexus, as it facilitates approximately 80% of global trade by volume (UNCTAD, 2017). The industry is currently navigating what UNCTAD (2024) defines as a "global polycrisis", characterised by two simultaneous and often conflicting imperatives, including resilience and sustainability. In recent years, unprecedented disruptions such as the Red Sea crisis, the Suez Canal blockage, and the Baltimore Bridge collapse (Caramuta et al., 2025) have paralysed global maritime industry. These events have not only triggered operational chaos and billions of dollars in economic losses but also significantly increased CO2 emissions due to prolonged port congestion and vessel rerouting. Simultaneously, the maritime industry faces intense pressure to achieve net-zero greenhouse gas emissions by or around 2050, a mandate that requires a fundamental systemic transformation of its technological and operational infrastructure (IMO, 2023). Examining this nexus is essential because these two domains operate through a mutually reinforcing mechanism, where organisational resilience provides the necessary adaptive capacity to protect and maintain sustainability commitments during periods of systemic instability. This interaction ensures that strategic sustainability objectives are not compromised by short-term operational shocks, yet the specific pathways through which that nexus enhances ORC, SP, and SCA remain theoretically underexplored. Therefore, this study seeks to bridge this gap by exploring the nexus between resilience and sustainability and its effects on ORC, SP and SCA. Given the aforesaid background, this paper proposes the theoretical framework to answer two research questions, namely, (1) "How do the resilience-sustainability interaction of practices contribute to ORC? and (2) How does ORC influence firms' SP and SCA in the maritime industry?". The remainder of the paper is presented as follows. The next section presents a review of related literature. This is followed by a theoretical framework and proposition development. Then, the paper concludes with a summary, implications, and future research directions.

LITERATURE REVIEW

The nexus between sustainability and resilience

Organisational sustainability is a strategic approach grounded in the Triple Bottom Line (TBL), often operationalised through ESG frameworks to integrate environmental, social, and governance factors into corporate decision-making (Chua et al., 2023). In the maritime sector, this orientation focuses on aligning port and shipping activities with decarbonisation trajectories to drastically reduce GHG emissions in pursuit of net-zero goals by 2050 (IMO, 2023). Meanwhile, organisational resilience is defined as a dynamic, capability-based construct that enables a firm to not only 'bounce back' from unanticipated threats but also to learn proactively from adversity, and is operationalised across three phases of pre-, during-, and post-disruption, to capture the specific capabilities required for anticipation, response, absorption, and adaptation (Ali et al., 2017). In the maritime context, this resilience is particularly critical due to the industry's vulnerability to global trade shocks and geopolitical shifts, requiring organisations to move beyond internal attributes to manage relational properties within interdependent shipping and port communities and global supply chains.

Drawing on the nexus between sustainability and resilience, this research adopts a selection mechanism that identifies practices by aligning the TBL dimensions of sustainability with the capability-based requirements of resilience-risk reduction, impact mitigation, and learning and growth (DiBella et al., 2023; Negri et al., 2024). However, the literature of this nexus remains fragmented, exploratory, and lacking a shared terminology to define these activities (DiBella et al., 2023; Negri et al., 2024). To address this gap, this study introduces the term Resilience-Focused Sustainability Practices (RFSP), defined as sustainability initiatives that are systematically designed to simultaneously enhance an organisation's core resilience capabilities across the disruption cycle. By synthesising existing literature in general management and supply chains and fragmented maritime-specific literature on this nexus, these practices are operationalised through four overarching themes: Governance, Human and Social Capital, Network and Partnership, and Research, Development, and Innovation (R&D&I). Governance and Assurance institutionalise preparedness through management systems and green digital technologies to strengthen anticipation and absorption. Workforce Development focuses on marine talent cultivation and welfare to build the institutional learning capacity essential for long-term adaptation. Moving beyond the "local network" focus found in general manufacturing, the Network and Partnership theme reflects the maritime industry’s global interdependence, leveraging strategic alliances and green shipping corridors to manage systemic vulnerabilities. Finally, R&D&I institutionalises continuous knowledge creation to upgrade the dynamic competences required to cope with systemic shocks. These four themes serve as the primary categories for the specific maritime RFSP indicators presented in Table 1.

Sustainability performance (SP)

Sustainability performance is mostly defined as a company’s performance across all dimensions and drivers of corporate sustainability, with 60% of the reviewed studies using the environmental, social, and economic dimensions, which reflects how sustainability performance is defined and measured in the literature (Saulick et al., 2023). Building on the TBL framework, the sustainability performance of this study is synthesised through the activities of ports and shipping lines – two major players in the maritime industry. Port sustainability performance is identified as consistently anchored in the TBL into specific themes: environmental efforts focus on pollution, social efforts on human resource management, and economic efforts on investment. However, its efficacy remains hindered by a lack of standardisation and the absence of a common reporting framework for effective benchmarking. Regarding shipping sustainability, financial performance acts as a critical antecedent enabling environmental and social investments, yet the industry faces a significant deficit in social performance and standardised global indicators, which often obscures actual impacts and increases the risks of greenwashing. The maritime sustainability performance is summarised and synthesised in Table 2.

Organisational resilience competence (ORC)

Synthesising the perspectives of Škrinjarić (2022), this paper defines organisational competence (OC) as a holistic integration of knowledge, skills, and abilities (KSA) required to mobilise

resources and master complex demands within a specific context. Such OC is characterised as a set of enduring qualities developed over time, nurtured from a firm's unique bundle of resources and capabilities (Bhattacharyya, 2022). Consequently, while market conditions may be transitory, the OC remains more stable within the firm, serving as a reliable foundation for long-term performance (Prahalad & Hamel, 1990). However, despite its strategic importance, the literature on ORC remains fragmented and requires further exploration across diverse organisational contexts, particularly regarding its constituent elements and internal relations (Herberg & Torgersen, 2021). To address this gap, this research defines ORC as an organisational-level competence that transcends the individual KSAs of employees; it is the collective integration of human expertise and institutional repositories embedded in non-human resources, such as formal processes, operational routines, and strategic systems. This configuration enables the firm to absorb disturbances while maintaining essential functions and adapting effectively to changing conditions during crises. The specific elements of ORC for the maritime industry are derived from existing ORC frameworks (Herberg & Torgersen, 2021; Lorenzoni et al., 2025) and industry-specific capabilities (Ali et al., 2017; Duchek, 2020), then synthesised through the lens of the disruption cycle, as illustrated in Figure 1.

Sustained competitive advantage (SCA)

Competitive advantage refers to a firm's ability to outperform its rivals by leveraging distinctive, VRIO (value, rarity, imitability, and organisation)-compliant resources and idiosyncratic capabilities that enable superior market positioning and performance. Sustained competitive advantage (SCA) is defined not only by the duration of superior performance, but also by a firm's ability to implement unique value-creating strategies that competitors cannot duplicate, a position increasingly preserved in volatile markets through the dynamic capability to continuously reconfigure resources for rapid adaptation (Teece, 2018). In the field of SCA, this study builds on the definition of the study of Wang et al. (2022), which is related to a company's ability to consistently defend its position in a competitive marketplace by leveraging its distinct resources and capabilities. This implies that the fundamental distinction between competitive advantage (CA) and SCA lies in consistency, where the competitive edge must demonstrate temporal durability and stability against market volatility over the long term. While competitiveness is a subject of intense debate with varying interpretations, recent studies highlight that there is currently no consistent indicator or measurement item for SCA (Liu & Zhang, 2024). This study operationalises SCA in the maritime industry through four key dimensions, as grounded in general SCA literature and tailored to the unique characteristics of the maritime sector, as demonstrated in Table 3.

Theoretical framework

The relationship between RFSP and ORC

While the Resource-Based View (RBV) focuses on rare and inimitable resources to explain competitive advantage, it often falls short in explaining performance heterogeneity in highly regulated and standardised industries where resources are frequently accessible to all players. The Practice-Based View (PBV) effectively fills this theoretical gap by shifting the analytical lens toward the logic that even common, day-to-day activities influence firm performance. From this perspective, organisational capabilities derive from the interaction of routines, learning mechanisms, and the explicit choices firms make about which practices to adopt. By focusing on the enactment of these practices, the PBV provides a robust foundation for understanding how specific activities lead to the formation of competence, which is the set of capabilities that accumulate not only through inter-organisational human interactions but also through their embedding within institutional repositories, such as formal processes and operational routines, which persist over time.

The PBV is, therefore, uniquely suited to explain the relationship between RFSP and ORC. Sustainability efforts in the maritime industry are increasingly characterised by transparency and widespread diffusion through global regulatory mandates like those of the International Maritime Organisation (IMO). Because these "best practices" are highly standardised and accessible to all industry players, performance heterogeneity - specifically the development of resilience competence - is driven not by the practices themselves, but by the fidelity and systematic depth

with which they are executed. Drawing on the behavioural tradition, PBV suggests that firms face bounded rationality in implementing these routines; thus, ORC is not a "black box" resource but a direct consequence of the consistent and firm-specific coordination of standardised resilience-focused sustainability efforts. Narrowing the focus to the maritime industry, the transformation of practices into competence is particularly vital due to the high degree of operational interdependence and global standardisation (Notteboom et al., 2021). Since maritime enterprises must adhere to rigid international mandates, such as IMO conventions, their competitive edge stems from the firm-specific competence to systemically coordinate these standardised routines during disruptions. This logic is validated that human resource management competences in the shipping industry, demonstrating that specific practices serve as direct precursors to building core organisational capabilities. Although the broader linkage between practices and competence is conceptually noted, the theoretical relationship between RFSP and ORC remains underexplored. Therefore, this study proposes the following proposition for formal assessment:

P1: There is a relationship between RFSP and ORC in the maritime industry

The relationship between ORC, SP and SCA

Meanwhile, the Competence-Based View (CBV) of the firm is an integrative strategic management theory that explains how organisations achieve and sustain competitive advantage (Freiling, 2004). The primary and, in past research, dominating explanandum of the competence-based approach is to explain performance differences among firms, even if they belong to the same market or the same strategic group. In a general research context, it is confirmed that organisational core competence affects organisational performance and firm competitive advantage, and emphasise organisational performance as the result of an organisation's sustainability management activities. Besides, it is emphasised that resilience is the primary driver for the “continuous renewal of competitive advantages” in volatile markets. In practice, fostering ORC is essential to ensure long-term well-being and organisational sustainability (Lorenzoni et al., 2025), as ORC also encompasses sustainability in an organisation (Herberg and Torgersen, 2021). Besides, competitive advantage is achieved not only by outperforming rivals but by organisational readiness to change and adapt in the face of disruption. These broader findings confirm that sustainability and resilience are prerequisites for long-term survival. Narrowing the focus to the maritime industry, the CBV is particularly suitable due to the industry’s operation as a globally connected and highly interdependent network (Notteboom et al., 2021). In such a complex environment, a firm's success depends not merely on owning assets, but on its ability to coordinate diverse internal and external capabilities to maintain operational continuity and sustainability commitments despite systemic shocks. The core tenet of CBV-that competitive advantage stems from the systemic integration of organisational competences-is further validated that shipping management practices are transformed into core organisational competence to achieve a competitive advantage. Similarly, it is proved that dynamic capabilities, which share common features with competence, directly drive performance and competitive edge in container shipping. Consistent with the findings that sustainability implementation leads to superior performance and competitive advantage in container ports, and sustainability performance is positively linked to competitive advantage, this study posits that sustainability performance acts as a critical pathway through which competences are transformed into long-term strategic positions. Therefore, this study proposes a link between ORC and sustained competitive advantage through sustainability performance. This relationship is formalised in the following proposition, and the integrated theoretical framework is illustrated in Figure 2.

P2: There is a relationship between ORC, SP, and SCA in the maritime industry.

CONCLUSION

The value of this study is established through the exploration of the nexus between resilience and sustainability, as one of the first to examine this connection in the maritime industry, a critical yet under-researched context. In terms of novelty, while previous literature has often treated sustainability and resilience as independent silos, this paper offers a pioneering

theoretical framework about their nexus and its effect on ORC, SP and SCA through the underpinning theories, i.e. PBV and CBV.

The expected contributions of this research are twofold, encompassing both theory enrichment and managerial advancement within the maritime industry. From an academic perspective, the study will shed light on the resilience-sustainability nexus literature. Besides, it will also help to expand the application of established theories, specifically the PBV and CBV, within the unique context of the maritime industry. From a managerial perspective, the research will leverage RFSP as a strategic driver for SCA. Furthermore, it also offers practical guidelines for building ORC through the RFSP implementation, helping maritime firms manage unexpected events while also achieving sustainability performance at the same time. In the next step, the research will proceed with a sequential exploratory design to conduct an empirical validation. The qualitative phase involves conducting semi-structured interviews to explore constructs and relationships, followed by a quantitative phase to explain and confirm the relationships. Although developed within the maritime context, the proposed framework offers broader theoretical implications applicable to various complex supply chain networks, reinforcing the significance of this research beyond its initial scope of investigation.

REFERENCES

Ali, A., Mahfouz, A., & Arisha, A. (2017). Analysing supply chain resilience: integrating the constructs in a concept mapping framework via a systematic literature review. Supply Chain Management: An International Journal, 22(1), 16-39.

Bhattacharyya, S. S. (2022). MANAGERIAL PERSPECTIVES TOWARDS ELUCIDATING ORGANIZATIONAL RESOURCES, CAPABILITIES AND COMPETENCIES. Journal of Services Research, 22(1).

Caramuta, C., Grosso, A., & Longo, G. (2025). Mitigating uncertainty due to the Red Sea Crisis: A scenario development application to the Port of Trieste, Italy. Case Studies on Transport Policy, 101703.

Chua, J. Y., Wang, X., & Yuen, K. F. (2023). Sustainable shipping management: Definitions, critical success factors, drivers and performance. Transport Policy, 141, 72-82.

DiBella, J., Forrest, N., Burch, S., Rao-Williams, J., Ninomiya, S. M., Hermelingmeier, V., & Chisholm, K. (2023). Exploring the potential of SMEs to build individual, organizational, and community resilience through sustainability-oriented business practices. Business strategy and the Environment, 32(1), 721-735.

Duchek, S. (2020). Organizational resilience: a capability-based conceptualization. Business research, 13(1), 215-246.

Freiling, J. (2004). A Competence-based Theory of the Firm. management revue, 27-52.

Herberg, M., & Torgersen, G.-E. (2021). Resilience competence face framework for the unforeseen: Relations, emotions and cognition. A qualitative study. Frontiers in psychology, 12, 669904.

IMO, I. M. O. (2023). Revised GHG reduction strategy for global shipping adopted.

Liu, X., & Zhang, D. (2024). Research on impact mechanism of organizational resilience on sustainable competitive advantage of enterprises. Sustainability, 16(16), 6954.

Lorenzoni, N., Simões de Almeida, R., Wimmer, D., Simbrig, I., Moscon, V., Carnelli, F., Sulkowski, N., Malaka, E. P., Schober, P., & Michel, K. (2025). Development of a Pandemic Resilience Competence Model for Healthcare Professionals—Individual and Organisational Aspects. International Journal of Environmental Research and Public Health, 22(5), 712.

Negri, M., Cagno, E., & Colicchia, C. (2024). Building sustainable and resilient supply chains: a framework and empirical evidence on trade-offs and synergies in implementation of practices. Production Planning & Control, 35(1), 90-113.

Notteboom, T., Pallis, T., & Rodrigue, J.-P. (2021). Disruptions and resilience in global container shipping and ports: the COVID-19 pandemic versus the 2008–2009 financial crisis. Maritime Economics & Logistics, 23(2), 179.

Prahalad, C. K., & Hamel, G. (1990). Core competency concept. Harvard Business Review, 64(3), 70-92.

Saulick, P., Bokhoree, C., & Bekaroo, G. (2023). Business sustainability performance: A systematic literature review on assessment approaches, tools and techniques. Journal of cleaner production, 408, 136837.

Škrinjarić, B. (2022). Competence-based approaches in organizational and individual context. Humanities and social sciences communications, 9(1), 1-12.

Teece, D. J. (2018). Business models and dynamic capabilities. Long range planning, 51(1), 40-49.

UNCTAD. (2017). Review of Maritime transport.

UNCTAD. (2024). Maritime transport in times of polycrisis. https://unctad.org/system/files/official-document/cimem7d32_en_0.pdf

Wang, J., Chen, R., & Zhang, S. (2022). The mediating and moderating effect of organizational resilience on competitive advantage: evidence from Chinese companies. Sustainability, 14(21), 13797.

World Economic Forum. (2024). The Future of Growth Report 2024. https://www3.weforum.org/docs/WEF_Future_of_Growth_Report_2024.pdf

World Economic Forum. (2025). Global Risks Report 2025. https://www.weforum.org/publications/global-risks-report-2025/

Appendix

Table 1. Synthesised RFSP in the maritime industry

Theme	Resilience-focused sustainability practices	Sustainability practices			Supporting literature	Resilience capabilities		
		Economy	Environment	Society		Risk reduction	Impact mitigation	Learning & Growth
Governance	Strategic direction							
	Commit to recognised sustainability frameworks and certifications	√	√	√	(Cunha et al., 2025)	√	√	
	Prioritise and approve long-term investments in green operational technologies	√	√		(Cholidis et al., 2025, Valioniene et al., 2024)	√	√	√
	Operational focus on governance							
	Design climate-resilient infrastructure		√		(Cunha et al., 2025, EcoPortsinSights, 2023)	√	√	
	Plan response measures to major incidents	√			(Zhu et al., 2025, Valioniene et al., 2024)	√		
	Mandate wastewater and effluent treatment before discharge		√		(Cunha et al., 2025)	√	√	
Human and social capital	Develop employees with a clear process of "cultivation, utilisation, retention, and recruitment"			√	(Wei et al., 2025, Liu and Yu, 2025)			√
	Ensure employees' welfare and safety			√	(Zhu et al., 2025)		√	
	Expand talent reserves (create jobs in the local community, attract high-quality talent, etc.)			√	(Zhu et al., 2025, Wei et al., 2025)	√		
	Construct public facilities			√	(Zhu et al., 2025)			√
Network and partnership	Build coalitions and alliances with key stakeholders (authorities, ports, shipping lines, LSP, etc.)		√	√	Proposed by the authors	√		√
R&D and innovation	Augment research funding			√	(Wei et al., 2025)	√		√
	Collaborate with academic institutions and universities	√		√	(Wei et al., 2025)	√		√

Table 2. Synthesised Maritime Sustainability Performance dimensions

Dimension	Scope	Port sector sustainability performance	Shipping lines sustainability performance	Synthesised Maritime sustainability performance
Economic	***Internal***	Safe and effective cargo handling rate	Operational risk control results	Operational productivity
		- Value generated productivity - Operating costs/revenue	-Net income after tax -Gross profit -Net operating profit margin	Financial return
	External	Port operator economic benefits	Payments to governments (taxes, duties, fees)	Value distribution to external stakeholders
Environmental	***Internal***	Effluent disposal, air and water quality maintenance, noise control and other related factors.	Resource efficiency (land, water, energy)	Resource intensity
		CO_2 emission per capita	Greenhouse gas per capita	Emission intensity
	External	- Ecological protection measures -Landscape improvement	-Biodiversity impact level -Climate change impact level	Ecosystem / biodiversity-related environmental impact
Social	***Internal***	- Employee health, safety, and professional development -Port traffic accident prevention -Port area safety and orders -Flood avoidance in the land-side operation area	- Human capital development -Health and safety of employees	Workforce wellbeing and development
	External	- Provision of employment opportunities - Neighbouring community requirement recognition -Historic relics protection - Mitigation of light influence on neighbouring residents - Minority groups' hiring rate	Human rights protection	Community engagement

Table 3. Dimensions of sustained competitive advantage

Dimensions	Operational definition	Supporting literature
Innovative offering	The application of ambidextrous innovation capabilities to provide unique services that adapt to rapidly changing maritime environments.	(Ed-Dafali et al., 2023, Clauss et al., 2021, Venkatraman and Ramanujam, 1986, Hooley et al., 2001, Bag et al., 2019)
Service quality	The consistent delivery of superior maritime logistics services that serve as a fundamental instrument for securing market leadership.	(Ahmad and Jais 2023, Xu et al., 2020, Wang et al., 2022b)
Network connectivity	The firm's capacity to function as an interdependent node and leverage network effects to create barriers to entry within global supply chains.	Vo et al. (2025)
Corporate Images	The strategic intangible asset built through reputation and CSR initiatives, serving as a non-imitable resource for long-term edge.	(Roberts and Dowling, 2002, Islam et al., 2023, Zhang et al., 2023, Xu et al., 2020)

Figure 1. Dimensions of organisational resilience competence in the maritime industry

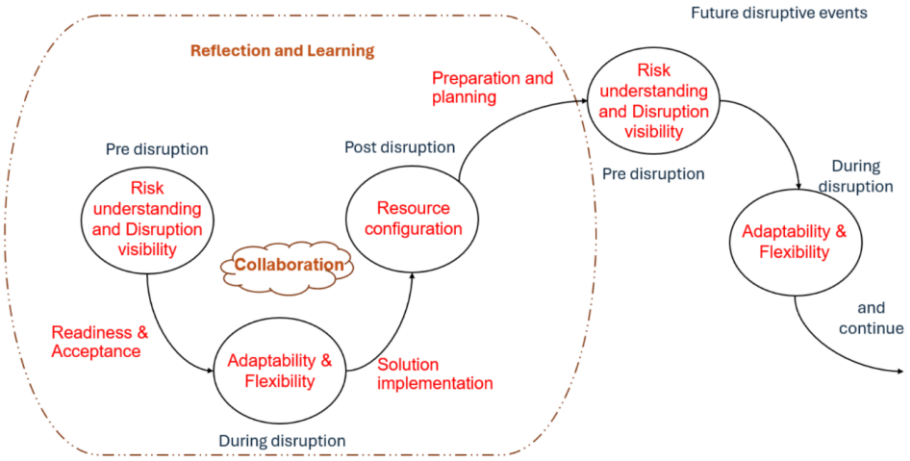
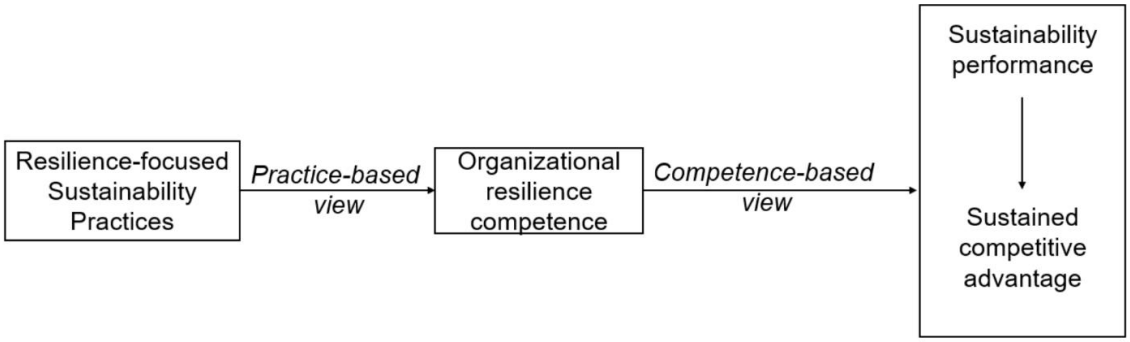


Figure 2. Proposed theoretical framework



Do Sustained Resilience Capabilities Lead to Sustained Competitive Advantage? - The Role of Resilience-Focused Strategic Intent and Sustained Supply Chain Performance

Doan Trinh Nguyen[1,2], Vinh Van Thai[1], Ton Hien Duc Truong[1], Priyabrata Chowdhury[1]

1: RMIT University, Australia; 2: College of Engineering, Can Tho University, Vietnam

INTRODUCTION

Research on organisational resilience has grown significantly in recent years, drawing considerable attention from researchers and industry professionals. As supply chain (SC) navigate an increasingly turbulent environment, creative strategies and new perspectives are essential for designing, developing, and operating supply chain networks that can endure various disturbances. The unexpected and widespread Coronavirus pandemic outbreak, for example, made it impossible for businesses to anticipate the massive scope of its impacts and cascading effects. Operational disruptions have affected nearly all global supply chains, substantially weakening their stability (Zhao et al., 2023). Moreover, unadaptable, unagile, and inconsistently dynamic organisations will not succeed in rapidly changing, unpredictable, and constantly evolving market conditions. Taking Brexit in 2020 and the Russia-Ukraine war as examples, while the wake of Brexit has caused major shipment postponements and disrupted just-in-time automotive producers, the Russia-Ukraine conflict has severely impacted global food SC, increasing costs and raising the risk of shortages (Li et al., 2024b). In contrast, when firms develop strong resilience capabilities, enabling them helps not only to recover from crises but also to evolve into resilient firms that sustain their competitive advantage amid disruptions. For instance, resilience has proven to be a key factor in helping manufacturers in Palestine (Badwan, 2024) or in China (Wang et al., 2022) achieve and sustain competitive advantages. Consequently, businesses must enhance their resilience to navigate crises and ensure sustainable growth (Xie et al., 2024) and sustained competitive advantage (SCA) (Wang et al., 2022).

From one perspective, prior research indicates a strong relationship between competitive advantage and firm performance, suggesting that improvements in performance can contribute to the enhancement of competitive advantage. For instance, in the hotel industry, enhanced environmental efficiency has been shown to reduce costs and improve corporate image, thereby creating a competitive edge in developing countries such as Thailand (Singjai et al., 2018). Similarly, sustainability-driven win–win strategies enable firms to promote societal development while adopting sustainable practices that enhance long-term competitiveness (Karman & Savanevičienė, 2021). Extending this perspective, firms with stronger resilience capabilities are better positioned to respond effectively to disruptions, leading to improved overall organisational performance, enhanced satisfactory performance levels (Huang et al., 2023), and strengthened competitive advantage (Chen, 2018). For example, in agricultural settings, supply chain resilience enhances supply chain performance, as resilient supply chains demonstrate a superior ability to maintain operational continuity, recover swiftly from disruptions, and sustain performance during adverse conditions, thereby supporting sustainable business operations and improved customer satisfaction (Yin et al., 2025). However, there is a lack of empirical research that particularly investigates resilience performance and supply chain performance resulting from the application of sustained resilience capabilities. In addition, the roles of resilience performance and sustained supply chain performance in driving sustained competitive advantage remain underexplored.

From another perspective, in the face of highly unpredictable and uncertain situations, strategic intent (SI) helps shape the organisation's future direction, developed by the CEO and top managers and communicated to its members (O'Shannassy, 2016). Firms such as Oweed, Google, and Amazon succeed by maintaining strategic intentions to allocate resources effectively and build essential capabilities, whereas General Electric and Procter & Gamble have experienced stagnant development despite their stability (Danook & Al. Obaidy, 2024). It emphasises

balancing exploration and exploitation activities to enable organisational ambidexterity and strengthen competitive advantage. Exploration focuses on uncovering new opportunities to boost performance, while exploitation aims to refine existing competencies and expand current capabilities and assets (Seepana et al., 2021). Thus, SI is a dynamic capability that underpins the identification of opportunities, the guidance of decision-making and resource allocation, and the organisation of alliances to achieve various performance outcomes (Seepana et al., 2021). Academic literature has not yet explored or validated the relationships and interactions among sustained resilience capabilities (SRC), resilience performance (RP), sustained supply chain performance (SSCP), and SCA. Building on the above background, this paper proposes a conceptual framework to address two research questions:

RQ1: How does SRC influence SCA in the presence of RP and SSCP?

RQ2: What is the role of resilience-focused SI between SRC and RP, SSCP, and SCA?

LITERATURE REVIEW

Antecedents of sustained competitive advantage

In an ever-evolving business landscape marked by uncertainty and rapid change, organisations face increasing challenges stemming from a range of crises, which have contributed to the widespread use of the term VUCA, volatility, uncertainty, complexity, and ambiguity, in contemporary business discourse (Minciu et al., 2024). Consequently, to achieve long-term growth and withstand disruptive events, organisations must strengthen their resilience capabilities, as understanding a system's resilience is essential for evaluating its response and overall performance (Xie et al., 2024). In line with this perspective, the present research conceptualises the antecedents of sustained competitive advantage as comprising SRC, RP, and SSCP. Organisational resilience has been characterized from multiple perspectives, including as a capability, outcome, procedure, strategy, performance, or a blend of these elements (Ma & Zhang, 2022). Within this framework, organisations emphasise that successfully adapting to changes, developing resilience strategies, and effectively implementing them are far more likely to enhance their chances of survival, underscoring the significance of resilience and its effect on outcomes. Duchek's (2020) definition of resilience capability is highly encompassing, encompassing three phases of the resilience process that address not only historical and current challenges but also future issues. Based on previous literature reviews about resilience capabilities (Duchek, 2020) and SCA (Wang et al., 2022), this study focuses on firm's SRC, which refers to the ability of the firm to sustain the necessary levels of anticipation, coping, and adaptation consistently to manage disruption risks and restore systems to their original state after interruptions in the long term. Three components of SRC are identified and classified into three stages: pre-, during-, and post-disruption (Duchek, 2020). The dimensions of SRC are anticipation, coping, and adaptation. The first dimension is anticipation, which emphasises a preventive, proactive approach to preparing for potential disruptions. The second dimension is coping, which refers to a business's ability to manage unexpected critical events effectively. The third dimension involves adaptation, whereby organisations adjust to challenging circumstances and leverage change to their advantage.

While anticipation, coping, and adaptation constitute the core determinants of a firm's SRC, the development of these resilience capabilities is expected to enhance resilience performance, which assesses how effectively an organisation responds to and recovers from disruptions. As noted by Lotfi & Saghiri (2018), a resilient system can be restored at lower cost and in less time, thereby reducing the severity of loss through its capacity to absorb crises and its inherent ability to return to a stable state. Han (2020) and Behzadi et al. (2020) identify recovery time and lost performance as critical indicators for assessing the overall outcomes of a firm's resilience. Recovery time is the duration needed for a facility to resume its regular operational stage in post-disruption (Behzadi et al., 2020); whereas lost performance during recovery refers to the profit loss from the onset of the disruption until the end of recovery (Behzadi et al., 2020). In addition, RP can be assessed through other metrics that enable forecasting of future performance over extended periods, such as the firm's or its supply chain's flexibility, responsiveness, quality, productivity, and accessibility. Following the literature review, six indicators are used to evaluate actual resilience performance (Behzadi et al., 2020; Singh, 2025), namely: the quality of

products and services, flexibility in adapting to market changes, productivity, availability and accessibility of products, recovery time, and lost profit.

Beyond RP at the organisational level, in highly volatile and uncertain environments, firms must maintain resilience capabilities to recover from crises and proactively adapt to future challenges, rapidly interpret changing circumstances to maintain supply chain performance (SCP) (Qader et al., 2022). SCP has emerged as a critical performance measure for organizations seeking to achieve and sustain competitive advantage (Qader et al., 2022). It is defined by the efficiency and effectiveness with which supply chain tasks are executed (Rana et al., 2025). Based on the definitions of SCP (Rana et al., 2025) and SCA (Wang et al., 2022), SSCP assesses the supply chain's effectiveness and efficiency in consistently executing tasks. The study by Chang et al. (2019) used SCP with a unidimensional construct: resource performance (return on investment, total cost of manufacturing, resources used, distribution, and inventory holding); output (profit, sales, on-time deliveries, stockout, customer response time, customer complaints, lead-time, and shipping errors); and flexibility (range flexibility and response flexibility). However, one of the primary challenges experienced by modern enterprises is assessing actual performance against required performance, which often results in uncertain and fragile supply chains (Türkeş et al., 2024). To address these difficulties and improve the outcomes, this study focuses on SSCP as a single factor, including customer service levels, lead times, operating costs, on-time delivery, and precisely ordered quantities (Li et al., 2024a).

Sustained competitive advantage

In the field of SCA, as noted by Wang et al. (2022), a firm is considered to possess an SCA when it employs differentiated resources that no current or potential competitors employ and can replicate. Leveraging this perspective, this study builds on the definition proposed by Wang et al. (2022), which focuses on a firm's ability to consistently defend its position in a competitive marketplace by leveraging its distinct resources and capabilities. More specifically, competitive advantage (CA) refers to an advantage that outperforms rivals by delivering superior value to customers, either through lower prices or by offering greater benefits and services that justify a higher price (YahiaMarzouk & Jin, 2022). Furthermore, higher levels of sustainability performance are commonly associated with competitive advantages, including sustained profits, stable financial returns, and long-term business success (Ooi & Memon, 2025). In addition, a strong corporate reputation is a valuable strategic asset, enabling organisations to establish lasting competitive advantages and enhance their credibility within service industries (Islam et al., 2023). Therefore, based on the literature review by YahiaMarzouk & Jin (2022) and Chang (2011), SCA is measured by six dimensions: price, quality of our products and services, R&D capability, managerial capability, corporate image, profitability, and the difficulty for competitors to match.

Resilience-focused Strategic Intent (SI)

Strategic intent defines an organisation’s direction and ambitions, largely conveyed through mission, vision, and objective statements. In addition, it embodies an obvious declaration of the firm’s aspirations and desired position as a market leader (Hamel & Prahalad, 1990). By providing strategic focus, this orientation promotes the development of foreign market knowledge, thereby enhancing international performance (Ciszewska-Mlinaric, 2016). Furthermore, it enables firms to build competitive advantage and sustain operations during periods of crisis (Chaudhuri et al., 2023). Building on the prior literature review, strategic intent begins with the collective vision and mission shared by top management, which enables the setting of ambitious goals. These goals provide clarity of purpose and direction for the future and also provide a compelling rationale, fostering sustained focus on their work over the long term, particularly in uncertain business environments (O’Shannassy, 2016). Furthermore, strategic intent entails establishing clear, specific objectives that drive the pursuit of collaborative research, aiming to acquire the knowledge, resources, and capabilities needed to advance innovation generations and maximize overall performance (Seepana et al., 2021). Also, a well-defined strategic direction can be instrumental in guiding business activities arising from rapid internationalisation toward effective integration (Demir et al., 2021). Based on the literature review, resilience-focused strategic

intent reflects an organization's prioritisation of resilience as a core strategic objective, embedded in its mission, vision, and overall strategic orientation, thereby guiding the development of resilience capabilities that enable rapid recovery from disruptions.

THEORETICAL UNDERPINNING

Dynamic capability theory (DCT) has developed as an expansion of the RBV, addressing its shortcomings in explaining firm success in fast-changing and unpredictable business environments. The DCT framework was applied to explain how diverse organisational assets and resources, both tangible and intangible, such as people, technology, organisation, finance, and reputation, are utilised to build resilience and improve outcomes and CA (Teece, 2007; YahiaMarzouk & Jin, 2022). In the same vein, according to Teece et al. (1997), dynamic capability (DC) refers to the ability to mix, construct, and restructure inner and outer capabilities to deal with the turbulence and uncertainty of rapidly changing environments. Furthermore, it provides a framework for identifying how firms enhance performance and retain CA. As previously discussed, a firm's CA comprises two interrelated aspects: the resource, such as marketplace position or resources, and the outcome, reflected in performance indicators such as profitability (Pu et al., 2023). While prior studies have conceptualised CA as an organisation's capability to achieve performance, the present study considers CA as the outcome of performance compared to competitors. Similarly, capacity building demands significant intellectual, physical, and financial investments, but these efforts can become futile if the capacity cannot withstand rapid changes in competitive forces and sustain its advantage over time.

Additionally, a study by Teece (2007) further identifies three vital sub-capabilities - sensing, seizing, and reconfiguring - highlighting that firms with strong dynamic capabilities exhibit a highly entrepreneurial approach. Sensing capability enables organisations to forecast, monitor environmental changes, identify emerging opportunities, and prepare for unexpected events. Seizing capability enables firms to allocate resources effectively in response to disruptions and to capitalise on identified opportunities. Reconfiguration capability refers to the management and reorganisation processes and structures to ensure continued adaptive viability (Abdullahi et al., 2025). Despite these advances, DCT development has primarily focused on distinguishing between dynamic and static capabilities (Bari et al., 2024), without explicitly incorporating performance-related constructs such as RP or SSCP. Although dynamic capabilities were recognised as drivers of CA, the critical roles of RP and SSCP in translating capabilities into sustained outcomes were largely overlooked. Integrating these performance factors into the framework alongside SRC allows a more comprehensive framework for explaining how firms achieve SCA. Building on the preceding discussion, this study proposes a conceptual framework to examine how SRC, RP, and SSCP collectively contribute to enhancing SCA within the DCT.

CONCEPTUAL FRAMEWORK AND RESEARCH PROPOSITION

Organisational resilience enables businesses to adapt and flourish in competitive environments (Wang et al., 2022). Building SCR requires proactive capabilities to anticipate, cope with, adapt to, and mitigate risks before they cause damage, with a critical focus on responding fast to competition during crises and turning disruptions into opportunities for sustaining competitive advantage compared to firms without resilience (Pu et al., 2023). For example, firms with robust situational awareness and adaptive capabilities are better prepared to handle crises and market changes, supporting them to outpace competitors in adapting to challenges (Pu et al., 2023). Sustaining a competitive advantage in dynamic environments is challenging, but organisations with dynamic capabilities, such as resilience, can achieve this by continually reconfiguring their resources. Moreover, continuous changes in the business environment, driven by disruptive forces, have made it increasingly difficult for many companies to maintain their competitive edge. For instance, resilience has proven to be a key factor in helping manufacturers across industries like leather and footwear, chemical, metal, biomedical, construction, textile, food, plastic, paper, computers, and software, and others, achieve and gain sustained competitive advantages (Wang et al., 2022; Badwan, 2024). In addition, the research of Ooi & Memon (2025) observed that the ability of SMEs in Malaysia to adapt to unexpected disruptions and restore

their operations quickly played a crucial role in enhancing a sustainable advantage over competitors.

In addition, building SRC can enhance resilience performance during disruptive events. To further enhance SRC, assessing its effectiveness and comparing it with historical performance using well-defined performance metrics is essential. For example, contingency planning and flexible supply chain capabilities enhance rapid response and recovery to normal operations and minimize the impact of interruptions, including recovery time and costs (Han, 2020). In particular, disruptions can affect various parts of a supply chain, prompting reactive strategies that adjust operational parameters to maintain service levels. In addition, an organisation's ability to recover quickly from disturbances while maintaining operational efficiency is greatly influenced by supply chain resilience, which has been shown to enhance timely product delivery, meet customer needs, and boost overall supply chain performance (Huang et al., 2023). To be more precise, a stronger response capability allows resource allocation in uncertain environments, continuous enhancement of the quality of product/service, and effective adaptation to market needs, thereby boosting SCP (Zhao et al., 2023). The above arguments lead to the following proposition:

Proposition 1: SRC contributes to strengthening SCA, RP, and SSCP by enabling organizations to effectively sense, seize, and reconfigure their strategic resources and capabilities during volatile events.

According to Seepana et al. (2021), a crucial aspect of strategic intent drives a firm to invest beyond its boundaries, enabling it to achieve its ambitions, strengthen capabilities, and maximize outcomes. The moderating effect of SI is investigated in several studies, such as the linkage concerning knowledge of foreign markets and the international performance of SMEs (Ciszewska-Mlinaric, 2016); entrepreneurial orientation, and operational and innovation performance (Seepana et al., 2021); dynamic capability of a family business and its sustainability during crises (Chaudhuri et al., 2023). For instance, strategic intent motivates firms to internationalize by aligning business activities with corporate-level goals, fostering integration, enhancing performance, and driving firms toward ambitious internationalization objectives (Demir et al., 2021). The study by Chaudhuri et al. (2023) also suggests that to achieve greater sustainability, even during crises, firms must leverage dynamic capabilities through well-articulated strategic planning and clear intent, maximizing their potential benefits. Based on the above, this study proposes the following proposition:

Proposition 2. The positive association of SRC with SCA, RP, and SSCP is stronger among firms with Resilience-focused SI.

Competitive advantage is central to a firm's performance in a competitive marketplace and is closely linked to achieving sustainable competitive advantage in strategic management. Firms must focus on enhancing quality and innovation in a changing environment to gain a competitive edge. For example, process innovation provides significant benefits, such as cost reduction, improved quality, faster delivery, and greater operational flexibility, which align with specific strategic capabilities. Similarly, supply chain agility describes the ability to achieve a competitive edge by efficiently managing supply chain operations to react to unpredictable market conditions (Chen, 2018). A study by Chen (2018) examines SC agility, defined as SCP, which enhances adaptability and flexibility, enabling rapid responses to market changes and customer demands, thereby driving competitive advantage. Also, SC agility helps organisations reduce production costs, boost customer satisfaction, and eliminate non-value-adding activities, ensuring a competitive edge in the market (Chen, 2018). Therefore, the subsequent proposition is proposed:

Proposition 3: RP and SSCP mediate the relation between SRC and SCA.

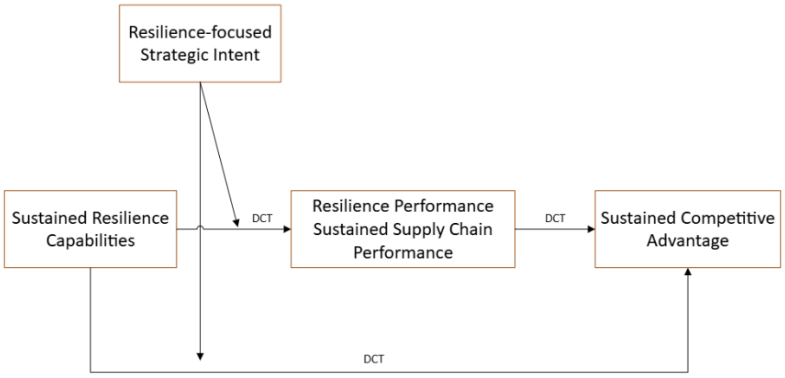


Figure 1. Conceptual framework of the research

CONCLUSION AND FUTURE RESEARCH

This paper presents a research framework outlining the relationship between SRC, SSCP, RP, resilience-focused SI, and SCA. These connections have received limited attention in prior research, leaving significant gaps in the literature. In response to limitations in the existing literature, this article draws on DCT to propose a framework illustrating how SRC improves outcomes and strengthens SCA. This conceptual framework offers important implications for both academia and practice. From an academic perspective, this research bridges a critical gap in the literature by investigating the mechanism underlying SCA enhancement through SRC construction, thereby providing a more comprehensive view of how SRC improves performance and strengthens SCA. Moreover, this research highlights the crucial role of resilience-focused SI in enhancing resilience and SC performance, including navigating and thriving in uncertain and volatile environments. In addition, the conceptual framework developed in this study has the potential to be applied across diverse contexts and industries, thereby creating opportunities for further investigation. These capabilities can serve as valuable tools for addressing challenges, exploiting opportunities, and enhancing competitiveness across diverse industrial settings. Moreover, further studies could investigate similar linkages from the perspectives of small and medium-sized enterprises (SMEs) and large firms for comparative purposes.

Practically, by clarifying the relationships among these factors, the research enables firms to develop targeted capabilities to strengthen their SCA, as developing SRC helps stabilise the entire supply chain, allowing all stakeholders to achieve higher performance and enhanced competitiveness. Next, managers should recognise that the effective use of sustained resilience capabilities depends on a clearly defined strategic intent that aligns the organisation's objectives and strategies. Without a clearly articulated strategic intent to guide organisational goals, firms are unlikely to generate favourable outcomes. Furthermore, this research contributes to the practical implications by providing deeper insights into the resilience-focused SI that firms exhibit through SRC. It underscores the advantages of firms adopting a performance-focused approach and illustrates how strategic intent can enhance performance under conditions of uncertainty. Furthermore, empirical testing of these relationships across different national contexts would help enhance the generalisability of the findings. Given that different types of enterprises or countries possess distinct resource endowments, future research could also explore which specific types and dimensions of SRC exert the most significant influence on organisational outcomes. Such insights would provide valuable guidance for practitioners in designing and implementing targeted policies to leverage particular resilience capabilities effectively.

REFERENCES

Abdullahi, U., Martadha Mohamed, A., & Senasi, V. (2025). Digital orientation and organizational resilience: the contingent effect of dynamic capabilities. Sustainable and resilient infrastructure, 10(4), 295-312.

Badwan, N. (2024). Role of supply chain partnership, cross-functional integration, responsiveness and resilience on competitive advantages: empirical evidence from Palestine. TQM journal.

Bari, N., Chimhundu, R., & Chan, K. C. (2024). Interrelation between Sustainable Dynamic Capabilities, Corporate Sustainability, and Sustained Competitive Advantage. Sustainability, 16(7), 2864.
Behzadi, G., O'Sullivan, M. J., & Olsen, T. L. (2020). On metrics for supply chain resilience. European journal of operational research, 287(1), 145-158.
Chang, C.-H. (2011). The influence of corporate environmental ethics on competitive advantage: The mediation role of green innovation. Journal of business ethics, 104(3), 361-370.
Chang, H. H., Wong, K. H., & Chiu, W. S. (2019). The effects of business systems leveraging on supply chain performance: Process innovation and uncertainty as moderators. Information & Management, 56(6), 103140.
Chaudhuri, R., Chatterjee, S., Kraus, S., & Vrontis, D. (2023). Assessing the AI-CRM technology capability for sustaining family businesses in times of crisis: the moderating role of strategic intent. Journal of Family Business Management, 13(1), 46-67.
Chen, C.-J. (2018). Developing a model for supply chain agility and innovativeness to enhance firms' competitive advantage. Management Decision, 57(7), 1511-1534.
Ciszewska-Mlinaric, M. (2016). Foreign market knowledge and SME's international performance: Moderating effects of strategic intent and time-to-internationalization. Entrepreneurial business and economics review, 4(4), 51-66.
Danook, A. A., & Al. obaidy, O.-F. H. (2024). Evaluating the dimensions of strategic intent according to the Hamel and Prahalad model/a case study in Oil Projects SCOP Company. Nankai Business Review International, 15(1), 67-87.
Demir, R., Campopiano, G., Kruckenhauser, C., & Bauer, F. (2021). Strategic agility, internationalisation speed and international success—The role of coordination mechanisms and growth modes. Journal of International Management, 27(1), 100838.
Duchek, S. (2020). Organizational resilience: a capability-based conceptualization. Business research, 13(1), 215-246.
Hamel, G., & Prahalad, C. (1990). Strategic intent. Mckinsey quarterly(1), 36-61.
Han, Y., Chong, W. K., & Li, D. . (2020). A systematic literature review of the capabilities and performance metrics of supply chain resilience. International Journal of Production Research, 58(15), 4541-4568.
Huang, Y.-F., Phan, V.-D.-V., & Do, M.-H. (2023). The Impacts of Supply Chain Capabilities, Visibility, Resilience on Supply Chain Performance and Firm Performance. Administrative Sciences, 13(10), 225.
Islam, T., Khan, M., Ghaffar, A., Wang, Y., Mubarik, M. S., Ali, I. H., Shahid, Z. A., Rehmani, M., & Sharma, A. (2023). Does CSR influence sustained competitive advantage and behavioral outcomes? An empirical study in the hospitality sector. Journal of Global Scholars of Marketing Science, 33(1), 107-132.
Karman, A., & Savanevičienė, A. (2021). Enhancing dynamic capabilities to improve sustainable competitiveness: insights from research on organisations of the Baltic region. Baltic journal of management, 16(2), 318-341.
Li, L., Liu, Y., Jin, Y., Cheng, T. E., & Zhang, Q. (2024a). Generative AI-enabled supply chain management: The critical role of coordination and dynamism. International Journal of Production Economics, 277, 109388.
Li, X., Krivtsov, V., Pan, C., Nassehi, A., Gao, R. X., & Ivanov, D. (2024b). End-to-end supply chain resilience management using deep learning, survival analysis, and explainable artificial intelligence. International Journal of Production Research, 1-29.
Lotfi, M., & Saghiri, S. (2018). Disentangling resilience, agility and leanness: Conceptual development and empirical analysis. Journal of Manufacturing Technology Management, 29(1), 168-197.
Ma, B., & Zhang, J. (2022). Tie strength, organizational resilience and enterprise crisis management: An empirical study in pandemic time. International Journal of Disaster Risk Reduction, 81, 103240.
Minciu, M., Veith, C., Dobrea, R. C., & Ionescu, V.-C. (2024). Adaptive strategies and sustainable investments: navigating organizations through a VUCA environment in and after COVID-19. Technological and Economic Development of Economy, 1-24.
O'Shannassy, T. F. (2016). Strategic intent: The literature, the construct and its role in predicting organization performance. Journal of Management & Organization, 22(5), 583-598.

Ooi, S. K., & Memon, K. R. (2025). Addressing Resource Scarcity: The Role of Responsible Innovation and Resilience in SMEs' Competitive Advantage and Sustainability Performance. Corporate social-responsibility and environmental management, 32(5), 5734-5746.
Qader, G., Junaid, M., Abbas, Q., & Mubarik, M. S. (2022). Industry 4.0 enables supply chain resilience and supply chain performance. Technological Forecasting and Social Change, 185, 122026.
Pu, G., Li, S., & Bai, J. (2023). Effect of supply chain resilience on firm's sustainable competitive advantage: a dynamic capability perspective. Environmental Science and Pollution Research, 30(2), 4881-4898.
Rajesh, R. (2016). Forecasting supply chain resilience performance using grey prediction. Electronic Commerce Research and Applications, 20, 42-58.
Rana, J., Daultani, Y., Goswami, M., & Kumar, S. (2025). Exploring the Impact of Supply Chain Digital Transformation on Supply Chain Performance: An Empirical Investigation. Business Strategy and the Environment, 34(3), 3497-3521.
Seepana, C., Huq, F. A., & Paulraj, A. (2021). Performance effects of entrepreneurial orientation, strategic intent and absorptive capacity within coopetitive relationships. International Journal of Operations & Production Management, 41(3), 227-250.
Singh, R. K. (2025). Measuring supply chain resilience performance: role of data analytics, collaboration and flexibility. Measuring Business Excellence, 29(1), 121-136.
Singjai, K., Winata, L., & Kummer, T.-F. (2018). Green initiatives and their competitive advantage for the hotel industry in developing countries. International Journal of Hospitality Management, 75, 131-143.
Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. Strategic management journal, 18(7), 509-533.
Teece, D. J. (2007). Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance. Strategic management journal, 28(13), 1319-1350.
Türkeș, M. C., Stăncioiu, A. F., & Marinescu, R.-C. (2024). Modeling the impact of resilience factors and relational practice on performance of the supply chain. Journal of Innovation & Knowledge, 9(3), 100533.
Wang, J., Chen, R., & Zhang, S. (2022). The mediating and moderating effect of organizational resilience on competitive advantage: evidence from Chinese companies. Sustainability, 14(21), 13797.
Xie, Y., Xia, Q., Song, J., & Hu, S. (2024). Can sustainability orientation make firms more resilient? Exploring the role of digital business model innovation, digital orientation, and environmental dynamism. Sustainable Development.
YahiaMarzouk, Y., & Jin, J. (2022). Impact of environmental scanning on organizational resilience and competitive advantage: a study of Egyptian SMEs. Continuity & Resilience Review, 4(2), 192-223.
Yin, F., Lo, M. C., Mohamad, A. A., & Sin, K. Y. (2025). The impact of AI applications, information sharing, and supply chain resilience on agricultural supply chain performance. Journal of Data, Information and Management, 1-14.
Zhao, N., Hong, J., & Lau, K. H. (2023). Impact of supply chain digitalization on supply chain resilience and performance: A multi-mediation model. International Journal of Production Economics, 259, 108817.

The Pursuit of Ambidexterity for Supply Chain Resilience: An Investigation of Resilience Capabilities Before, During and After Covid-19

Łukasz Marzantowicz[1], Anja Hergesell[2], Rene Bauer[3], Nils-Ole Hohenstein[4], David M. Herold[5]

1: SGH Warsaw School of Economics, Poland; 2: University of Technology Sydney, Australia; 3: Vienna University of Business and Economics, Austria; 4: Cooperative State University Mannheim, Germany; 5: Queensland University of Technology, Australia

INTRODUCTION

As the Covid-19 pandemic caused significant uncertainties to both supply and demand, it highlighted the importance of organisations to design and manage capabilities to cope with supply chain risk and disruptions. Organisations were forced to enhance the *resilience* of their supply chains to secure the continuity of their operations and therefore built up and utilised their intra-organisational dynamic capabilities to address, for example, mismatches between supply and demand, labour shortages and lack of transport capacity (Dovbischuk, 2022; Gebhardt et al., 2022; Hohenstein, 2022). Dynamic capabilities, an extension of the Resourced-Based View (RBV) of the firm (Barney, 2001; Wernerfelt, 1984), can be defined as "the firm's ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments" (Teece et al., 1997, p. 516) and refer thus to the organization's capability to renew competencies to adequately respond to business and market changes.

In line with existing research, we argue that in times of crisis (for example, Covid-19 related supply chain disruptions), the build-up of resilience capabilities is achieved by *temporal ambidexterity* (O'Reilly III & Tushman, 2011). Temporal ambidexterity is characterised by a sequential approach, that is, switching between exploitation to exploration. According to Ponomarov and Holcomb (2009), the build-up of supply chain resilience follows a three-phase cycle of *before, during and after*. *Before* and in the beginning of the pandemic, companies focused on exploiting resources to maintain continuity of their supply chain operations, but the focus shifted to exploring new resilience capabilities *during* the pandemic to better respond to the disruption, followed by an exploitation focus of the newly acquired capabilities *after* the pandemic.

As response, the aim of this study is to assess to what extent supply chain resilience capabilities have been both exploited and explored before, during and after Covid-19. Our main theoretical focus is the distinction between exploitative and exploratory capabilities in a temporal ambidexterity environment to investigate the extent of supply chain resilience capabilities changes in the context of Covid-19. To do so, we conducted a survey among supply chain senior managers in Australia in June 2023, which can be considered after Covid-19 (WHO, 2023). Following Mandal et al. (2016), the questions focused on specific supply chain resilience capabilities and to what extent these capabilities have been exploited and explored before, during and after Covid-19. Our sample comprises survey responses from 447 senior managers in Australia from various supply chain industries.

The contribution of this article is twofold. First, using the concept of temporal ambidexterity, we present a more nuanced empirical, as well as theoretical, understanding of the mechanisms through which exploitative and exploratory capabilities influence supply chain resilience. Second, we empirically assess the extent of specific supply chain resilience capabilities before, during and after Covid-19, thereby providing insights into whether and how these capabilities have evolved.

THEORETICAL BACKGROUND

Dynamic capabilities for supply chain resilience

The dynamic capability view is extensively used to examine the role of supply chain disruptions (Birkie et al., 2017). Supply chain processes and activities are inherently vulnerable to

disruptions as an error in one part along the supply chain may lead to fail of the entire supply chain network (Kochan & Nowicki, 2018). As a consequence, supply chain managers are not only regularly confronted with these inherent risks and vulnerabilities that can cause disruptions, but aim to develop capabilities to absorb, anticipate and overcome these disturbances (Adobor & McMullen, 2018). In a Covid-19 context, it could be argued that managers focused extensively on building *resilience* capabilities to secure the continuity of their operations (Scholten et al., 2020).

One major issue seems to be the lack of consensus about the measurement of supply chain resilience. Wieland and Wallenburg (2013) use both proactive and reactive measurements including robustness and agility. Others conceptualize and develop scales to measure resilience, with Ambulkar et al. (2015) defining the antecedents of "firm resilience' and using four dimensions for measurement. Chowdhury and Quaddus (2017) develop a scale with based on three components of proactive and reactive capability as well as supply chain design quality, broken down into twelve sub-dimensions. We can conclude that not only supply chain resilience as a concept is subject to multiple views, but that no standardized form how to measure resilience exist and is often context specific.

(Temporal) ambidexterity

Previous research has indicated that dynamic capabilities can be linked to *exploiting* existing technologies and resources to safeguard efficiency as well as the creation of product and service variations through *exploration* (Brady & Davies, 2004). According to March (1991), exploitation can be defined as "the refinement and extension of existing competencies, technologies, and paradigms exhibiting returns that are positive, proximate, and predictable", thus it corresponds in dynamic capabilities context with what Teece (2007) calls 'seizing', i.e., the "mobilization of resources to address needs and opportunities, and to capture value from doing so" (p. 332). Exploration, however, can be defined as "experimentation with new alternatives having returns that are uncertain, distant, and often negative" (March, 1991, p. 85) and in a dynamic capabilities content, corresponds with the Teece's (2007) definition to attempt to 'transform', i.e. the "continued renewal" (p. 332) of organizations by reconfiguring resources to strategically respond the risks and capture opportunities.

Ideally, organisations are ambidextrous, that is, they have the 'ability to orchestrate the complex trade-offs that the simultaneous pursuit of exploration and exploitation requires' (O'Reilly & Tushman, 2004, p. 6). However, given the competition for limited internal resources, the literature points to tensions between exploitation and exploration and the need for trade-offs to achieve an optimal balance. Often, companies choose to focus either on exploiting their existing capabilities or exploring new capabilities (Li et al., 2008; Luger et al., 2018). Investigating these tensions to better understand how or whether organisations may balance the opposing concepts has led to large body of work.

We argue, however, that in times of disruption, in particular caused by an external shock of high impact and low probability, companies adopt a temporal ambidexterity approach (O'Reilly III & Tushman, 2011). Temporal ambidexterity suggests that exploitation and exploration build on each other, that is, the pursuit is sequential, and organisations switch periodically from an exploitative state to an exploratory state, and so forth (Birkinshaw et al., 2016; Simsek, 2009). In other words, temporal ambidexterity is characterised by taking a break from 'converging' capabilities for exploitation and moves to 'diverging', thereby broadening its focus to explore new approaches and concepts (Zabiegalski & Marquardt, 2022). This approach is commensurate with the three-phase cycle of resilience suggested by Ponomarov and Holcomb (2009), dividing the resilience stages into readiness (before), response (during), and recovery (after).

Although ambidexterity is increasingly applied as a lens to examine supply chain management issues (Eltantawy, 2016; Roldan Bravo et al., 2018), it appears that the role of temporal ambidexterity is rather limited for investigating exploitative and exploratory capabilities and their interactions in the context of supply chain resilience in Covid-19. We argue that this gap warrants further investigation to better understand the role of exploitative and exploratory capabilities in building supply chain resilience; and, moreover, that temporal ambidexterity offers a robust theoretical foundation for assessing the extent of resilience capabilities before, during and after Covid-19.

RESEARCH DESIGN

To address the research aim of understanding the extent of supply chain resilience capabilities utilized before during and after Covid-19, we adopted a quantitative survey methodology that gathered data through the online research panel provider Dynata. Dynata is subscription data platform that allows researchers to create surveys that are sent in a in double-blind process to a potential respondent panel. The selection process of potential participants is based on knowledge of the survey topic and specific characteristics of the participants.

Sample selection

Our target population were senior managers and senior professionals in Australia with global supply chain responsibilities, as our research required expert company assessments. To ensure participant and data quality, a robust screening process based a list of criteria around demographics, behavioural and attitudinal in line with the study's research aims was applied by Dynata. Particular attention was paid to the verification of respondents and their familiarity with supply chain capabilities as a qualification for participation. A qualifying question was used as a 'gatekeeper' in which participants were screened whether they have sufficient knowledge about the companies supply chainThis was followed by a rigorous validation process to prevent fake identities and double entries. After participants were confirmed, they were routed to the online survey questionnaire.

Survey Instrument and Measurement

To explore differences in supply chain resilience capabilities, we developed a questionnaire using an adapted version of the measuring instrument proposed by Mandal et al. (2016) to measure five supply chain resilience capabilities, namely *supply chain robustness*, *supply chain visibility, supply chain collaboration, supply chain flexibility* and *supply chain velocity.* To better reflect the Covid-19 and the temporal perspective, we adjusted and consolidated the original items from the instrument and focused on clear structure for each capability. Each of the resilience capabilities was measured by three items describing resilience management practices (RMPs). The measurement instrument was included twice to measure a) resilience capabilities at the beginning of Covid-19, and b) after Covid-19, and thus, to allow for a direct comparison between the periods. Respondents were asked to rate each of the RMPs retrospectively on a 6-point Likert scale, ranging from 'Disagree very strongly' (1) to 'Agree very strongly'(6). In addition, company size was recorded, differentiating small, medium and large companies by employee size.

Data collection and analysis

The online survey was designed that the participants had to answer all questions, i.e. participants were not able to further proceed (i.e. see the next page) unless all questions were answered. The potential participants were informed about this requirement. Furthermore, the online panel provider used an incentive scale per completed response which was based on set time increments and the participants characteristics. The incentive options include e.g. gift cards, points for loyalty programs, charity donations, and partner collaborations. The final sample comprised the responses of 447 senior managers from a range of Australian industries, a large enough sample to sufficiently describe the phenomenon of interest and address the research aim. Changes in resilience capabilities before and after Covid-19 were calculated by comparing the rating at the two times. The numbers were subtracted and categorised as strong decrease (level decrease by two or more levels), slight decrease (decrease by one level), constant (same level), slight increase (increase by one level) and strong increase (increase by two or more levels). Comparisons in the changes by company size (small, medium, large) were then explored with Chi-square tests.

RESULTS

The analysis shows the extent of the companies' resilience capabilities for responding to supply chain disruptions before, during and after Covid-19. Table 1 shows the results according to the following five sections: supply chain robustness; supply chain collaboration; supply chain visibility; supply chain flexibility; and supply chain velocity and its associated RMPs. For better understanding, we converted the scores into percentages, that is, the table shows the level of resilience capabilities utilised. Overall, it can be observed that two-thirds of the companies (66%) had built sufficient supply chain resilience capabilities before Covid-19 to respond to disruptions.

After Covid-19, this number increased to 83%; that is, we can observe an increase of 18 points, which emphasises that companies reacted, implementing both exploitative and exploratory RMPs to build further capabilities for responding adequately to disruptions.

Interestingly, the results show that before Covid-19, companies focused on supply chain collaboration (73%), followed by supply chain flexibility (66%), supply chain robustness (63%), supply chain visibility (63%) and supply chain velocity (62%). After Covid-19, the results show a different picture: with 85%, supply chain visibility emerges as the focus of capability development, followed by supply chain collaboration (84%), supply chain flexibility (83%), supply chain robustness (82%) and supply chain velocity (81%). While all capabilities have significantly improved between before, during and after Covid-19, companies seem to have changed their scope from collaboration to visibility.

The analysis of the respective RMPs also provides interesting insights into the drive behind the development of capability. The largest increase between RMPs could be observed for supply chain robustness with 26 points, in the category 'Preparedness for unexpected events'. This is in line with a 22-point increase in 'Ability to rapidly deal with threats in the environment', demonstrating not only a focus for exploratory capabilities but also an increasing awareness about being prepared for future external shocks. Visibility also played a great role in exploratory capabilities to better respond to supply chain disruptions of high impact and low probability. With a 23-point increase, companies increased the availability of information within their operations ('Operations information available within company'). It also seems that companies aimed to expand their reach to include information available beyond the first tier/customers ('Operations information available first tier/customers'), showcasing a 21-point increase.

Resilience Capabilities	**Proportion of Organisations with Resilience Capabilities**		
RMPs	*Before Covid-19 - Exploitation Focus (Readiness)*	*During Covid-19 - Exploration Focus (Response)*	*After Covid-19 - Exploitation Focus (Recovery)*
Supply Chain Robustness	**63%**	**+19**	**82%**
Preparedness for unexpected events	*56%*	+26	82%
Ability to adequately respond	*66%*	+16	82%
Ability to maintain structure and function	*68%*	+15	83%
Supply Chain Collaboration	**73%**	**+11**	**84%**
Ability to work with key suppliers	*76%*	+7	*83%*
Ability to work with key customers	*70%*	+16	*86%*
Ability to develop strategic objectives jointly with partners	*73%*	+11	*84%*
Supply Chain Visibility	**63%**	**+22**	**85%**
Operations information available within company	*63%*	+23	*86%*
Operations information available 1st Tier/Customers	*64%*	+21	*85%*
Operations information available beyond 1st Tier	*63%*	+20	*83%*
Supply Chain Flexibility	**66%**	**+17**	**83%**
Ability to adjust suppliers' order quantities	*68%*	+15	*83%*
Ability to adjust delivery time of suppliers' order	*67%*	+16	*83%*
Ability to substitute products due to shortages	*65%*	+17	*82%*
Supply Chain Velocity	**62%**	**+19**	**81%**
Ability to rapidly deal with threats in the environment	*59%*	+22	*81%*
Ability to rapidly address opportunities in the environment	*62%*	+19	*81%*
Ability to quickly respond to changes in the environment	*65%*	+17	*82%*
Supply Chain Capabilities Total	**66%**	**+17**	**83%**

Table 1: Supply chain resilience capabilities before, during and after Covid-19

DISCUSSION

The results provide interesting insights into the level and level changes of supply chain resilience capabilities before, during and after Covid-19. More specifically, the results for both supply chain capabilities and RMPs focus on four changes: (1) descriptive aggregated capability, (2) company-level changes overall, (3) RMP changes and (4) changes by company size.

First, the results show that more than half of all respondents agree to have had relevant resilience capabilities before Covid-19; thus, most companies could be described as prepared for

disruptive events. In fact, the relatively high level of agreement between 62-73% shows that most companies had supply chain resilience capabilities in place to respond to external shocks before Covid-19, in other words, they had the ability to 'maintain continuity of operations' (Gölgeci & Ponomarov, 2015, p. 270) during a disruptive event. With resilience capabilities increasing to 81-85% after Covid-19, the rise in companies with resilience capabilities suggests that companies lacking resilience capabilities used the disruptions as an opportunity to learn, prepare their supply chains for future disruptions and develop capabilities for operational improvements along their supply chains. Interestingly, although companies adopt different paths and trajectories in their capability accumulation (Eisenhardt & Martin, 2000; Teece et al., 1997), the aggregated descriptive results also suggested that uptake across all five capabilities has developed similarly, highlighting an interdependency between these capabilities.

Second, looking at changes at the company level, one major finding was that 38% to 52% of all companies did not change in their level of capabilities, i.e. their resilience capabilities were unaffected by the Covid-19 disruption. This suggests that major disruptions may not encourage long-term change necessarily (Hopp et al., 2008). In contrast, 34% to 48% of all companies developed further resilience capabilities. In other words, the proportion of companies that did not change in their resilience capabilities and the proportion that did was almost equal. As such, these companies seem to have sensed and seized new value-creating capabilities, not leading only to changes within their companies' broader resource base, but potentially also to changes in performance (Laaksonen & Peltoniemi, 2018).

Third, we could also observe some interesting findings on an RMP level. For example, the biggest increase in respondent agreement between before, during and after Covid-19 could be observed in the supply chain robustness. In particular, the question of 'Preparedness for unexpected events' to which 26% more respondents agreed to have these after Covid-19. It seems that more companies have developed the two key components for robust supply chains, preparedness and anticipation for more resilient supply chains. This corresponds with current research that the adoption of a robust supply chain approach is crucial for a resilient supply chain.

Fourth, the results become even more interesting when we examined companies according to their company size, i.e. the difference in resilience capabilities between small and large companies. The results show that between 38% to 52% of all companies did not note any changes (no-effect) in their capabilities, but small companies were significantly more likely not to change their level of agreement with 47% to 60% rating their capabilities identically before, during and after Covid-19. Studies show that in times of disruption and the associated deferred investments, cash flow limitations and layoffs made it difficult for SMEs to embrace novel digital technologies and find the amount of investment that is required for resilience capabilities for collaboration (Mishra & Singh, 2023).

CONCLUSION

By expanding insight into the implications of ambidextrous capabilities for supply chain resilience capabilities before, during and after Covid-19, this article advances and expands existing supply chain literature in three ways. First, this study is one of the first to empirically assess the extent of supply chain resilience capabilities before, during and after Covid-19, thereby providing insights into whether and how these capabilities have evolved. Second, our paper expands the literature on ambidexterity in organisations by highlighting how companies build exploitative and exploratory capabilities in times of crisis. Third, by explicating five specific supply chain resilience capabilities and 15 associated measurable resilience practices, this study deepens knowledge of resilience and thus provides insights into where supply chain managers should place their focus to drive resilience in their operations.

However, the study's findings and their implications must be viewed in the light of their research limitations. Although the results provide insights and a better understanding of resilience capabilities before, during and after Covid-19, the participants had to answer the questions retrospectively, so responses may have been subject to measurement bias. Future researchers are invited to extend our framework by considering other concepts beyond the concept of ambidexterity. Overall, research dealing with temporal ambidexterity in the supply chain resilience domain seems still to be in its infancy. Further research will help to better understand

how ambidexterity impacts supply chain resilience, and how organisations can capture innovation from newly acquired capabilities after a disruptive event.

REFERENCES

Adobor, H., & McMullen, R. S. (2018). Supply chain resilience: a dynamic and multidimensional approach. The International Journal of Logistics Management, 29(4), 1451-1471.

Ambulkar, S., Blackhurst, J., & Grawe, S. (2015). Firm's resilience to supply chain disruptions: Scale development and empirical examination. Journal of Operations Management, 33, 111-122.

Barney, J. B. (2001). Resource-based theories of competitive advantage: A ten-year retrospective on the resource-based view. Journal of Management, 27(6), 643-650.

Birkie, S. E., Trucco, P., & Fernandez Campos, P. (2017). Effectiveness of resilience capabilities in mitigating disruptions: leveraging on supply chain structural complexity. Supply Chain Management: An International Journal, 22(6), 506-521.

Birkinshaw, J., Zimmermann, A., & Raisch, S. (2016). How do firms adapt to discontinuous change? Bridging the dynamic capabilities and ambidexterity perspectives. California Management Review, 58(4), 36-58.

Brady, T., & Davies, A. (2004). Building project capabilities: from exploratory to exploitative learning. Organization Studies, 25(9), 1601-1621.

Chowdhury, M. M. H., & Quaddus, M. (2017). Supply chain resilience: Conceptualization and scale development using dynamic capability theory. International Journal of Production Economics, 188, 185-204.

Dovbischuk, I. (2022). Innovation-oriented dynamic capabilities of logistics service providers, dynamic resilience and firm performance during the COVID-19 pandemic. The International Journal of Logistics Management, 33(2), 499-519.

Eisenhardt, K. M., & Martin, J. A. (2000). Dynamic capabilities: what are they? Strategic Management Journal, 21(10-11), 1105-1121.

Eltantawy, R. A. (2016). The role of supply management resilience in attaining ambidexterity: a dynamic capabilities approach. Journal of Business & Industrial Marketing, 31(1), 123-134.

Gebhardt, M., Spieske, A., Kopyto, M., & Birkel, H. (2022). Increasing global supply chains' resilience after the COVID-19 pandemic: Empirical results from a Delphi study. Journal of Business Research, 150, 59-72.

Gölgeci, I., & Ponomarov, S. Y. (2015). How does firm innovativeness enable supply chain resilience? The moderating role of supply uncertainty and interdependence. Technology Analysis & Strategic Management, 27(3), 267-282.

Hohenstein, N.-O. (2022). Supply chain risk management in the COVID-19 pandemic: strategies and empirical lessons for improving global logistics service providers' performance. The International Journal of Logistics Management, 33(4), 1336-1365.

Hopp, W. J., Iravani, S. M., & Liu, Z. (2008). Strategic risk from supply chain disruptions. Management Science, 2008, 1-63.

Kochan, C. G., & Nowicki, D. R. (2018). Supply chain resilience: a systematic literature review and typological framework. International Journal of Physical Distribution & Logistics Management, 48(8), 842-865.

Laaksonen, O., & Peltoniemi, M. (2018). The essence of dynamic capabilities and their measurement. International Journal of Management Reviews, 20(2), 184-205.

Li, Y., Vanhaverbeke, W., & Schoenmakers, W. (2008). Exploration and exploitation in innovation: Reframing the interpretation. Creativity and innovation management, 17(2), 107-126.

Luger, J., Raisch, S., & Schimmer, M. (2018). Dynamic balancing of exploration and exploitation: The contingent benefits of ambidexterity. Organization Science, 29(3), 449-470.

Mandal, S., Sarathy, R., Korasiga, V. R., Bhattacharya, S., & Dastidar, S. G. (2016). Achieving supply chain resilience: The contribution of logistics and supply chain capabilities. International Journal of Disaster Resilience in the Built Environment, 7(5), 544-562.

March, J. G. (1991). Exploration and exploitation in organizational learning. Organization Science, 2(1), 71-87.

Mishra, R., & Singh, R. K. (2023). A systematic literature review on supply chain resilience in SMEs: learnings from COVID-19 pandemic. International Journal of Quality & Reliability Management, 40(5), 1172-1202.

O'Reilly, C. A., & Tushman, M. L. (2004). The ambidextrous organization. Harvard Business Review, 82(4), 74-83.

O'Reilly III, C. A., & Tushman, M. L. (2011). Organizational ambidexterity in action: How managers explore and exploit. California Management Review, 53(4), 5-22.

Roldan Bravo, M. I., Ruiz-Moreno, A., & Llorens Montes, F. J. (2018). Examining desorptive capacity in supply chains: The role of organizational ambidexterity. International Journal of Operations & Production Management, 38(2), 534-553.

Scholten, K., Stevenson, M., & van Donk, D. P. (2020). Dealing with the unpredictable: supply chain resilience. International Journal of Operations & Production Management, 40(1), 1-10.

Simsek, Z. (2009). Organizational ambidexterity: Towards a multilevel understanding. Journal of Management Studies, 46(4), 597-624.

Teece, D. J. (2007). Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance. Strategic Management Journal, 28(13), 1319-1350.

Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. Strategic Management Journal, 18(7), 509-533.

Wernerfelt, B. (1984). A resource-based view of the firm. Strategic Management Journal, 5(2), 171-180.

WHO. (2023). Coronavirus disease (COVID-19) pandemic - Overview. https://www.who.int/europe/emergencies/situations/covid-19

Wieland, A., & Wallenburg, C. M. (2013). The influence of relational competencies on supply chain resilience: a relational view. International Journal of Physical Distribution & Logistics Management, 43(4), 300-320.

Zabiegalski, E., & Marquardt, M. J. (2022). Action learning and the ambidextrous organization. Journal of Work-Applied Management, 14(2), 170-183.

German Carmakers Moving from Task Force Mode to Resilience Building In The 2020ff Semiconductor Supply Crisis

Peik Bremer

Technical University of Applied Sciences Würzburg-Schweinfurt, Germany

ABSTRACT

Purpose of this paper

This paper examines how German automotive original equipment manufacturers (OEMs) have responded to the semiconductor supply disruptions triggered by the COVID-19 pandemic and subsequent geopolitical shocks. The study aims to systematize OEMs' strategic responses by applying Supply Chain Resilience Theory (SCRT) as the primary analytical lens, while drawing on Resource Dependence Theory (RDT) and Global Value Chain Theory (GVCT) to contextualize inter-firm dynamics and upstream and downstream governance structures.

Design/methodology/approach

This research is based on a desk-based case study that draws exclusively on secondary data sources, including industry reports, press reports, and company publications. The analysis applies a qualitative, theory-driven coding framework based on the SCRT and supplemented by constructs from the RDT and the GVCT. The study reconstructs how OEMs have adapted their sourcing, product design and architecture, and collaboration and coordination practices to mitigate long-term vulnerability to high-tech component shortages.

Findings

The analysis shows two predominant categories of strategic actions that go hand in hand: (1) redefining the approach to electronic control unit development towards standardized platforms and architectures (2) redefining the approach to the supply chain towards direct sourcing of semiconductors and 'deep-tier' collaboration. These actions are underpinned by capabilities such as flexibility in production planning and product design decisions, as well as end-to-end supply chain visibility. OEMs are increasingly integrating resilience considerations into the early stages of product development as a strategic response to supply uncertainties.

Value

This study contributes to the SCRT by providing an empirically grounded typology of resilience strategies used by OEMs during a supply crisis in systemic components. It also shows how design-based and relational interventions interact with structural features of global value chains and resource asymmetries and provides a multi-theoretical perspective on building resilience in complex manufacturing environments.

Research limitations/implications

The study is based on secondary data and does not include primary field research or interviews. Further research could extend this work by empirically testing the effectiveness of different resilience levers over time or by taking the perspective of other supply chain actors.

Practical implications

The results offer actionable insights for supply chain and product strategists seeking to reduce technology dependency and improve upstream resilience. Proactive modularity of design, early supplier integration, and visibility capabilities are highlighted as critical tools for building adaptability in high-risk ecosystems.

INTRODUCTION

The COVID-19 pandemic triggered an unprecedented disruption of global supply chains, fundamentally destabilizing international trade and industrial production in virtually all sectors

(Ivanov, 2020; Gereffi, 2020). In the German automotive industry, the crisis led to significant declines in production, sales and finances, highlighted weaknesses in global supply chains and prompted the industry to strategically reassess (Ramani et al., 2022; Münch and Hartmann, 2023). The German Association of the Automotive Industry (VDA) reported that car production in Germany fell to around 3.5 million vehicles in 2020, the first year of the pandemic, representing a 25% year-on-year decline and marking the lowest level since 1975 (VDA, 2021). While the initial decline in 2020 was mainly caused by production shutdowns and falling demand, the subsequent decline in 2021 by further 10% was mainly due to an acute shortage of semiconductors, which had become critical bottlenecks in automotive production (VDA, 2022).

The semiconductor industry is the technological backbone of modern electronics and is indispensable for automotive engineering, as it is at the heart of most innovations in the automotive sector. Analysts at the French market research company YOLE Group estimate that the average car in 2022 contained semiconductors worth around USD 540 and forecast that this figure will rise by around 70% by 2028. The global market for automotive semiconductors is expected to grow at a compound annual growth rate (CAGR) of 11% between 2023 and 2029 (YOLE, 2023). Given the rapidly evolving shift towards technologies such as electric powertrains, advanced driver assistance systems (ADAS), enhanced infotainment features and autonomous driving, other market analysts even predict a value of USD 4,000 per car by 2030 (Zhang, 2024).

Even before the COVID-19 pandemic, the automotive industry often struggled with semiconductor supply due to structural issues in the supply chain, such as long lead times (up to four months) in a geographically dispersed supply chain, high capacity utilization making demand shifts problematic, and the high potential of bullwhip effects because semiconductor manufacturers only receive „interpreted" demand figures from Tier 1 or Tier 2 suppliers and not directly from the automotive industry. This has been exacerbated by the fact that the industry has long relied on just-in-time production systems, which leave little buffer for upstream volatility (Chien et al., 2011; Mönch et al., 2018; Magdy et al., 2024).

As the semiconductor supply crisis exemplifies the combined effects of short-term supply chain disruptions and long-term structural problems in the supply chain (Frieske and Stieler, 2022), it is important to understand how the automotive industry has responded to this challenge. This is all the more interesting as the industry managed to introduce long-term strategic measures to improve resilience while still facing disruptions (Kravchenko et al., 2024), i.e. it gradually moved from a reactive 'taskforce mode' to more institutionalized forms of risk management and resilience building (Hoppe and Podkowik, 2022).

This study aims to analyze the operational and strategic responses of German OEMs, namely Volkswagen, BMW and Mercedes-Benz, and place their actions in the context of building resilience to address deep systemic vulnerabilities. Based on a data corpus comprising press releases, industry and consumer media and public statements from 2020 to 2025, the measures are formulated using the Supply Chain Resilience Theory as a guiding framework in combination with the Global Value Chain Theory and the Resource-Dependence Theory as complementary frameworks.

The results of the study show, firstly, how badly car manufacturers were caught unprepared by the supply crisis and how they managed to implement task force measures to stabilize their operations and companies with great effort. Secondly, the study also sheds light on how the automotive industry implemented risk management and built resilience through a combination of redefining product architecture and design, and supply chain cooperation and collaboration, while combating disruptions.

The rest of the paper is organized as follows: The literature review provides an overview of supply crises in general and a specific account of the supply crisis in automotive semiconductors in 2020ff. The methodology section motivates the case study approach and justifies the theoretical frameworks. The case analysis begins with a description of the automotive semiconductor market and then outlines how individual car manufacturers have responded to the supply crisis. In the results chapter, the empirical findings are integrated into the theoretical framework to develop a structured understanding of the resilience of the automotive supply chain.

LITERATURE REVIEW

In this section, a distinction is made between supply shortages (or bottlenecks) and comprehensive supply crises. It also provides an overview of the general literature on supply disruptions, with a focus on academic papers dealing with the crisis in the automotive industry in 2020 and beyond.

Supply Shortages and Disruptions

From a system perspective, Beer (2015) describes a bottleneck as the system element that limits the throughput of a system. The downstream supply chain suffers when demand exceeds the capacity of the bottleneck.

If a system element, which is not necessarily a bottleneck, is temporarily unable to provide capacity, the supply chain is interrupted at that point, leading to a collapse of the downstream supply chain once inventories are exhausted (Chopra and Sodhi, 2004). Even short disruptions can have long-lasting effects on supply chains, as demonstrated by the Suez Canal incident in 2021 (Wan et al., 2023). The study of supply chain disruptions has developed into a theoretical field of its own within operations and supply chain management. Disruptions differ from routine fluctuations in that they are low-probability, high-impact events that significantly affect the normal flow of goods, services or information in a supply network (Tang, 2006).

Christopher and Peck (2004) emphasize that vulnerability results from structural characteristics such as global complexity, tight coupling and lean practices such as just-in-time (JIT), which increase efficiency but reduce buffers and adaptability. They argue for a resilience-oriented approach that emphasizes redundancy, flexibility and visibility.

Sheffi and Rice Jr. (2005) distinguish between triggers of disruptions (e.g. natural disasters, political unrest) and the structural vulnerability of supply networks that amplifies their effects. Their resilience framework comprises four pillars: robustness, redundancy, response and recovery. Supply disruptions can be triggered by events that are either reasonably predictable (e.g. a strike at a seaport) or completely unpredictable, such as natural disasters (Burriel et al., 2024).

Craighead et al. (2007) empirically confirm that density (number of nodes), complexity (connections) and criticality of nodes are the most important factors for the severity of disturbances. They show how tightly coupled systems tend to amplify rather than absorb shocks, especially in the absence of buffers or real-time visibility.

Supply Crises

Both supply shortages and supply disruptions can trigger a so-called supply crisis. Although there is no universally recognized definition of a supply crisis, the term generally refers to a critical situation, „*a time of intense difficulty, extreme trouble or danger for and within a supply chain*" (Durugbo and Al-Balushi, 2024).

Some authors classify supply crises on the basis of the nature of the triggering event. For Ponis and Ntalla (2015), the crisis is caused by an unpredictable event with the potential for severe disruptions. Xiong et al. (2024) distinguish between security-related issues such as geopolitical tensions and health-related issues such as pandemics. Durugbo and Al-Balushi (2023) include probability and impact and define a supply crisis as „*a supply chain state or situation triggered by a low probability, high-impact incident that emerged gradually or abruptly from organisational, institutional and state (or regional) causes and conditions, threatening the values and viability of suppliers, manufacturers, and distributors, and imposing time pressures for supply chain decisions under high uncertainty*."

From a phenomenological point of view, the probability and predictability of the event are secondary. For the purposes of this study, we define a supply crisis as a persistent supply shortage or a prolonged supply disruption that affects entire industries on a global or supra-regional level. Such crises can have far-reaching economic consequences (Lagarde, 2022) and in some cases create a 'new normal' — as seen in numerous drug shortages (Pashapour et al.,

2019; Postma et al., 2023). They can even lead to permanent changes in industry structure and product design (Leslie, 2022).

The causes of supply crises are complex. One source is the scarcity of resources, particularly in connection with a concentration of suppliers or oligopolistic structures. For example, the helium-3 shortage in 2009 was the result of rising demand coupled with a gradual decline in production by a few global suppliers (Arkharov et al., 2013). Similarly, natural graphite is considered a strategic material subject to export restrictions (Wang et al., 2018). In an exploratory study, Hittle and Moustafa Leonard (2011) identify important causes such as dependence on a single source of supply and weak supplier relationships.

Another structural factor is the phenomenon of cascading failure — the chain reaction of disruptions triggered by the failure of a single supplier or node, especially in highly interconnected supply networks. These failures are facilitated by tight coupling, limited inventory buffers and delayed information flows, which often exacerbate the initial shock (Sun et al., 2022; Yan et al., 2024). The automotive sector is particularly vulnerable due to its globalized procurement, high parts complexity and reliance on just-in-time processes.

Finally, certain triggers can also lie outside the scope of the supply chain. The so-called 'oil crisis' in Germany in 1973 is an early example of how the media can influence public perception and create demand pressures that accelerate supply-side tensions (Kepplinger and Roth, 1979).

The Semiconductor Supply Crisis

The global semiconductor shortage that began in early 2020 shows how vulnerabilities in the supply chain can develop into systemic crises with industry-wide repercussions. Initially triggered by COVID-19 lockdowns and changing consumer demand, the disruption quickly escalated due to structural vulnerabilities such as supplier concentration, JIT practices and long lead times in chip manufacturing (Xiong et al., 2024). Shih (2020) highlights the multi-tiered nature of semiconductor supply chains, where downstream players — especially in the automotive sector — had no insight into the constraints of upstream chip manufacturing.

The automotive industry was hit disproportionately hard, even though it only accounts for a small share of global demand for semiconductors. Frieske and Stieler (2022) outline a causal chain that begins with a pandemic-related decline in demand for automobiles. As OEMs reduced their orders, chipmakers shifted their capacity to consumer electronics, which surged. This shift, combined with external events such as factory fires and extreme weather conditions, exacerbated the shortage. Other authors point to additional demand-side factors such as rising semiconductor demand due to electrification (Panchal et al., 2024) or supply-side constraints, including geopolitical trade restrictions and access to key raw materials (Beibit et al., 2023).

Beyond linear causality, several authors emphasize the systemic interplay between exogenous shocks and endogenous reactions of supply chain actors (Ramani et al., 2022). In this view, the pandemic served not as a cause but as a catalyst for an already fragile supply system characterized by technical and geographical complexity (Mohammad et al., 2022).

Response strategies in the automotive sector have evolved over time. In the short term, manufacturers relied on reactive tactics such as allocating scarce chips to high-margin vehicle models or omitting non-critical functions associated with unavailable semiconductors (Wang et al., 2025). Medium-term measures include design changes towards zonal architectures (Santos et al., 2024) and chipset-based modular systems (Mathes, 2025), which aim to reduce semiconductor diversity and dependency. Medium- to long-term measures aim to strengthen strategic partnerships, including joint development agreements, between OEMs and semiconductor manufacturers (Xiong et al., 2024). Long-term strategic responses focus on supply chain transformation, including near-shoring, as exemplified by the European Union Chip Act, which aims to localize 20% of global semiconductor production in Europe by 2030 (Bargmann et al., 2022).

More generally, the question arises as to how resilient supply chains in the automotive industry were during the semiconductor crisis and how supply chain management has changed in response to the crisis.

METHODOLOGY

Our research relies on a desk-based case study that uses archival records and documents as primary sources of evidence (Yin, 2018, 113ff). Case studies lend themselves well to exploring the complexity of a real-world phenomenon and allow for a context-rich, in-depth examination (Yin, 2018, 14ff) of how and why the disruption occurred and how different actors responded. The case study approach provides a specific, appropriately bounded example of the application of theoretical frameworks that supports both theoretical depth and practical relevance. This is consistent with Eisenhardt's (1989) recommendation to use case studies to build or extend theories. The crisis has evolved over time (2020 onwards), which is useful for understanding the temporal dynamics in the study of resilience building, adaptation and strategic shifts. This study relies on publicly available documents to reconstruct a detailed timeline and strategy profile, as direct access to decision makers was not possible.

The semiconductor crisis is a complex interplay of global supply chains, geopolitical factors, technological dependencies and decisions at company level. Therefore, this study uses a combination of three theoretical frameworks to examine the crisis in the automotive semiconductor supply crisis (**Fig. 1**).

- Supply Chain Resilience Theory (SCRT) is used as the main theoretical basis for analyzing the response strategies of OEMs, assuming that a resilient supply chain would not get stuck in a supply crisis. Resilience, a firm's ability to withstand and recover from disruptions, is seen as (1) a design feature of supply chains (Sheffi and Rice Jr., 2005) and is therefore a collaborative effort between supply chain actors and, in a broader perspective as (2) social-ecological resilience, "*the capacity of a supply chain to persist, adapt, or transform in the face of change*" (Wieland and Durach, 2021). It builds on a risk management culture established in each link of the supply chain (Christopher and Peck, 2004) and relies on absorptive, adaptive, restorative (Hosseini and Barker, 2016) and transformative supply chain capacities (Gaudenzi et al., 2023). This 'bounce-forward-and-adapt' approach is creating viability, i.e., resilience in open systems (Ivanov and Dolgui, 2020), as opposed to a mere 'bounce-back' in closed systems.

- Global Value Chain Theory (GVCT) is used as a complementary lens to capture structural perspectives on supply chains such as dependencies and governance (Gereffi et al., 2005). GVCT analyzes how firms reconfigure their roles and partnerships across the global supply network. The automotive semiconductor supply chain is associated with two concepts of GVCT: relational governance, which manifests itself in close collaboration, e.g., in the co-design of automotive microcontrollers, and captive governance, which leads to power asymmetry because fabless chip designers are dependent on one of the few large foundry companies. In this environment, OEMs and Tier 1 suppliers must balance cost considerations with strategic relationships across the supply chain (Garcia et al., 2024). The presence of captive governance suggests using Resource Dependence Theory (RDT) for a special power dynamics focus on the semiconductor supply chain. RDT looks at how firms reduce reliance on external resources to secure critical input.

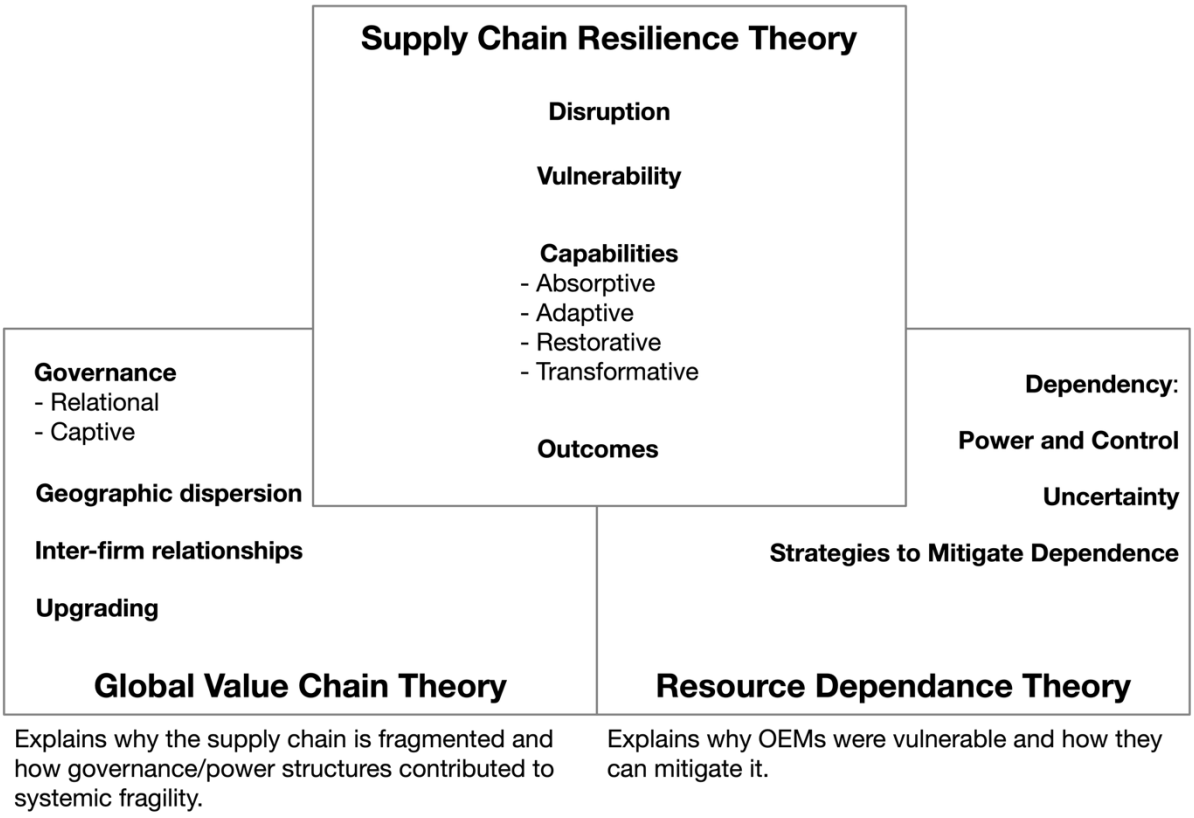


Fig. 5: Theory frameworks

This combination of theoretical frameworks has recently proven to be a solid foundation for studies examining the impact mechanisms of the digital economy on supply chain resilience in cross-border e-commerce in healthcare (Liu et al., 2025), the impact of pricing and export diversification on the resilience of Russian manufacturing firms during the COVID-19 pandemic and international sanctions in 2022 (Gorodnyi et al., 2025), and the influence of different types of relationship governance on resilience at four levels of the Australian Defense Force supply network (Statsenko et al., 2025).

With this solid theoretical and empirical foundation, the case study approach provides both the exploratory as well as the explanatory power needed to better understand the management of a supply crisis that is relatively new in its scale and impact (Meredith, 1998). This provides actionable contextual insights (Ketokivi and Choi, 2014) for both policy makers and supply chain managers to support the development of future resilience strategies.

Only secondary sources were used for data collection: Statements from company representatives, company publications, market reports and articles in German and English-language consumer media and websites. We used ChatGPT for this part of the research. We then integrated this information into the theoretical framework.

DATA ANALYSIS

The section on data analysis first looks at the automotive semiconductor market and then examines the specific situation and the measures taken by the individual OEMs. We refer to the source of the information presented by figures in brackets (e.g. [44]), which refer to the links provided in **Appendix 1**.

The Automotive Semiconductor Market

The global semiconductor market grew from USD 466 billion in 2020 to USD 602 billion in 2022 [53, 54], showing remarkable resilience and expansion during the COVID-19 pandemic.

Demand for smartphones and cloud computing (including streaming services) accounts for the majority of semiconductor usage at around 40% each. 20% of semiconductor demand is accounted for by industrial goods, which includes the automotive semiconductor sector. Although it only accounts for around 8% of total semiconductor demand, the automotive segment is expected to grow rapidly, with demand forecasted to increase by 30–35% in the coming years [7]. The global market for automotive semiconductors exceeded USD 69.9 billion in 2022 and is expected to more than double to USD 148 billion by the end of 2029. This corresponds to a CAGR of 11% [44].

The automotive segment's relatively small share of the overall semiconductor market meant that automotive OEMs and Tier 1 suppliers had limited bargaining power in an industry with severely constrained capacity. As global demand for consumer electronics skyrocketed during the pandemic, foundries reallocated their wafer capacity to more profitable segments such as smartphones and data centers.

The average semiconductor share per vehicle is expected to increase from around USD 500 in 2020 to USD 1,400 in 2028, with even higher values forecasted for electric vehicles [45]. Some market analysts even predict that the semiconductor value per car will reach USD 4,000 by 2030. Trends such as advanced driver assistance systems (ADAS), infotainment, powertrain electrification and autonomous driving are the key growth drivers (Zhang, 2024).

The five leading suppliers of automotive semiconductors — Infineon (13.7 %), NXP (10.8 %), STMicroelectronics (10.2 %), Texas Instruments (8.5 %) and Renesas (6.7 %) — have a combined market share of around 50% [42, 43]. The market is moderately consolidated at the top but remains fragmented at the bottom.

While older nodes (technology generations > 90nm) still dominate due to long product lifecycles, demand for advanced nodes (28nm–7nm) is growing rapidly, driven by electric vehicles and ADAS applications [47–49]. Both have an impact on available capacity: Older nodes are low-margin and semiconductor manufacturers are reluctant to add new capacity; for capacity in more advanced nodes, OEMs are competing with other industries.

In semiconductor production, capacity utilization of around 80% is considered full capacity. During the global chip shortage (2019–2023), capacity utilization peaked at 97.2% in 2021 [39]. The situation began to ease in 2022 when the inflation rate reduced demand in the consumer electronics industry, which helped to increase capacity for automotive semiconductors again [7], reaching a utilization rate of 94.1% [40] and not falling below 85% until 2023.

Production capacities were already at a historically high level before the crisis. The peak in capacity utilization in 2021 left virtually no scope for short-term reallocations to cope with unexpected shifts in demand.

Lead times for automotive chips increased from 10–15 weeks before the pandemic [50] to 40 weeks for common semiconductors and 52+ weeks for some critical microcontrollers and power management chips [51]. Lead times normalized by 2023 and returned to pre-pandemic levels (around 15 weeks) by early 2024 [52].

Overall, the crisis revealed a systemic mismatch between the economic importance of semiconductors in the automotive sector and their structural position within the global chip ecosystem, with long lead times and limited capacity flexibility exacerbating the impact.

The German OEMs in the Supply Crisis

To discuss the situation of OEMs in the crisis years, we start from financial performance and use return on sales (RoS) as a financial performance indicator, as it measures operational efficiency by showing how much of a company's revenue is converted into operating profit. In a crisis, this shows how well a company is managing its cost structure and pricing under pressure. In addition, a stable or improving RoS during a crisis indicates strategic agility and good operational cost discipline. As a relative indicator, RoS allows for direct comparability between companies of different sizes, which is useful when comparing smaller (such as BMW) and larger OEMs (such as Volkswagen). Overall, these benefits outweigh the limitation that RoS does not capture

underlying strategic or structural challenges, such as a misalignment between a company's product mix and evolving consumer demand.

Volkswagen Group

The Volkswagen Group sold 11 million vehicles in 2019. In the first year of the pandemic, the figure was only 9.3 million units, a decline of more than 15%. This level was not exceeded again during the semiconductor supply crisis. Overall, Volkswagen showed the lowest financial performance of the three car manufacturers in terms of RoS. In 2020, the RoS was 4.3%. It then rose to 8.0% in 2021 and 8.1% in 2022, before falling slightly to 7.1% in 2023.

Despite these figures, Volkswagen managers report that purchasing and plant management were able to cushion the crisis well until mid-December 2020 [1]. In spring 2021, the supply situation had deteriorated significantly and those responsible tried to keep operations going in a „house-to-house battle" [2]. By mid-March 2021, Volkswagen was unable to build 100,000 cars [8]. The supply crisis reached its peak in summer 2021 [3]. Daily problem solving continued into the fall of 2021 [9]. In 2022, the situation eased only slightly [4, 6] and continued to require agile management of daily production [5], including reducing the prioritization of certain vehicle models, the number of shifts per week, short-time work arrangements and production shutdowns [20]. In 2023, the supply crisis had not yet been overcome, but Volkswagen was able to produce as planned [6].

In early 2022, Volkswagen established a group-wide task force for semiconductor supply at Volkswagen, called COMPASS (Cross Operational Management Parts & Supply Security), in which more than 1,000 employees were involved [18]. Volkswagen purchased semiconductors via brokers on the spot market [7] and used Wavetrade, an AI-driven digital marketplace for matchmaking [19]. From 2023, the company was able to build up a safety stock of critical components [17].

In addition to the activities of the task force, Volkswagen worked on new supply contracts for semiconductors in 2022 and initiated strategic partnerships that helped to reduce the supply crisis to a manageable level [7]. Volkswagen began purchasing semiconductors it considered strategically important directly from chipmakers such as NXP, Infineon and Renesas in October 2022, a decision that had been under discussion since early 2021 [11]. Volkswagen signed a long-term contract with Onsemi, a US-based manufacturer of power semiconductors that is highly vertically integrated (from raw material extraction to chip development and manufacturing). Onsemi is also considering becoming active in the EU [14]. Close cooperation and coordination with all players involved in the supply chain has helped to identify semiconductor demand more accurately, without the tendency to exaggerate demand seen in previous years [7].

In 2023, the Volkswagen Group founded the Semiconductor Sourcing Committee (SSC), which brings together experts from Research and Development and Purchasing from all Volkswagen brands and the software subsidiary CARIAD to work together with Tier 1 suppliers to define the semiconductors contained in the electronic control units of Volkswagen Group vehicles [15]. The SSC aims at complexity (reducing the number of variants, promoting system-on-chip solutions), standardization and implements component-level risk management [18] based on end-to-end transparency linking vehicle configurations and semiconductor use [55]. Volkswagen began the joint development of an automotive semiconductor with STMicroelectronics for the first time in fall 2022 [12]. In the future, Tier 1 suppliers will only use the jointly developed system-on-chip (SoC) or Stellar standard microcontrollers from STMicroelectronics to support the standardized zonal architecture designed by CARIAD. TSMC, the world's largest foundry based in Taiwan, was selected to manufacture the semiconductors for the SoC packages [16].

BMW Group

BMW has reportedly suffered less than other car manufacturers due to its close relationships with semiconductor manufacturers [13]. However, this is not fully backed up by company figures. In 2020, sales fell by 11% to 2.26 million units. In 2023, the pre-pandemic sales level was exceeded for the first time since the start of the pandemic, reaching 2.66 million units. In 2020,

the return on sales was only 4.9%, the second worst result of the three OEMs. In 2021, the company recovered strongly (12.1% RoS), while RoS fell again in 2022 (9.5%) and 2023 (9.8%).

Apart from a temporary shutdown of MINI production in the United Kingdom and at a plant in Germany, the car manufacturer was able to maintain production, albeit with a modified production plan that prioritizes high-margin vehicle models in order to secure revenue [22].

Temporarily, in 2021, BMW changed the configuration of the vehicles by removing (a) certain non-essential electronic functions such as the touchscreen function of the infotainment system [25] and (b) functions in the vehicle configurator [26]. In order to maintain production, components were also replaced, even if this meant upgrading the vehicle [26].

In collaboration with Amazon Web Services, BMW developed a smart data analytics platform that was used during the supply crisis to aggregate expected and confirmed supplier inputs and production schedules to mitigate disruptions [24]. The platform was expanded into a cloud-based data hub that integrates information that was previously isolated and not only provides basic component-level forecasts, but also puts the components into perspective, such as the modules the semiconductors are going into and the cars the modules are going into. The platform serves as a central source for suppliers to retrieve information about BMW's semiconductor needs, enriched with contextual information [28].

BMW concluded direct supply agreements with INOVA Semiconductors (fabless) and GlobalFoundries (third-party foundry) to secure the long-term supply of semiconductors. The aim of this agreement was to improve planning security and transparency by coordinating capacity planning directly with the semiconductor manufacturers and developers [21, 23, 27]. Another direct strategic partnership was agreed with Qualcomm, which provides a platform solution for advanced driver assistance and autonomous driving, including semiconductors, software and services [27].

As early as autumn 2021, BMW initiated projects to embed lessons learned into a risk management strategy and ensure that the company is less vulnerable in the future in order to institutionalize resilience [29].

Mercedes-Benz Group

Mercedes-Benz sold 2.09 million cars and vans in 2020, the first year of the pandemic. This corresponds to a drop of 15% compared to the previous year. Output recovered to 2.39 million cars in 2021, and in 2023 the pre-pandemic level was reached again. With the exception of 2020, when the return on sales was only 6.9%, Mercedes-Benz showed a strong financial performance with an adjusted return on sales of over 12%.

Mercedes-Benz dynamically adjusted the production mix to maintain sales by allocating semiconductors to premium models and even temporarily suspending lower-margin product lines such as the E-Class, but also leaving a small amount of nearly finished vehicles at the plant for retrofitting [30]. Mercedes-Benz removed or delayed non-critical functions for later retrofitting, such as the hands-free system for the trunk [31] or the control for extending and retracting the rear view camera [32], if the corresponding chips were not available to avoid a backlog. Depending on the availability of semiconductors, short-time working and controlled factory shutdowns helped to avoid chaos and last-minute production stoppages [33].

Mercedes-Benz acknowledged that transparency in the semiconductor supply chain was initially low and that improving this transparency was a top priority [30]. In 2022, Mercedes-Benz partnered with Microsoft to implement MO360, a data platform that connects all its global plants in the cloud and provides real-time production and supply chain information. In the event of supply bottlenecks, MO360 helps with the dynamic reprioritization of production processes [37].

Mercedes-Benz has expanded its semiconductor supplier base by contracting new suppliers and entering into strategic partnerships with mutual commitments to ensure preferred long-term supply, e.g. with WolfSpeed for power semiconductors [34]. As part of a "deep-tier" approach, Mercedes-Benz also aimed to directly control a larger part of the critical supply chains, including agreements with governments to secure the supply of critical raw materials [35, 36].

Reducing complexity and increasing standardization in the use of semiconductors is also a long-term goal [34]. This is also reflected in Mercedes' push towards proprietary MB.OS software, which gives the company full control over the software architecture of its vehicles and therefore control over which chips are used and how they are used [38].

FINDINGS

In this section, we categorize the results from the case analysis into the theory frameworks and relate our findings to the literature. We have identified four categories of measures:

- Short-term: Flexible production and agile product design changes
- Short-term to medium-term: Increase transparency and implement a semiconductor-specific risk management
- Medium-term to long-term: Redefining the semiconductor supply chain approach
- Medium-term to long-term: Redefining the electronic control unit (ECU) design approach

The short-term measures are what Hoppe and Podkowik (2022) refer to as task force mode, while the medium-term measures focus on risk management and the long-term measures focus on building resilience. The medium to long-term measures also fit with Tang's (2006) four basic approaches to supply chain risk management, which address risk from the perspectives of supply, demand, information and product management, as shown in **Fig 2**.

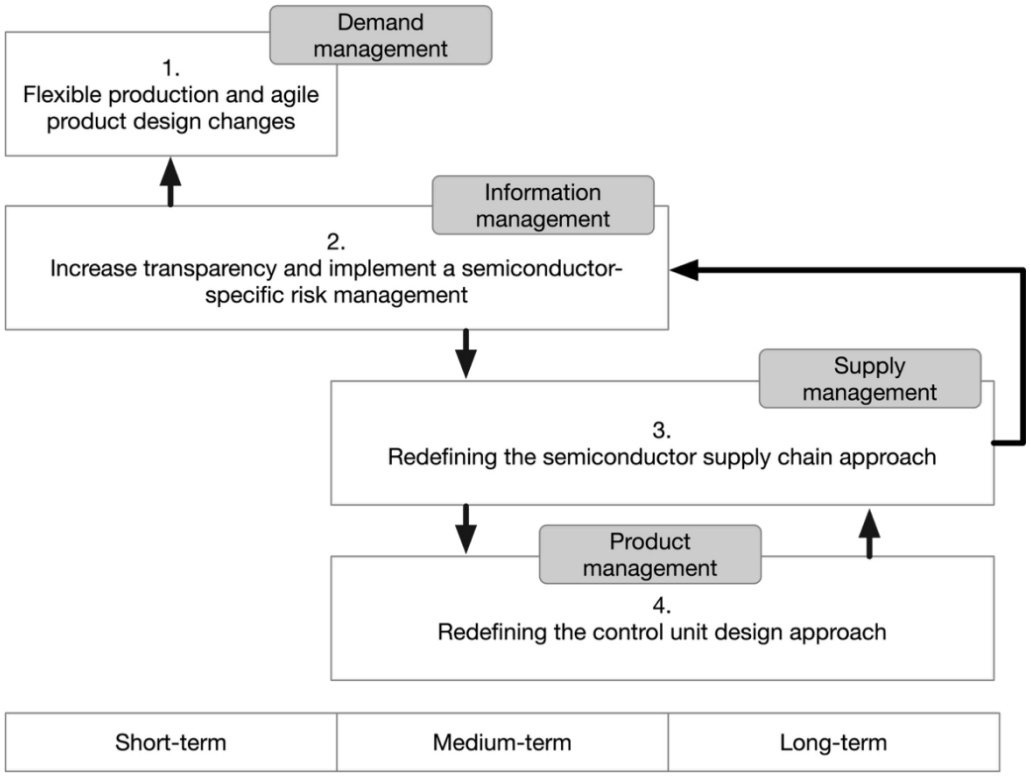


Fig. 2: From task force mode to resilience building

In the following section, we discuss the measures from the perspective of the Supply Chain Resilience Theory (SCRT), the Global Value Chain Theory (GVCT) and the Resource Dependence Theory (RDT). This discussion shows that the measures are anchored with different connotations in all three theoretical frameworks.

1. Flexible production and agile product design changes

The short-term goal was to stabilize the company during the supply crisis, with two main objectives: (1) stabilizing operations and (2) optimizing financial performance in the context of available semiconductor supply. The key resource was matching demand to available

semiconductor supply based on production flexibility and product design. Both were crucial for the OEMs to create a secure basis for further medium and long-term measures.

SCRT: Companies aimed to maximize value despite constraints by demonstrating agile operations and ensuring revenue protection in the face of supply chain disruptions. To increase business resilience, they focused on avoiding inefficiencies and protecting revenue. A key strategy was to stabilize operations through agile production planning. This included deliberately scaling back production, grouping unavoidable plant shutdowns into planned blocks and thus minimizing costs while avoiding chaotic production stops and restarts. In addition, some manufacturers decoupled final vehicle assembly from semiconductor availability. This was achieved by (a) buffering near-finished vehicles lacking certain features for later retrofitting at the factory and (b) temporarily reconfiguring products — for example, by upgrading, downgrading, replacing components or offering customers the opportunity to retrofit at a later date. These measures utilized flexibility at the product design level to maintain continuity of production. Flexibility and agility are proven building blocks of supply chain resilience (Ponomarov and Holcomb, 2009; Tukamuhabwa et al., 2015).

GVCT: Manufacturers prioritized specific product lines as a form of internal reconfiguration of the supply chain, aligning production more closely with available supply. They maintained control over sales and product mix to manage upstream bottlenecks, partially decoupling the downstream supply chain from upstream bottlenecks. Planned production stoppages were used strategically to allow the supply chain to recover and restock. OEMs maintained production throughput by changing the value proposition of the vehicle, taking an adaptive approach to downstream value creation. They also left vehicles unfinished to be retrofitted later either at the factory or in the field, effectively splitting production into two phases — initial assembly and later completion — which can be understood as a forced but deliberate postponement blurring assembly, warehousing and retail (Yang and Burns, 2003). To bridge supply gaps, they synchronized production capacity with the availability of critical components.

RDT: From the RTD perspective, OEMs used various buffer strategies to protect themselves from disruptions and restore stability (Bode et al., 2011). Dependence on semiconductors was not eliminated, but OEMs mitigated the impact of the supply crisis by focusing limited chip resources on vehicle models that ensured financial stability. This strategy indirectly strengthened their position to withstand the shortage over time. It also allowed them to manage their dependence by reducing semiconductor demand, which was achieved by changing vehicle configurations. By stockpiling unfinished vehicles, dependency could be mitigated over time, buying time so that production was not entirely dependent on real-time chip deliveries. Instead of being at the mercy of irregular supply streams, OEMs decided to accept short-term restrictions. By introducing planned production stops, they regained control of their operations and strategically accepted short-term production cuts to maintain long-term stability.

2. Increase transparency and implement a specific risk management

In response to the supply crisis, OEMs have had to put enormous effort and resources into managing the chip shortage, i.e., allocate chips to vehicle models and rescheduling production. Creating end-to-end transparency in the semiconductor supply chain helped to implement short-term measures and prepared the ground for defining new supply chain structures.

SCRT: OEMs increased transparency by providing comprehensive, end-to-end information about their semiconductor requirements by linking chips to ECUs, vehicle models, configurations, brands and production sites. This approach enabled a shift from reactive to proactive planning, allowing bottlenecks to be identified earlier and countermeasures to be initiated more effectively. The shared information environment supported agile decision making as all supply chain actors worked from a common perspective. This improved anticipation, adaptability and the speed of response and recovery in the event of disruptions. In addition, the experience gained from the projects helped OEMs to move from ad hoc resilience to planned resilience and integrate it as a core element of their long-term supply chain strategy. As a result, their supply chains gained flexibility and improved their ability to proactively mitigate risk. From the SCRT perspective, end-to-end visibility is a key capability that is essential for building resilient supply chains (Christopher and Peck, 2004).

GVCT: OEMs gained end-to-end real-time visibility, which improved their control over the value chain and the reliability of demand information. This was made possible by reducing fragmented, independent sourcing decisions within the organization.

They also changed the information structure of the value chain by moving from a linear pipeline model to a digitally integrated network. In this way, OEMs transformed their role from pure vehicle manufacturers to supply chain orchestrators. By establishing themselves as central data hubs, they enabled coordinated decision making between supply chain actors and introduced a new form of governance through data. From the GVCT perspective, end-to-end visibility facilitates networked governance (Kano et al., 2020), with OEMs assuming the role of orchestrator (Keller et al., 2024).

RDT: By investing in data hubs and promoting the exchange of information, OEMs strengthened their position in supplier relationships through superior knowledge and transparency. They reduced external dependencies by building an integrated knowledge base and aligning suppliers' interests more closely with their own. As a result, supply decisions shifted from a pure market orientation to a response to the OEMs' clearly identifiable and coordinated demand. OEMs became less reliant on reactive problem solving and gained more proactive control over semiconductor supply. Through strategic information sharing, they also created more symmetrical dependencies and used data transparency as a means to influence supplier behavior and strengthen coordination. In terms of RTD, supply chain resilience is created through a combination of buffering and bridging strategies. Bridging strategies build inter-organizational relationships that connect the company more closely with external actors (Blackhurst et al., 2011). Although end-to-end transparency projects initially served the immediate need to support short-term buffering strategies, they formed the backbone for the bridging measures that redefined the supply chain approach.

3. Redefining the supply chain approach

OEMs abandoned their traditional position in the supply chain (buying ECUs from Tier 1 suppliers). Instead, they worked to gain direct control of semiconductor supply by (a) buying semiconductors directly from semiconductor manufacturers, (b) entering into long-term supply agreements, and (c) negotiating with foundries for production capacity.

SCRT: By leveraging end-to-end visibility, OEMs were able to increase the resilience of their supply chain by establishing deep collaboration with semiconductor manufacturers, which is an essential element of resilience (Scholten and Schilder, 2015) and gave them greater control over the upstream supply chain. They were aware of the complexity of semiconductor production and recognized that this required not only negotiating component supplies, but also securing production capacity itself. By concluding long-term supply agreements, OEMs were able to secure certain chip quantities and thus protect themselves against market fluctuations. These efforts also improved transparency and visibility throughout the supply chain, especially in the upstream phases. In addition, OEMs strengthened their resilience to geopolitical risks by building a more regionalized supply base, reducing their vulnerability to global disruptions.

GVCT: In their quest for greater integration and control over the value chain, OEMs moved beyond their traditional role as buyers and positioned themselves as direct partners of semiconductor manufacturers and coordinators of the entire supply chain (Gereffi et al., 2005). Semiconductor manufacturers thus evolved from traditional Tier n suppliers to strategic partners of OEMs. This shift to upstream control, in some cases even extending to the sourcing of critical raw materials, fundamentally changed the governance structure of the supply chain. In parallel, OEMs invested in building regional production capacity, enabling more nearshoring and reducing the geographic concentration of semiconductor manufacturing, thereby mitigating location-specific risks.

RDT: OEMs reduced their dependence on the volatile and anonymous semiconductor market by securing more stable and predictable supply agreements. By gaining influence over semiconductor production, they were able to reduce the existing power imbalance in supplier relationships. They also increased their influence over critical resources by securing raw materials directly, a form of quasi-vertical integration that is indicative of an evolving interdependence given the growing importance of the automotive semiconductor submarket

(Casciaro and Piskorski, 2005). This approach helped to reduce dependence on intermediaries, especially traditional Tier 1 suppliers.

4. Redefining the product design approach

Original equipment manufacturers have a direct influence on the development of new ECUs by defining standardized architectures for vehicle electronics (hardware and software) and ultimately co-developing the semiconductors.

SCRT: OEMs sought to achieve a stable design by reducing the number of individual components and limiting the variety of semiconductor types used in their vehicle platforms. Using standardization, a standard tool aimed at aligned, more resilient supply chains (Pero et al., 2010), they sought to simplify system complexity and increase the substitutability of critical parts. This design approach, which favored the use of more generic and multi-purpose chips, enhanced resilience by making sourcing more flexible and crisis response more effective. In addition, OEMs built close partnerships with semiconductor manufacturers at the design stage, which helped align incentives across the supply chain and further strengthen system-wide resilience.

GVCT: OEMs improved their strategic control over the value chain by making coordinated, platform-based design decisions for all brands and models. By co-designing with semiconductor manufacturers, they were able to move up the value chain technologically and gain a greater share of the overall value creation. The standardization of components for all vehicle models reduced the coordination effort within the supply chain and streamlined the integration processes, a well-known effect of standardized product architectures (Fixson, 2005). These efforts to build strategic alliances through collaboration at the design level marked a shift towards a more relational global value chain (GVC) governance model.

RDT: OEMs reduced their external dependence by entering into formal partnerships with key semiconductor suppliers, securing long-term access to critical components and mitigating uncertainty on the supply side. This bridging strategy (Casciaro and Piskorski, 2005) enabled them to reduce their dependence on the fluctuating availability of semiconductors on the open market. At the same time, they simplified the architecture of the electronic control units, reducing the number of critical chip types required. This not only reduced complexity, but also allowed OEMs to take advantage of economies of scale in procurement.

CONCLUSION AND FUTURE RESEARCH DIRECTIONS

This paper examined how original equipment manufacturers (OEMs) in the automotive sector have responded to the disruptions in semiconductor supply in recent years. Based on the conceptual frameworks of Supply Chain Resilience Theory, Global Value Chain Theory and Resource Dependence Theory, the analysis identified two main categories of strategic responses that go hand in hand:

(1) redefining the product design approach with adjustments to architecture and product design to reduce component variety and technical complexity, and

(2) redefining the supply chain approach based on deep-tier collaboration and formalized partnerships with semiconductor suppliers to secure access to critical resources and mitigate market volatility.

The study shows that OEMs have chosen a dual approach that combines internal design-related structural strategies with external coordination and cooperation mechanisms. This hybrid model has allowed them to mitigate dependencies, absorb environmental uncertainties and improve sourcing flexibility. In particular, platform-based design and standardization not only lead to cost efficiency gains, but also serve to reduce vulnerability to supplier-specific risks. At the same time, integrating suppliers in the early stages of product development aligns incentives and promotes mutual engagement across the supplier network. OEMs are increasingly integrating resilience considerations into the early stages of product development and design as a strategic response to supplier uncertainty.

It is important to note that the strategic responses are based on two fundamental capabilities: (1) flexible production and product design decisions and (2) end-to-end supply chain visibility. Together, these two enablers are not stand-alone strategic responses, but rather the operational enablers that support and enhance the implementation of resilience-oriented measures.

Limitations

This analysis is conceptual in nature and is mainly based on secondary sources and theoretical considerations. Furthermore, the focus was limited to OEMs; perspectives from upstream actors (e.g. Tier 1 and Tier 2 suppliers, foundries) and institutional stakeholders (e.g. governments, consortia) were not systematically included.

Future Research Directions

Future research may benefit from the following extensions: (1) Empirical validation in longitudinal studies: Examining the actual effectiveness of OEM strategies in enhancing semiconductor supply resilience, (2) Extended actor perspective: Incorporating upstream supply chain tiers and intermediary actors to better understand network-level dependencies, and (3) Policy interaction: Investigation of how regulatory interventions and industrial policy shape the semiconductor market and firm behavior.

REFERENCES

Arkharov, A.M., Arkharov, I.A., Dolgopyatov, D.A. & Bondarenko, V.L. (2013) ^{3}He supply crisis: reasons and challenges. *Chemical and Petroleum Engineering*, 49(1-2), 41-45.

Bargmann, S., Helms, M., Kroge, F.V. & Westermann, M. (2022) Risiko- und Krisenmanagement – Halbleiterknappheit in der Automobilindustrie. *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, 117(7-8), 498-502.

Beer, J.E. (2015) Bottleneck Management in Supply Networks: Lessons to Learn from a Synoptic Systems Perspective. In *Lecture Notes in Mechanical Engineering: Engineering Asset Management - Systems, Professional Practices and Certification,* Springer International Publishing, Cham, pp. 483-494.

Beibit, R., Fatahi Valilai, O. & Wicaksono, H. (2023) Estimating the COVID-19 Impact on the Semiconductor Shortage in the European Automotive Industry using Supervised Machine Learning. *Proceedings of the 2023 10th International Conference on Industrial Engineering and Applications*, 302-308.

Blackhurst, J., Dunn, K.S. & Craighead, C.W. (2011) An Empirically Derived Framework of Global Supply Resiliency. Framework of Global Supply Resiliency. *Journal of Business Logistics*, 32(4), 374-391.

Bode, C., Wagner, S.M., Petersen, K.J. & Ellram, L.M. (2011) Understanding Responses to Supply Chain Disruptions: Insights from Information Processing and Resource Dependence Perspectives. *Academy of Management Journal*, 54(4), 833-856.

Burriel, P., Kataryniuk, I., Pérez, C.M. & Viani, F. (2024) A new supply bottlenecks index based on newspaper data. *International Journal of Central Banking*, April, 17-67.

Casciaro, T. & Piskorski, M.J. (2005) Power Imbalance, Mutual Dependence, and Constraint Absorption: A Closer Look at Resource Dependence Theory. *Administrative Science Quarterly*, 50(2), 167-199.

Chien, C.F., Peres, S.D., Ehm, H., Fowler, J.W., Jiang, Z., Krishnaswamy, S., Lee, T.E., Monch, L. & Uzsoy, R. (2011) Modelling and analysis of semiconductor manufacturing in a shrinking world: challenges and successes. *European J. of Industrial Engineering*, 5(3), 254.

Chopra, S. & Sodhi, M.S. (2004) Managing Risk to Avoid Supply-Chain Breakdown. *MIT Sloan Management Review*, 46 (1, Fall), 53-61.

Christopher, M. & Peck, H. (2004) Building the Resilient Supply Chain. *The International Journal of Logistics Management*, 15(2), 1-14.

Craighead, C.W., Blackhurst, J., Rungtusanatham, M.J. & Handfield, R.B. (2007) The Severity of Supply Chain Disruptions: Design Characteristics and Mitigation Capabilities. *Decision Sciences*, 38(1), 131-156.

Durugbo, C.M. & Al-Balushi, Z. (2023) Supply chain management in times of crisis: a systematic review. *Management Review Quarterly*, 73(3), 1179-1235.

Durugbo, C.M. & Al-Balushi, Z. (2024) Supply chain management in times of crisis: a multi-case study. *Production Planning & Control*, 1-29.

Eisenhardt, K.M. (1989) Building Theories from Case Study Research. *The Academy of Management Review*, 14(4), 532.

Fixson, S.K. (2005) Product architecture assessment: a tool to link product, process, and supply chain design decisions. *Journal of Operations Management*, 23(3-4), 345-369.

Frieske, B. & Stieler, S. (2022) The "Semiconductor Crisis" as a Result of the COVID-19 Pandemic and Impacts on the Automotive Industry and Its Supply Chains. *World Electric Vehicle Journal*, 13(10), 189.

Garcia, J.A.C., Arvidsson, A. & Jonsson, P. (2024) An analysis of automakers navigating an evolving semiconductor landscape. *International Journal of Physical Distribution & Logistics Management*, 54(6), 586-609.

Gaudenzi, B., Pellegrino, R. & Confente, I. (2023) Achieving supply chain resilience in an era of disruptions: a configuration approach of capacities and strategies. *Supply Chain Management: An International Journal*, 28(7), 97-111.

Gereffi, G. (2020) What does the COVID-19 pandemic teach us about global value chains? The case of medical supplies. *Journal of International Business Policy*, 3(3), 287-301.

Gereffi, G., Humphrey, J. & Sturgeon, T. (2005) The governance of global value chains. *Review of International Political Economy*, 12(1), 78-104.

Gorodnyi, N.A., Fedyunina, A.A. & Simachev, Y.V. (2025) The role of pricing and export diversification in global value chains resilience: Evidence from Russian manufacturing firms under dual shocks. *Russian Journal of Economics*, 11(1), 27-46.

Hittle, B. & Moustafa Leonard, K. (2011) Decision making in advance of a supply chain crisis. *Management Decision*, 49(7), 1182-1193.

Hoppe, M. & Podkowik, W. (2022) Ways to Build Resilient Inbound Transportation Logistics in the Automotive Industry. In *Springer Series in Supply Chain Management: Supply Chain Resilience,* Springer International Publishing, Cham, pp. 315-323.

Hosseini, S. & Barker, K. (2016) A Bayesian network model for resilience-based supplier selection. *International Journal of Production Economics*, 180, 68-87.

Ivanov, D. (2020 Apr) Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case. *Transp Res E Logist Transp Rev*, 136, 101922.

Ivanov, D. & Dolgui, A. (2020) Viability of intertwined supply networks: extending the supply chain resilience angles towards survivability. A position paper motivated by COVID-19 outbreak. *International Journal of Production Research*, 58(10), 2904-2915.

Kano, L., Tsang, E.W.K. & Yeung, H.W.-c. (2020) Global value chains: A review of the multi-disciplinary literature. *Journal of International Business Studies*, 51(4), 577-622.

Keller, J., Lasch, R. & Matook, S. (2024) Governance of digital supply networks: Systematic literature review and research agenda. *Australian Journal of Management*, 49(4), 740-789.

Kepplinger, H.M. & Roth, H. (1979) Creating a Crisis: German Mass Media and Oil Supply in 1973-74. *Public Opinion Quarterly*, 43(3), 285.

Ketokivi, M. & Choi, T. (2014) Renaissance of case research as a scientific method. *Journal of Operations Management*, 32(5), 232-240.

Kravchenko, K., Gruchmann, T., Ivanova, M. & Ivanov, D. (2024) Responding to the ripple effect from systemic disruptions: empirical evidence from the semiconductor shortage during COVID-19. *Modern Supply Chain Research and Applications*, 6(4), 354-375.

Lagarde, C. (21.07.2022) Monetary Policy Statement. *European Central Bank Press Conference*, 21.07.2022).

Leslie, M. (2022) Pandemic Scrambles the Semiconductor Supply Chain. *Engineering*, 9, 10-12.

Liu, J., Mao, S., Lu, L., Jing, Y., Yang, X., Xu, H. & Ren, Y. (2025) The impact of digital economy on the supply chain resilience of cross-border healthcare e-commerce. *Frontiers in Public Health*, 13.

Magdy, M., Grida, M. & Hussein, G. (2024) Disruption mitigation in the semiconductors supply chain by using public blockchains. *The Journal of Supercomputing*, 80(2), 1852-1906.

Mathes, J. (2025) Chiplets at the Very Heart of the Revolution. *ATZ worldwide*, 127(2-3), 62-62.

Meredith, J. (1998) Building operations management theory through case and field research. *Journal of Operations Management*, 16(4), 441-454.

Mohammad, W., Elomri, A. & Kerbache, L. (2022) The Global Semiconductor Chip Shortage: Causes, Implications, and Potential Remedies. *IFAC-PapersOnLine*, 55(10), 476-483.

Mönch, L., Uzsoy, R. & Fowler, J.W. (2018) A survey of semiconductor supply chain models part I: semiconductor supply chains, strategic network design, and supply chain simulation. *International Journal of Production Research*, 56(13), 4524-4545.

Münch, C. & Hartmann, E. (2023) Transforming resilience in the context of a pandemic: results from a cross-industry case study exploring supply chain viability. *International Journal of Production Research*, 61(8), 2544-2562.

Panchal, N., Topre, P. & Kabir, G. (2024) Evaluation of Semiconductor Risk Mitigation Strategies in the Electric Vehicle Supply Chain. *ICIMP 2024*, 30.

Pashapour, S., Bozorgi-Amiri, A., Azadeh, A., Ghaderi, S.F. & Keramati, A. (2019) Performance optimization of organizations considering economic resilience factors under uncertainty: A case study of a petrochemical plant. *Journal of Cleaner Production*, 231, 1526-1541.

Pero, M., Abdelkafi, N., Sianesi, A. & Blecker, T. (2010) A framework for the alignment of new product development and supply chains. *Supply Chain Management: An International Journal*, 15(2), 115-128.

Ponis, S.T. & Ntalla, A. (26-28 November 2015) Crisis Management Practices and Approaches: Insights from Major Supply Chain Crises. *3rd Global Conference on Business, Economics, Management and Tourism*, *Procedia Economics and Finance* 39, pp. 668-673,

Ponomarov, S.Y. & Holcomb, M.C. (2009) Understanding the concept of supply chain resilience. *The International Journal of Logistics Management*, 20(1), 124-143.

Postma, D.J., Notenboom, K., De Smet, P.A.G.M., Leufkens, H.G.M. & Mantel-Teeuwisse, A.K. (2023 Mar 14) Medicine shortages: impact behind numbers. *Journal of Pharmaceutical Policy and Practice*, 16(1), 44.

Ramani, V., Ghosh, D. & Sodhi, M.S. (2022) Understanding systemic disruption from the Covid-19-induced semiconductor shortage for the auto industry. *Omega*, 113, 102720.

Santos, F.C., Silva, A.L., Paterlini, B., Pedroso, H.G., Alves, J.M., Milani, P.H.P. & Klepa, R.B. (2024) Zonal Architecture: A Way of Using of the CAN Protocol. *SAE Technical Paper Series*, 2024-36-0127.

Scholten, K. & Schilder, S. (2015) The role of collaboration in supply chain resilience. *Supply Chain Management: An International Journal*, 20(4), 471-484.

Sheffi, Y. & Rice Jr., J.B. (15.10.2005) A Supply Chain View of the Resilient Enterprise. *MIT Sloan Management Review*, 47(1) Fall 2005, 41-48.

Shih, W.C. (2020) Global Supply Chains in a Post-Pandemic World. *Harvard Business Review*, 5 (September-October), 82-89.

Statsenko, L., Scholten, K. & Stevenson, M. (2025) The influence of global value chain governance on supply network resilience. *Supply Chain Management: An International Journal*, 30(2), 161-177.

Sun, X., Shi, Q. & Hao, X. (2022) Supply crisis propagation in the global cobalt trade network. *Resources, Conservation and Recycling*, 179, 106035.

Tang, C.S. (2006) Perspectives in supply chain risk management. *International Journal of Production Economics*, 103(2), 451-488.

Tukamuhabwa, B.R., Stevenson, M., Busby, J. & Zorzini, M. (2015) Supply chain resilience: definition, review and theoretical foundations for further study. *International Journal of Production Research*, 53(18), 5592-5623.

VDA. (05.01.2022) *Deutscher Pkw-Markt 2021: Erholung ausgebremst,* Press release, German Association of the Automotive Industry, Berlin.

https://www.vda.de/de/presse/Pressemeldungen/2022/220105_Deutscher-Pkw-Markt-2021_Erholung-ausgebremst

VDA. (08.01.2021) *Coronaeffekt: Austausch älterer Autos stockt,* Press release, German Association of the Automotive Industry, Berlin. https://www.vda.de/de/presse/Pressemeldungen/2021/210108-Corona-Effekt--Austausch--lterer-Autos-stockt

Wan, Z., Su, Y., Li, Z., Zhang, X., Zhang, Q. & Chen, J. (2023) Analysis of the impact of Suez Canal blockage on the global shipping network. *Ocean & Coastal Management*, 245, 106868.

Wang, L., Deng, T. & Li, Q. (2025) Can feature removal benefit the automotive manufacturers amid supply shortages? An analytical investigation. *Omega*, 132, 103227.

Wang, X., Li, H., Yao, H., Zhu, D. & Liu, N. (2018) Simulation analysis of the spread of a supply crisis based on the global natural graphite trade network. *Resources Policy*, 59, 200-209.

Wieland, A. & Durach, C.F. (2021) Two perspectives on supply chain resilience. *Journal of Business Logistics*, 42(3), 315-322.

Xiong, W., Wu, D.D. & Yeung, J.H.Y. (2024) Semiconductor supply chain resilience and disruption: insights, mitigation, and future directions. *International Journal of Production Research*, 1-24.

Yan, J., Guo, Y. & Zhang, H. (2024) The dynamic evolution mechanism of structural dependence characteristics in the global oil trade network. *Energy*, 303, 131914.

Yang, B. & Burns, N. (2003) Implications of postponement for the supply chain. *International Journal of Production Research*, 41(9), 2075-2090.

Yin, R.K. (2018) *Case Study Research and Applications: Design and Methods, 6th*. SAGE Publications, Thousand Oaks.

YOLE (17.10.2023) *Automotive semiconductor: A 100 billion device industry in 2028,* Press release, YOLE Group, https://www.yolegroup.com/press-release/automotive-semiconductor-a-100-billion-device-industry-in-2028/

Zhang, F. (16.07.2024) *EV and ADAS trends drive carmakers into the semiconductor arena,* EV Design & Manufacturing, https://www.evdesignandmanufacturing.com/news/semiconductor-testing-pivotal-meeting-quality-cost-time-to-market-demands/

APPENDIX

[1] „Wir sind bisher gut durch die Krise gekommen, dank eines hervorragenden Beschaffungs- und Produktionsmanagements. Allerdings bekommen wir nun die Auswirkungen der globalen Engpässe bei Halbleitern zu spüren. Wir tun alles, um Produktionsausfälle so gering wie möglich zu halten, um unsere Kunden schnellstmöglich beliefern zu können."

Quote: Murat Aksel, 18.12.2020 (designated CPO)

Source: https://www.google.com/url?sa=t&source=web&rct=j&opi=89978449&url=https://www.volkswagen-group.com/de/pressemitteilungen/schnelle-erholung-der-automaerkte-hat-halbleiter-engpass-zur-folge-konzern-muss-produktion-anpassen-17118/download%3Fdisposition%3Datt

[2] „Wir sind im Häuserkampf."

Quote: Murat Aksel, 23.03.2021 (CPO)

Source: https://deutsche-wirtschafts-nachrichten.de/510641/wir-sind-im-haeuserkampf-chip-lieferketten-fuer-europas-autobauer-an-mehreren-stellen-gebrochen

[3] „Im Moment sind wir am tiefsten Punkt in der Versorgungskrise angekommen. Wir stehen vor den härtesten sechs Wochen."

Quote: Murat Aksel, 14.06.2021 (CPO)

Source: https://www.handelsblatt.com/unternehmen/industrie/murat-aksel-im-interview-vw-einkaufsvorstand-zum-chipmangel-wir-stehen-vor-den-haertesten-sechs-wochen/27263554.html

[4] „Im Gesamtjahr erwarten wir gegenüber 2021 eine leichte Verbesserung in der Halbleiterversorgung."

Quote: Murat Aksel, 08.12.2021 CPO)

Source: https://www.automobilwoche.de/agenturmeldungen/vw-sieht-stabilere-lage-bei-chipversorgung

[5] „Wir agieren flexibel und steuern täglich bestmöglich aus. … Ich blicke daher vorsichtig optimistisch ins Jahr 2022."

Quote: Oliver Blume, 04.02.2022 (CEO Porsche AG)

Source: https://newsroom.porsche.com/de/2022/unternehmen/porsche-vorstandsvorsitzender-oliver-blume-interview-handelsblatt-corona-halbleitermangel-chancen-krise-27150.html

[6] „In den letzten sechs bis acht Monaten haben wir kein einziges Fahrzeug in der Produktion wegen Halbleiter verloren."

„Die Halbleiterkrise ist nicht vorbei, aber wir haben die Lage jetzt unter Kontrolle."

Quote: Dirk Große-Loheide, 24.08.2023 (CPO)

Source: https://www.autohaus.de/nachrichten/autohersteller/halbleitermangel-volkswagen-gibt-entwarnung-3425519#:~:text=Mittwoch%20in%20Wolfsburg.-

,%22In%20den%20letzten%20sechs%20bis%20acht%20Monaten%20haben%20wir%20kein,normalen%20Niveau%20vor%20der%20Krise.%22

[7] „Der Volkswagen-Konzern hat im vergangenen Jahr viele neue Lieferverträge und strategische Abkommen mit der Halbleiterindustrie geschlossen. Dadurch hat sich unsere Versorgung, aber auch unsere Produktion deutlich stabilisiert."

Quote: Karsten Schnake, 17.04.2023, CPO Škoda Auto, Head of Taskforce Semiconductors Volkswagen

Source: https://edison.media/umwelt/die-antriebswende-ist-der-richtige-schritt/25236015/

[8] „We've been unable to build 100,000 cars due to an ongoing chip shortage."

Quote: Herbert Diess, 16.03.2021, CEO of Volkswagen AG

Source: https://www.reuters.com/business/autos-transportation/volkswagen-ceo-100000-cars-lost-due-chip-shortage-2021-03-16/

[9] "We are dealing with the shortage pretty well, but it's a day-to-day troubleshooting process."

Quote: Markus Duesmann, 04.10.2021, CEO Audi

Source: https://www.streetinsider.com/Reuters/Audi+CEO+sees+chip+shortage+as+perfect+storm+but+will+get+through+it/19015255.html

[10] Volkswagen strikes direct supply deals for chips to avoid global shortage.

Source: https://www.reuters.com/business/autos-transportation/volkswagen-strikes-direct-supply-deals-chips-avoid-global-shortage-2023-08-23/

23.08.2023

[11] Volkswagen looks at direct buying to secure scarce chips

Source: https://www.reuters.com/article/business/volkswagen-looks-at-direct-buying-to-secure-scarce-chips-idUSKBN2A2203/

02.02.2021

[12] Volkswagen to develop new semiconductor with STMicro amid chip crunch

Source: https://www.reuters.com/technology/volkswagen-develop-new-semiconductor-with-stmicro-amid-chip-crunch-2022-07-20/

20.07.2022

[13] BMW says chip shortage, raw material prices to hit second half

Source: https://www.reuters.com/business/autos-transportation/bmw-swings-q2-profit-versus-pandemic-hit-2020-2021-08-03/

03.08.2021

[14] VW bestellt SiC-Halbleiter für die SSP bei Onsemi

Source: https://www.electrive.net/2024/07/23/vw-bestellt-sic-halbleiter-fuer-die-ssp-bei-onsemi/?utm_source=chatgpt.com

23.07.2024

[15] Volkswagen Konzern richtet Halbleiter Beschaffung neu aus

Source: https://www.volkswagen-group.com/de/pressemitteilungen/volkswagen-konzern-richtet-halbleiter-beschaffung-neu-aus-17553

24.08.2023

[16] Cariad und ST entwickeln Chip für softwaredefinierte Autos

Source: https://www.springerprofessional.de/halbleiter/halbleitertechnik/cariad-und-st-entwickeln-chip-fuer-softwaredefinierte-autos/23289928?utm_source=chatgpt.com

26.07.2022

[17] Volkswagen gibt Entwarnung bei Halbleitermangel

Source: https://www.automobil-produktion.de/technologie/volkswagen-gibt-entwarnung-bei-halbleitermangel-984.html#:~:text=Kontrolle.,Einkaufsvorstand%20Karsten

25.08.2023

[18] Volkswagen entmachtet seine Zulieferer bei Halbleitern

Source: https://www.manager-magazin.de/unternehmen/autoindustrie/volkswagen-entmachtet-zulieferer-bei-der-chip-versorgung-und-vorproduktion-a-8d5b43ed-4172-4445-a700-0b2d243e05d2

23.08.2023

[19] Von Sparzwängen und digitalen Tauschbörsen

Source: https://www.waz-online.de/wirtschaft/regional/von-sparzwaengen-und-digitalen-tauschboersen-CMJBQ3I4ARA6XC4ACDNBJHAHZY.html#:~:text=Lehren%20aus%20der%20jüngeren%20Vergangenheit,Verkauf%20von%20Chips%20und%20Halbleitern

12.12.2023

[20] Volkswagen Bratislava steht wegen des Ukraine-Kriegs eine Woche still

Source: https://www.handelsblatt.com/unternehmen/industrie/produktionsstopp-volkswagen-bratislava-steht-wegen-des-ukraine-kriegs-eine-woche-still/28220312.html

01.04.2022

[21] BMW secures several million chips per year from INOVA, GlobalFoundries

Source: https://www.reuters.com/business/autos-transportation/bmw-secures-several-million-chips-per-year-inova-globalfoundries-2021-12-08/

08.12.2021

[22] BMW confirms its 2021 targets despite worsening chip shortages.

Source: https://www.reuters.com/business/autos-transportation/bmw-confirms-outlook-says-rest-2021-be-volatile-2021-05-07/#:~:text=BMW%20is%20known%20for%20its,carmaker%20has%20not%20been%20affected

07.05.2021

[23] BMW Group signs direct agreement with chip suppliers to secure supplies

Source: https://www.press.bmwgroup.com/global/article/detail/T0362334EN/bmw-group-signs-direct-agreement-with-chip-suppliers-to-secure-supplies?language=en

08.12.2021

[24] Data-Driven Disruption: How BMW is Reinventing Supply Chain Management with AI & Analytics

Source: https://www.linkedin.com/pulse/data-driven-disruption-how-bmw-reinventing-supply-chain-rzechorzek-bghre/

16.03.2025

[25] Would you buy a car without its promised tech? BMW latest to make compromises due to chip shortage

Source: https://thenextweb.com/news/would-you-buy-a-car-without-its-promised-tech-bmw-latest-to-make-compromises-due-to-chip-shortage#:~:text=This%20week%20BMW%20confirmed%20with,to%20the%20semiconductor%20chip%20shortage

09.11.2021

[26] Halbleiter-Engpässe: Auch BMW muss erste Optionen streichen

Source: https://www.bimmertoday.de/2021/02/25/halbleiter-engpasse-auch-bmw-muss-erste-optionen-streichen/#:~:text=Werksschließungen%20geführt%2C%20ohne%20Auswirkungen%20gehen,eine%20der%20fehlenden%20Komponenten%20beinhalten

25.02.2021

[27] BMW secures 'millions of semiconductors

Source: https://autovista24.autovistagroup.com/news/bmw-secures-millions-of-semiconductors/

10.12.2021

[28] How the BMW Group analyses semiconductor demand with AWS Glue

Source: https://aws.amazon.com/de/blogs/big-data/how-the-bmw-group-analyses-semiconductor-demand-with-aws-glue/

26.04.2023

[29] BMW CFO remains bullish despite chip shortage, other challenges

Sources: https://www.autonews.com/automakers/bmw-cfo-remains-bullish-despite-chip-shortage-other-challenges/

14.09.2021

[30] Daimler sees chip shortage dragging on into 2022

Source: https://www.reuters.com/business/autos-transportation/daimler-says-chip-shortage-will-continue-second-half-2021-2021-07-21/

21.07.2021

[31] Update: These are the latest developments on the chip shortage in 2021

Source: https://www.power-and-beyond.com/update-these-are-the-latest-developments-on-the-chip-shortage-in-2021-a-a259cf333ff4ecd243eb491337757493/

15.12.2021

[32] Halbleiter erst wieder Mitte 2022 zuverlässig lieferbar

Source: https://jesmb.de/7671/#:~:text=Seit%20Anfang%202021%20gibt%20es,in%20Steuergeräten%20die%20Stromkreise%20schalten

05.06.2021

[33] Halbleiter fehlen: Kurzarbeit in Mercedes Werken

Source: https://jesmb.de/7272/

03.05.2021

[34] Automotive semiconductors to the rescue

Source: https://electronics-sourcing.com/2023/03/15/automotive-semiconductors-to-the-rescue/

15.03.2023

[35] Mercedes CEO sees semiconductor shortage dragging on into 2023

Source: https://www.reuters.com/business/autos-transportation/mercedes-ceo-sees-semiconductor-shortage-lasting-into-2023-2022-06-29/

29.06.2022

[36] Annual Report 2022, Mercedes-Benz Group

Source: https://group.mercedes-benz.com/documents/investors/reports/annual-report/mercedes-benz/mercedes-benz-annual-report-2022-incl-combined-management-report-mbg-ag.pdf

2023

[37] Mercedes-Benz and Microsoft collaborate to boost efficiency, resilience and sustainability in car production

Source: https://news.microsoft.com/source/2022/10/12/mercedes-benz-and-microsoft-collaborate-to-boost-efficiency-resilience-and-sustainability-in-car-production/

12.10.2022

[38] Auf MBUX folgt bei Mercedes-Benz dieses Jahr MB.OS

Source: https://mbpassion.de/2025/01/auf-mbux-folgt-bei-mercedes-benz-mb-os/

27.01.2025

[39] TechInsights: Semiconductor week, 29. Juli 2022

Source: https://www.techinsights.com/blog/semiweek-semicon-west-and-forecast-perspectives-smics-7nm-chips-euv-changing-fab-economics?utm_source=direct&utm_medium=website

29.07.2022

[40] TechInsights: Semiconductor week, 10. February 2023

Source: https://www.techinsights.com/blog/semiweek-caution-prevails-dark-clouds-linger-semiconductor-sales-fell-9-last-week-stocks-fell?utm_source=direct&utm_medium=website

29.04.2022

[41] Lin Jones, Sarah Krulikowski, Nathan Lotze, and Samantha Schreiber: U.S. Exposure to the Taiwanese Semiconductor Industry. U.S. International Trade Commission, Economics Working Paper 2023–11–A

November 2023

[42] TechInsights: Automotive Semiconductor Market Shares 2023

Source: https://www.techinsights.com/blog/automotive-semiconductor-market-shares-2023

[43] Evertiq: Five companies control 50% of the automotive semiconductor market

Source: https://evertiq.com/news/57120

22.01.2025

[44] S&P AutoTechInsight: Automotive Semiconductor Market Tracker - January 2023

Source: https://autotechinsight.ihsmarkit.com/shop/product/5003356/automotive-semiconductor-market-tracker-january-2023

02.03.2023

[45] Navigating Complexities: The Semiconductor Shortage's Effect on the Auto Industry

Source: https://www.appliedenergysystems.com/semiconductor-shortages-effect-on-auto-industry

30.11.2023

[46] EV and ADAS trends drive carmakers into the semiconductor arena

Source: https://www.evdesignandmanufacturing.com/news/semiconductor-testing-pivotal-meeting-quality-cost-time-to-market-demands

16.07.2024

[47] Legacy Process Nodes Going Strong

Source: https://semiengineering.com/legacy-process-nodes-going-strong

23.07.2024

[48] Boston Consulting Group: Automotive Industry Semiconductor Outlook

Source: https://web-assets.bcg.com/5e/f8/953dc62240ddb4207dd751edda86/tracking-the-next-phase-of-the-automotive-semiconductor-shortage.pdf

October 2022

[49] ADAS Further Extends 7nm Challenges

Source: https://semiengineering.com/adas-further-extends-7nm-challenges/

11.10.2018

[50] Global chip shortage 2022 - updates in October

Source: https://www.power-and-beyond.com/global-chip-shortage-2022-updates-in-october-a-510db42b2e833e64672a1680b51aa8ff

12.10.2022

[51] Electronic Component Allocation & Lead Times: 2022 Update

Source: https://www.ultralibrarian.com/2022/03/22/electronic-component-allocation-lead-times-2022-update-ulc

22.03.2022

[52] Tracker: Lead Times for Automotive Semiconductors Q1 2024

Source: https://www.techinsights.com/blog/tracker-lead-times-automotive-semiconductors-q1-2024

[53] Gartner Says Worldwide Semiconductor Revenue Grew 1.1% in 2022

Source: https://www.gartner.com/en/newsroom/press-releases/2023-01-17-gartner-says-worldwide-semiconductor-revenue-grew-one-percent-in-2022

17.01.2023

[54] Gartner Says Worldwide Semiconductor Revenue Grew 10.4% in 2020

Source: https://www.gartner.com/en/newsroom/press-releases/2020-04-12-gartner-says-worldwide-semiconductor-revenue-grew-10-4-percent-in-2020

12.04.2021

[55] Volkswagen Group reorganises semiconductor procurement strategy

Source: https://siliconsemiconductor.net/article/117992/Volkswagen_Group_reorganises_semiconductor_procurement_strategy?utm_source=chatgpt.com

06.11.2023

Exploring the Impact of Port Congestion on the Delivery Schedule of Food Cold Chain Companies in Ireland

Marzieh Nazemzadeh Goki, Darshak Bhatt, Hrithik Kumar Raghavendra

Technological University Dublin, Ireland

ABSTRACT

Purpose of this paper

Port congestion represents a persistent operational challenge for food cold chain logistics, particularly within peripheral island economies that rely heavily on maritime gateways. Ireland's food supply chains are especially vulnerable to congestion-related disruptions due to concentrated port activity, limited infrastructure redundancy and strict temperature-control requirements for perishable goods. While existing literature has examined port congestion primarily from infrastructural, capacity and efficiency perspectives, limited attention has been paid to its effects on delivery schedules within food cold chain operations and the organisational responses adopted by practitioners. Moreover, much of the existing research relies on quantitative or macro-level analyses often overlooking the experiential and organisational dimensions of congestion as encountered in practice.

The purpose of this study is to examine the impact of port congestion on the delivery schedules of food cold chain companies operating in Ireland and to explore the resilience mechanisms employed by supply chain actors to manage congestion-induced delays. Specifically, the study investigates how congestion affects time-sensitive delivery schedule, temperature compliance, coordination across stakeholders and operational decision-making within cold chain logistics. By focusing on Ireland as a peripheral island economy, the study seeks to address a contextual gap in the literature and contribute empirically grounded insights into congestion management within food cold chain supply networks.

Design / Methodology / Approach

The study adopts an interpretivist research philosophy and an inductive qualitative research design to capture in-depth insights into how port congestion is experienced and managed by stakeholders within Ireland's food cold chain. A qualitative approach was selected to reflect the complex, context-dependent and socially embedded nature of congestion-related disruption, which cannot be fully understood through quantitative indicators alone.

Primary data were collected through eight semi-structured interviews with stakeholders directly involved in port operations and food cold chain logistics. Participants included representatives from port authorities, logistics service providers, freight forwarders and food supply chain operators with direct responsibility for managing congestion-related challenges. Semi-structured interviews enabled consistent exploration of key themes while allowing participants to elaborate on their experiences and operational practices.

Interviews were transcribed verbatim and analysed using NVivo-supported thematic analysis. An inductive coding approach was employed to allow themes to emerge from the data rather than being predefined. The analysis followed established qualitative rigor procedures, including iterative coding, cross-case comparison and thematic validation across participant accounts. This approach enabled the identification of recurring patterns related to congestion drivers, delivery schedule impacts, coordination challenges and resilience practices within Ireland's food cold chain logistics.

Findings

The findings indicate that port congestion has a direct and sustained impact on the delivery schedules of food cold chain companies in Ireland. Participants consistently reported congestion-related delays ranging between four and six hours per shipment, with cumulative downstream effects on transport scheduling, cold storage utilisation and delivery reliability. These delays increased the risk of temperature deviations, intensified pressure on time-sensitive operations and reduced overall schedule predictability.

Multiple interconnected causes of congestion were identified, including infrastructure constraints, vessel bunching, customs and regulatory processing delays, labour shortages and coordination inefficiencies among port stakeholders. Seasonal demand fluctuations and external disruptions further amplified congestion pressures.

The analysis highlights the critical role of organisational and relational resilience mechanisms in mitigating congestion impacts. Participants described reliance on informal communication channels, flexible scheduling adjustments, contingency planning and collaborative problem-solving with port authorities and logistics partners. Human judgement and experiential knowledge were central to managing congestion in real time, often compensating for limitations in technological and infrastructural systems. Although digital tools and tracking technologies were viewed as supportive, their effectiveness was constrained by uneven adoption and limited integration across stakeholders.

Value

This study contributes empirically and conceptually to research on port congestion, food cold chain logistics and supply chain resilience. Empirically, it provides context-specific insights into delivery schedule disruptions within Ireland's food cold chain, a setting that remains underrepresented in the literature. Conceptually, the findings extend resilience discourse by demonstrating the importance of organisational, relational and human capabilities in managing congestion, complementing dominant infrastructure-focused perspectives. Practically, the study offers insights for port authorities, logistics managers and policymakers seeking to improve delivery reliability through integrated congestion mitigation strategies.

Practical Implications

The results indicate that in order to reduce delivery delays caused by congestion, port authorities and cold chain logistics managers should give priority to better coordination systems, real-time information exchange and cooperative planning. Schedule reliability can be improved by supporting cross stakeholder communication methods and investing in integrated digital systems. In order to improve congestion resilience in time-sensitive food supply chains, policymakers should also take into account specific infrastructural and personnel capacity upgrades.

Research Limitations

There are a number of limitations to this study that should be noted. First and foremost the results cannot be applied outside of the Irish context due to the qualitative approach and small sample size. Second, insights are derived from self-reported experiences which could be influenced by subjective interpretation or recall bias. Third, the study ignores the viewpoints of regulators and end retailers who could provide more information in favor of concentrating on operational stakeholders.

Keywords

Cold chain logistics, port congestion, delivery schedule, supply chain resilience, perishable food, lead time, stakeholder collaboration

INTRODUCTION

Within marine logistics networks, ports play a crucial role as nodes where capacity limitations and inefficient processes can result in bottlenecks that have a domino effect on interconnected supply chain participants. (Li, 2008; Gülmez et al., 2023). Drawing on network and bottleneck theory, port congestion increases systemic vulnerability by disrupting the synchronisation of cargo handling, hinterland transportation and vessel arrivals. In recent years, regulatory changes, labour shortages and external shocks such as geopolitical events and pandemics have exacerbated these vulnerabilities, leading to persistent congestion at major ports and undermining supply chain performance in terms of lead time predictability, delivery reliability and cost efficiency (Li et al., 2024).

These risks are particularly acute for food cold chain logistics, where strict temperature control and delivery precision are essential to maintain product integrity, regulatory compliance and food safety. Delays within port operations can rapidly translate into spoilage risks, increased operational and inventory costs and reduced service reliability (Iyer & Robb, 2024). Ireland, as a peripheral island economy with a high dependence on maritime trade, is especially vulnerable to port-related disruptions. Over 90% of Ireland's foreign trade by volume passes through its ports, making port performance a critical determinant of national food supply continuity and economic stability (Central Statistics Office, 2024).

Port congestion has emerged as a structural constraint within the Irish port system. Dublin Port operates close to capacity and handles the majority of containerised traffic, while Rosslare Europort, despite its increased strategic importance following Brexit, faces limitations in specialised cold chain infrastructure, including reefer plug availability and cold storage capacity (Irish Maritime Development Office, n.d.). The redirection of trade flows away from the UK landbridge towards direct European routes, combined with broader global shipping disruptions, has further intensified operational pressure on Irish ports, exposing systemic capacity constraints and coordination gaps.

Despite the significance of ports to Ireland's agri-food sector, limited empirical research examines how port congestion affects the variable nature of delivery schedules within Ireland's food cold chain. Existing studies tend to focus on major global hubs, offering limited insight into the challenges faced by peripheral port systems. Addressing this gap, this study investigates the impact of port congestion on delivery schedules and examines the resilience mechanisms employed by food cold chain stakeholders operating through Irish ports, with particular attention to Dublin Port and Rosslare Europort.

LITERATURE REVIEW

This literature review examines the impact of port congestion on cold chain logistics, with particular emphasis on delivery performance, supply chain resilience and the operational context of Ireland's food cold chain. The chapter first explores the vulnerability of cold chain logistics to port congestion, focusing on how delays affect lead times, product quality and service reliability. It then reviews the concept of supply chain resilience within cold chain operations, highlighting strategies employed to mitigate congestion-related disruptions. The discussion subsequently examines technological and organisational enablers, including digitalisation, automation and infrastructure development and critically evaluates their limitations. Finally, the review identifies key gaps in the existing literature, particularly the limited attention given to human and organisational perspectives within peripheral port systems, thereby positioning the present study within the academic discourse.

Cold chain logistics are inherently vulnerable to delays due to their reliance on precise timing and strict temperature control. As global trade has intensified, ports have become critical nodes within time- and temperature-sensitive supply chains, especially for perishable food products (Fang et al., 2018; Shashi et al., 2021). Port congestion increases dwell times during unloading, inspection and customs clearance, amplifies lead-time variability and undermines delivery reliability. The literature consistently identifies congestion as a key driver of quality deterioration, increased operational costs and service instability within cold food supply chains (Onwude et al., 2020; Chen et al., 2022; Shashi et al., 2021). Disruptions at ports, including congestion, infrastructure constraints and procedural delays, have therefore attracted growing scholarly

attention due to their disproportionate effects on cold chain reliability, food safety and food waste (Chen et al., 2022; Kumar et al., 2023). For island economies reliant on maritime gateways, such as Ireland, port congestion poses systemic risks to food availability and supply chain continuity.

In response to increasing disruption, supply chain resilience has emerged as a central concept in logistics research. Resilience is commonly defined as the capacity of supply chains to anticipate, absorb and adapt to disruptions while maintaining core operational functions (Shashi et al., 2021). Within cold chain contexts, resilience capabilities such as collaboration with logistics partners, flexible scheduling and contingency planning are particularly critical due to the high cost of failure and the irreversibility of product spoilage (Fang et al., 2018). Empirical studies suggest that resilient cold chains are better positioned to mitigate congestion impacts by reallocating resources, rerouting shipments and enhancing coordination across supply chain actors (Chen et al., 2022).

Technological and organisational enablers are frequently proposed as mechanisms to address port congestion and cold chain inefficiencies. Digitalisation initiatives, including real-time cargo tracking, Internet of Things (IoT) sensors, blockchain-based traceability and AI-driven scheduling systems, have the potential to enhance visibility, improve throughput and support proactive decision-making (Kumar et al., 2023; Niu et al., 2024). These technologies also support regulatory compliance by enabling continuous monitoring of temperature and handling conditions throughout transit. However, the literature cautions against technology-centric approaches that overlook organisational readiness and human factors. Studies indicate that workforce capability, trust in automated systems and organisational culture significantly influence the effectiveness of digital transformation initiatives (Blanka et al., 2022; Madzík & Sieber, 2024). Similarly, while infrastructure expansion is widely advocated as a long-term solution to congestion, research suggests that physical capacity increases alone are insufficient unless complemented by organisational adaptation and collaborative governance mechanisms (Muadzah & Suryanto, 2024; Georgescu et al., 2024).

Despite extensive discussion of congestion, resilience and technological solutions, the literature remains fragmented and predominantly focused on major global hub ports. Limited attention has been paid to the experiential, human and organisational dimensions of congestion within peripheral port systems, where operational constraints and limited redundancy are more pronounced (Emenike et al., 2016; Peng et al., 2020). Furthermore, existing studies often rely on quantitative or macro-level analyses, offering limited insight into how logistics professionals interpret regulatory requirements and make real-time decisions under congestion conditions (Zhang et al., 2024). Qualitative approaches, particularly semi-structured interviews, are increasingly recognised as effective for capturing these insights and bridging the gap between strategic planning and operational practice (Lim et al., 2021; Ding & Lee, 2024). Addressing these gaps, the present study adopts a qualitative, stakeholder-focused approach to examine how port congestion affects delivery schedules and how resilience is enacted in practice within Ireland's food cold chain (Bai et al., 2023).

METHODOLOGY

This study adopts an interpretivist research philosophy and an inductive qualitative design to explore how port congestion is experienced and managed within Ireland's food cold chain. A qualitative approach is appropriate given the socially embedded and context-dependent nature of congestion-related disruption, which is shaped by organisational behaviour, regulatory interactions and stakeholder coordination (Walsham, 2006; Saunders et al., 2019; Creswell & Poth, 2013).

Primary data were collected through eight semi-structured interviews with stakeholders directly involved in port operations and cold chain logistics, including port authorities, logistics service providers and freight forwarders. Semi-structured interviews enabled in-depth exploration of congestion impacts, coordination challenges and mitigation strategies, while allowing flexibility to probe participant experiences and interpretations (Bryman, 2012; Peters & Halcomb, 2015; Onwuegbuzie & Leech, 2005; Saunders et al., 2019).

Data were transcribed verbatim and analysed using NVivo-assisted thematic analysis. An inductive coding approach was employed to allow patterns and themes to emerge directly from the data, consistent with theory-building research in complex logistics environments (Thomas, 2006; Gioia et al., 2013). Analytical rigor was ensured through iterative coding, cross-participant comparison and alignment between research design, data collection and analysis procedures, enhancing credibility and ecological validity (Bryman, 2012).

FINDINGS

The findings indicate that port congestion has a direct and sustained impact on delivery schedules within Ireland's food cold chain. Participants reported congestion-related delays ranging from four to six hours per shipment, leading to increased lead-time variability, inventory pressure and heightened risk of temperature deviations.

Causes of Congestion

Question 1: In what ways have port congestion incidents influenced your company's decision-making, including route planning, supplier contracts or stockholding policies?

Figure 3 NVivo Empirical Analysis for Parent Theme Causes Of Port Congestion

Congestion was attributed to infrastructure constraints, customs and regulatory delays, weather disruptions and high traffic volumes. Procedural inefficiencies, including limited pre-clearance mechanisms, further extended waiting times during peak periods.

Operational Impacts

Question 2: From your perspective, what were the most significant operational challenges you faced during these congestion periods and how did you respond to them?

Figure 4 NVivo Empirical Analysis for Parent Theme Causes Of Port Congestion

Delays resulted in increased storage costs, stockouts and reduced schedule predictability. Firms reported reliance on buffer stocks and schedule adjustments to mitigate spoilage risks, with some increasing safety stock levels by up to 25%.

Resilience Mechanisms

Organisational and relational capabilities played a central role in managing congestion. Stakeholders relied on informal communication channels, flexible planning and trust-based collaboration to respond to disruptions. Human judgement and experiential knowledge were critical in compensating for infrastructural limitations.

Policy Implications

Participants emphasised the need for targeted investment in cold chain infrastructure, improved customs coordination and real-time communication mechanisms. Integrated approaches combining infrastructure, technology and organisational readiness were viewed as essential for sustained congestion mitigation.

CONCLUSION

This study demonstrates that port congestion represents a persistent challenge for delivery schedule reliability within Ireland's food cold chain. As an island economy heavily dependent on maritime trade, Ireland's agri-food sector is particularly exposed to congestion-related disruption at key port gateways. The findings confirm that congestion increases lead times, costs and operational uncertainty, reinforcing the vulnerability of perishable supply chains (Meersman et al., 2012; Notteboom et al., 2021).

Importantly, the study highlights that congestion impacts are mediated by organisational and relational resilience capabilities. Cold chain actors actively deploy adaptive strategies, combining technological tools with human judgement and collaboration to maintain service continuity. These findings extend resilience theory by emphasising the interplay between infrastructure, organisation and human agency, supporting prior work on digitalisation and social capital in resilience development (Tsang et al., 2018; Johnson et al., 2013).

From a practical perspective, the results indicate that improving cold chain performance requires coordinated investment in port-specific infrastructure, streamlined regulatory processes and enhanced stakeholder collaboration. These findings align with broader supply chain disruption literature highlighting the systemic nature of congestion and the need for cross-actor coordination (Ivanov & Dolgui, 2021). While the study is limited by its qualitative and context-specific design, it provides empirically grounded insights into congestion management within peripheral port systems. Future research may adopt longitudinal and quantitative approaches to further examine resilience outcomes across different cold chain contexts.

REFERENCES

1. Bai, Y., Wu, H., Huang, M., Luo, J., & Yang, Z. (2023). How to build a cold chain supply chain system for fresh agricultural products through blockchain technology—A study of tripartite evolutionary game theory based on prospect theory. *PLOS ONE*, *18*(11), e0294520. https://doi.org/10.1371/journal.pone.0294520
2. Blanka, C., Krumay, B., & Rueckel, D. (2022). The interplay of digital transformation and employee competency: A design science approach. *Technological Forecasting and Social Change*, *178*, 121575. https://doi.org/10.1016/j.techfore.2022.121575
3. Bryman, A. (2012). *Social Research Methods*. OUP Oxford.
4. Chen, S., Meng, Q., & Choi, T.-M. (2022). Transportation research Part E-logistics and transportation review: 25 years in retrospect. *Transportation Research Part E: Logistics and Transportation Review*, *161*, 102709. https://doi.org/10.1016/j.tre.2022.102709
5. Creswell, J. W. (2013). *Qualitative Inquiry and Research Design: Choosing Among Five Approaches*. SAGE Publications. https://books.google.ie/books?id=Ykruxor10cYC
6. Ding, J., & Lee, E.-S. (2024). Promoting Consumers' Sustainable Consumption of Online Retail Cold Chain Logistics Services: Extended Applications of SOR and Cognitive-Affective-Conative Theories. *Behavioral Sciences*, *14*(9), 771. https://doi.org/10.3390/bs14090771

7. Emenike, C. C., Hoffman, A. J., & Van Eyk, N. P. (2016). *Improving Cold Chain Logistics through RFID temperature sensing and Predictive Modelling*. 2331–2338. https://doi.org/10.1109/itsc.2016.7795932
8. Georgescu, I., Bocean, C. G., Vărzaru, A. A., Rotea, C. C., Mangra, M. G., & Mangra, G. I. (2024). Enhancing Organizational Resilience: The Transformative Influence of Strategic Human Resource Management Practices and Organizational Culture. *Sustainability*, *16*(10), 4315. https://doi.org/10.3390/su16104315
9. Gioia, D. A., Corley, K. G., & Hamilton, A. L. (2013). Seeking Qualitative Rigor in Inductive Research: Notes on the Gioia Methodology. *Organizational Research Methods*, *16*(1), 15–31. https://doi.org/10.1177/1094428112452151
10. Gülmez, S., Denktaş Şakar, G., & Baştuğ, S. (2023). An overview of maritime logistics: Trends and research agenda. Maritime Policy & Management, 50(1), 97–116. https://doi.org/10.1080/03088839.2021.1962557
11. Ivanov, D. (2021). Exiting the COVID-19 pandemic: after-shock risks and avoidance of disruption tails in supply chains. *Annals of Operations Research*, *235*(1), 1627–1644. https://doi.org/10.1007/s10479-021-04047-7
12. Iyer, P., & Robb, D. (2024). *Cold Chain Optimisation Models: A Systematic Literature Review* (SSRN Scholarly Paper No. 4608611). Social Science Research Network. https://doi.org/10.2139/ssrn.4608611
13. Johnson, N., Elliott, D., & Drake, P. (2013). Exploring the role of social capital in facilitating supply chain resilience. *Supply Chain Management: An International Journal*, *18*(3), 324–336. https://doi.org/10.1108/SCM-06-2012-0203
14. Kumar, A., Bhattacharyya, S. S., & Krishnamoorthy, B. (2023). Automation-augmentation paradox in organizational artificial intelligence technology deployment capabilities; an empirical investigation for achieving simultaneous economic and social benefits. *Journal of Enterprise Information Management*, *36*(6), 1556–1582. https://doi.org/10.1108/JEIM-09-2022-0307
15. *Li, K. X. (2008). Maritime logistics in Asia. Maritime Policy & Management, 35(1), 1–3. https://doi.org/10.1080/03088830701848631*
16. Li, K. X., Wang, H., Yang, Y., & Li, M. (2024). Resilience in maritime logistics: Theoretical framework, research methodology and indicator system. *Ocean & Coastal Management*, *259*, 107465. https://doi.org/10.1016/j.ocecoaman.2024.107465
17. Lim, M. K., Li, Y., & Song, X. (2021). Exploring customer satisfaction in cold chain logistics using a text mining approach. *Industrial Management & Data Systems*, *121*(12), 2426–2449. https://doi.org/10.1108/IMDS-05-2021-0283
18. Madzík, P., & Sieber, J. (2024). The Strategic Path to Success: Key Aspects of Business Digital Transformation in the Post-Pandemic Era. *IEEE Access*, *12*, 65595–65605. https://doi.org/10.1109/ACCESS.2024.3398209
19. Meersman, H., Van De Voorde, E., & Vanelslander, T. (2012). Port Congestion and Implications to Maritime Logistics. In D.-W. Song & P. M. Panayides (Eds.), *Maritime Logistics* (pp. 49–68). Emerald Group Publishing Limited. https://doi.org/10.1108/9781780523415-004
20. Muadzah, S., & Suryanto, S. (2024). ORGANIZATIONAL CULTURE AND RESILIENCE: SYSTEMATIC LITERATURE REVIEW. *Jurnal Ilmiah Manajemen, Ekonomi, & Akuntansi (MEA)*, *8*(2), 1426–1440. https://doi.org/10.31955/mea.v8i2.4175
21. Niu, B., Dong, J., & Wang, H. (2024). Smart port vs. port integration to mitigate congestion: ESG performance and data validation. *Transportation Research Part E: Logistics and Transportation Review*, *191*, 103741. https://doi.org/10.1016/j.tre.2024.103741
22. Notteboom, T., Pallis, A., & Rodrigue, J.-P. (2021). *Port Economics, Management and Policy* (1st ed.). Routledge. https://doi.org/10.4324/9780429318184
23. Onwude, D. I., Chen, G., Eke-emezie, N., Kabutey, A., Khaled, A. Y., & Sturm, B. (2020). Recent Advances in Reducing Food Losses in the Supply Chain of Fresh Agricultural Produce. *Processes*, *8*(11), 1431. https://doi.org/10.3390/pr8111431
24. Onwuegbuzie, A. J., & Leech, N. L. (2005). On Becoming a Pragmatic Researcher: The Importance of Combining Quantitative and Qualitative Research Methodologies. *International Journal of Social Research Methodology*, *8*(5), 375–387. https://doi.org/10.1080/13645570500402447

25. Peng, B., Wang, Y., Zahid, S., Wei, G., & Elahi, E. (2020). Platform ecological circle for cold chain logistics enterprises: The value co-creation analysis. *Industrial Management & Data Systems*, *120*(4), 675–691. https://doi.org/10.1108/IMDS-10-2019-0531
26. Peters, K., & Halcomb, E. (2015). Interviews in qualitative research: A consideration of two very different issues in the use of interviews to collect research data. *Nurse Researcher*, *22*(4), 6–7. https://doi.org/10.7748/nr.22.4.6.s2
27. *Quarterly Statistics | IMDO - Irish Maritime Development Office*. (n.d.). Retrieved 7 April 2025, from https://www.imdo.ie/Home/site-area/statistics/quarterly-statistics/quarterly-statistics
28. Saunders, M. N. K., Lewis, P., & Thornhill, A. (2019). *Research Methods for Business Students*. Pearson Education. https://books.google.ie/books?id=TMGYDwAAQBAJ
29. Shashi, S., Centobelli, P., Cerchione, R., & Ertz, M. (2021). Food cold chain management: What we know and what we deserve. *Supply Chain Management: An International Journal*, *26*(1), 102–135. https://doi.org/10.1108/SCM-12-2019-0452
30. *Statistics of Port Traffic Q4 and Year 2023—Central Statistics Office*. (2024, May 28). CSO. https://www.cso.ie/en/releasesandpublications/ep/p-spt/statisticsofporttrafficq4andyear2023/
31. Thomas, D. R. (2006). A General Inductive Approach for Analyzing Qualitative Evaluation Data. *American Journal of Evaluation*, *27*(2), 237–246. https://doi.org/10.1177/1098214005283748
32. Tsang, Y. P., Choy, K. L., Wu, C. H., Ho, G. T. S., Lam, C. H. Y., & Koo, P. S. (2018). An Internet of Things (IoT)-based risk monitoring system for managing cold supply chain risks. *Industrial Management & Data Systems*, *118*(7), 1432–1462. https://doi.org/10.1108/IMDS-09-2017-0384
33. Walsham, G. (2006). Doing interpretive research. *European Journal of Information Systems*, *15*(3), 320–330. https://doi.org/10.1057/palgrave.ejis.3000589
34. Zhang, J., Xie, C., & Huang, S. (Sam). (2024). Resilient leadership in hospitality and tourism enterprises: Conceptualization and scale development. *International Journal of Contemporary Hospitality Management*, *36*(4), 1299–1326.

Enhancing Resource Efficiency in Regenerative Agricultural Supply Chains Using an Input-Narrowing-Focused Circularity Index

Kwok Hung Lau, Priyabrata Chowdhury

RMIT University, Australia

INTRODUCTION

Circularity in agricultural supply chains during the production stage is critical for enhancing resource efficiency, reducing crop loss, and lessening environmental impact. This is particularly important for the Australian banana industry, where annual crop loss and waste per farm can range from 20% to 30% of production (Downham 2022; Slatter 2023, 2024). In 2024, Australia produced 369,000 tonnes of bananas worth $697.8 million (ABS 2025). However, the industry continues to face significant crop losses, with an average farm-level waste rate of 21% in 2024, compared with 24% in 2023 and 29% in 2022 (Slatter 2024, 2023; Downham 2022). Such losses occur across various stages, including cultivation, harvesting, transportation, and distribution, often due to inefficient use of resources, suboptimal handling, market oversupply, and perishability (Al-Dairi *et al*. 2023). Incorporating circularity not only mitigates the environmental consequences of banana cultivation, such as greenhouse gas emissions from waste decomposition, but also adds economic value through by-product recovery and recycling organic waste into biofertilisers. For example, banana peels and stems can be processed into animal feed or bioenergy, contributing to a closed-loop system. Adopting precision agriculture to optimise resource inputs is another effective strategy for building a circular supply chain and a regenerative future (Alzate Acevedo *et al*. 2021, Stathatou *et al*., 2023).

An input-narrowing circularity approach in banana cultivation provides a practical pathway towards a regenerative agricultural future by reducing reliance on external inputs while enhancing on-farm resource cycling (Kotyal, 2023). By reutilising banana biomass and organic residues as soil amendments, such systems improve soil organic matter, microbial activity, and nutrient availability, thereby restoring key ecological functions (Zhang et al., 2019). The reduced dependence on synthetic fertilisers and agrochemicals lowers greenhouse gas emissions and mitigates soil and water degradation, while circular practices such as mulching, composting, and cover cropping enhance biodiversity and climate resilience (Liu et al., 2015). Collectively, these processes move banana production beyond efficiency-driven sustainability towards regeneration, in which agroecosystems actively rebuild ecological capital and strengthen long-term farmer resilience. As such, input-narrowing circularity is critical to the Australian banana industry currently facing high crop loss and waste at farm level.

Although circularity in agricultural supply chains can be measured through various approaches, such as product or material circularity (Caraceni *et al*. 2025), nutrient circularity (Van Loon *et al*. 2023), and Life Cycle Assessment-based alignment (Møller *et al*. 2024), these methods are often complex and demand extensive farm-level data that are difficult to obtain. A more practical alternative is to use a smaller set of indicators, which can provide an effective benchmarking tool to help farms advance circularity, especially at the production stage. These indicators, such as usage of fertiliser and packaging at farms, may not directly reflect circularity but serve as proxies in reducing inputs during the narrowing phase of a circular supply chain. Efficient use of resources in the banana supply chain is essential for promoting circularity by minimising waste and maximising value creation (Fiallos-Cárdenas *et al*. 2022). For example, optimising wages and contract labour services ensures fair employment practices while enhancing productivity through skilled labour (Geissdoerfer *et al*. 2017). Reduced fertiliser and chemical use, achieved through precision farming or organic alternatives, minimises environmental degradation and aligns with sustainable farming practices (Mgendi 2024). Similarly, efficient packaging design reduces material use and waste, contributing to lower carbon footprints and enabling recyclability or reuse (Radhakrishnan 2016). Streamlining on-costs and owner salary ensures financial stability while reinvesting savings into circular initiatives, such as waste-to-resource innovations or renewable energy adoption. By focusing on these resource efficiencies, farmers can achieve

balanced economic, social, and environmental outcomes. This not only enhances the overall sustainability of the supply chain but also strengthens its resilience to resource constraints, aligning with global goals for sustainable agriculture and circular economy principles. Furthermore, improving resource efficiency lowers production expenses, enhances farm profitability, and encourages the adoption of regenerative farming practices (Ecoganics, 2026).

This research develops an entropy-weighted circularity index to evaluate farm-level resource-use efficiency in the narrowing phase of agricultural supply chains, using the Australian banana industry as a case study. The aim is to create a relatively simple index that can be readily applied to benchmark farm performance in this regard to help promote regenerative farming in the industry. Owing to intense competition, Australian banana growers are typically reluctant to share sensitive production data. As a proof of concept, this study relies on secondary data from 27 banana farms across Queensland, New South Wales, and Western Australia. The dataset, extracted from the Banana Enterprise Performance Comparison report by Horticulture Australia Limited (Comiskey 2011), remains one of the most detailed publicly available sources, despite its age. Although the banana industry has evolved since 2010 placing higher priority on sustainability, water efficiency, reduced chemical use, and integrated pest management (Hort Innovation, 2022), its core production structure has remained relatively stable. The industry's fundamental structure and market orientation remain broadly consistent, making the 2011 dataset a suitable reference for this proof-of-concept study. The richness of the dataset makes it suitable for testing the feasibility of the circularity index concept. To enhance robustness and account for variability within the dataset, Shannon's (1948) entropy, an essential concept in information theory, is used to calculate indicator weights. This approach enables objective, data-driven weighting by quantifying the informational content and variability of each indicator, thereby reducing subjectivity.

LITERATURE REVIEW

Circular supply chain (CSC) integrates the principles of circular economy (CE) into supply chain management (SCM) (Viscardi *et al*. 2023). The CE concept, introduced by Boulding (1966), emphasises the Earth's finite resources and the need to circulate them within the economic system. The term "circular supply chain" first appeared in 2006 (Farooque *et al*., 2019), after which researchers began linking CE with SCM (*e.g.*, Aminoff and Kettunen 2016; De Angelis *et al*. 2018; Genovese *et al*. 2017; Jain *et al*. 2018). Building on McDonough and Braungart's (2002) focus on closing and recycling loops, and the Ellen MacArthur Foundation's (2025a) adoption of these as foundational principles, Bocken *et al*. (2016) proposed a framework centred on closing, slowing, and narrowing resource loops to enhance efficiency and retain value. Extending this logic, Batista *et al*. (2018, p. 446) define CSCs as "*the coordinated forward and reverse supply chains through purposeful business ecosystem integration, aiming for value creation from products, by-products, and waste, and improving economic, social, and environmental sustainability by extending product life cycles*," with a focus on closing material loops and extending product life cycles. This definition applies to both manufacturing and agricultural supply chains. Achieving circularity in agricultural supply chains is crucial for reducing crop loss and waste, transforming waste to value, minimising environmental impacts, and enhancing the sector's overall sustainability (Haque *et al*. 2023).

To measure circularity of agricultural supply chains, various indicators can be leveraged. The most commonly used ones include the Material Circularity Indicator (MCI) developed by Ellen MacArthur Foundation (2025b), which assesses material reuse and recycling; Circular Footprint Formula (CFF) developed by European Commission (De Rosa-Giglio *et al*. 2018), a Life Cycle Assessment-based indicator that quantifies the degree of circularity; and specific indicators for waste reduction (Rizwan *et al*. 2023), by-product valorisation (Maina *et al*. 2017), resource efficiency (Kumar *et al*. 2020), product longevity (Ojha and Yadav, 2024), and the integration of renewable energy sources (Chel and Kaushik 2011). These metrics help evaluate how well a supply chain closes loops, reduces waste, and maintains materials at high value. The use of indicators varies from case to case depending on the focus of the investigation and the availability of data.

Circularity measures in agricultural supply chains assess value retention by (i) narrowing flows (reducing virgin inputs), (ii) slowing cycles (extending produce shelf life), and (iii) closing loops (reuse, recycling, recirculation) (see for example Ambler *et al*. 2018; Martinez *et al*. 2022). The Material Circularity Indicator (MCI) remains the dominant basis, adapted to agri-food contexts through adjustments for biogenic inputs, multi-output systems, and temporal cycling (Caraceni *et al*. 2025; Rocchi *et al*. 2021). Extensions include pairing MCI with the Circular Flow Index (CFI) to capture recirculation (Barros *et al*., 2023; Tetteh *et al*. 2025) or integrating Life Cycle Assessment (LCA) for environmental alignment (Møller *et al*. 2024; Rufi-Salis *et al*. 2021). Other work examines packaging and logistics innovations such as reusable crates (Pauer *et al*. 2019; Sazdovski *et al*. 2024; Zambujal-Oliveira and Fernandes 2024), nutrient circularity metrics (Harder *et al*. 2021; Van Loon *et al*. 2023), and farm- or chain-level indicator frameworks (Ahmed *et al*. 2025; Cavicchi and Vagnoni 2022). While comprehensive, these measures are often data-intensive, with limited farm-level granularity and quality constraining robust index development and comparability. Despite its own shortcomings, a simpler index may offer more practical value for benchmarking and cross-farm assessment.

Addressing overproduction and waste in the banana supply chain, driven by retailer-imposed contractual arrangements and cosmetic standards stemming from power imbalances, is a complex challenge that requires long-term solutions. However, crop loss and waste resulting from inefficient use of labour, water, energy, fertilisers, and packaging can be mitigated more effectively in the short term through improvements in farming practices and enhanced farm management skills (Goodwin 2023). Less efficient farms can learn from more efficient ones through the support of trade association or government. Smaller farms can also collaborate to maximise usage of resources or merge to form larger farms to improve efficiency and adopt regenerative farming practices. Prior to that, it is necessary to find an easy and less data hungry way to benchmark the efficiency of farms. A simple, easy-to-use circularity index will be a valuable yardstick for guiding and assessing sustainability efforts on the ground.

METHODOLOGY

Developing a composite index, a circularity index in this case, entails selecting appropriate indicators aligned with circular economy principles, applying a suitable weighting scheme, and aggregating the data into a composite score (Elia *et al*. 2017; Lau 2011; Saidani *et al*. 2019). The process begins with identifying relevant dimensions of circularity, such as resource efficiency, waste reduction, and recycling, and selecting measurable indicators that capture these aspects. These indicators form the foundation of the index framework, which may vary in focus. For instance, the Material Circularity Indicator (MCI) by the Ellen MacArthur Foundation (2025) emphasises material flows. To ensure comparability across indicators, data are then normalised using techniques like min-max scaling or z-score normalisation (Joint Research Centre 2008). Weights are assigned based on indicator importance using approaches such as equal weighting, entropy-based methods (Shannon 1948), expert judgment, or the Analytic Hierarchy Process (AHP) (Saaty 1987). The weighted indicators are subsequently aggregated, typically through additive or multiplicative models, to produce a single circularity score (Di Maio and Rem 2015; Rosa and Terzi 2021). Prior to application, the index should undergo validation for consistency and reliability, with sensitivity analysis used to assess the effects of different weighting schemes (Gan *et al*. 2017). Once validated, the index can serve as a benchmarking tool and may be adapted to specific contexts, such as agriculture or manufacturing. For example, Rocci *et al*. (2021) adapted the MCI for the poultry sector by integrating it with Life Cycle Assessment methodology.

The data for this study are drawn from the Banana Enterprise Performance Comparison report published by Horticulture Australia Limited (HAL) in 2011 (Comiskey 2011). The report is based on a survey of 46 banana growers, representing approximately 22% of Australia's total banana production area at the time. These growers varied widely in business scale, with annual turnovers ranging from under $250,000 to over $10 million. The data reflect industry conditions in the 2008/09 period and may not capture performance trends across multiple years. Owing to potential respondent reluctance and limitations in measurement methods, the dataset contains several gaps and anomalies. After excluding cases with missing values and extreme

observations, a final sample of 27 growers was retained for analysis. For a proof-of-concept study, this sample is deemed adequate, offering a solid foundation for examining circular supply chain practices during production and constructing a circularity index based on the principle of narrowing inputs.

The selected variables: cartons packed per hectare, wages and contract labour services, fertiliser and chemical costs, packaging costs, and on-costs including owner salary, capture key aspects of resource efficiency critical to circularity in banana production. These indicators reflect the economic, social, and environmental dimensions of sustainability by promoting value creation, reducing waste and environmental impact, supporting fair labour practices, and enabling reinvestment into circular initiatives, thereby aligning banana farming with broader circular economy and sustainable agriculture goals. Cartons packed per hectare, a proxy for resource efficiency, aligns with circularity principles by assessing productivity relative to land use. Cost variables like fertiliser, chemicals, and packaging reflect resource consumption and waste generation, critical for evaluating environmental impact (Mgendi 2024; Radhakrishnan 2016). Wages, contract labour, and owner salary represent the social aspect of circularity by linking fair remuneration to sustainable practices (Geissdoerfer *et al*. 2017). Table 1 gives a profile of the dataset.

Table 1 Variables and average values of the sample data.

Variable	**Type**	**Unit**		**2008/2009**
Cartons packed per farmed hectare	Output	carton	Mean	2246.5
			S.D.	716.6
			Min.	1115
			Max.	3575
Wages and contract labour services	Input 1	$/carton	Mean	4.08
			S.D.	1.30
			Min.	2.10
			Max.	7.20
Fertiliser and chemical cost	Input 2	$/carton	Mean	2.39
			S.D.	1.12
			Min.	0.90
			Max.	4.90
Packaging cost	Input 3	$/carton	Mean	2.55
			S.D.	0.43
			Min.	1.60
			Max.	3.60
On-costs and owner salary	Input 4	% of total on-farm costs	Mean	2.71
			S.D.	1.71
			Min.	0.62
			Max.	7.36

Source: Comiskey, S. (2011), "Banana Enterprise Performance Comparison", Horticulture Australia Ltd., Project No. BA09039 (May 2011)

The dataset's granularity enables the application of entropy-based weighting method derived from Shannon's (1984) entropy concept, allowing for unbiased aggregation of these variables into a composite circularity index. Shannon's (1948) entropy is a measure of uncertainty or variability in data. The entropy-based weighting mechanism assigns weights based on the variability or discriminative power of each variable. Variables with higher variability and more informative content are given higher weights, as they provide more meaningful distinctions between farms. This ensures that variables with significant contributions to operation efficiency are emphasised over less impactful variables. Entropy-based weights enhance the discriminative power of the analysis as it allows for a finer differentiation of performance levels (Xie *et al*. 2014). This aligns with established practices in sustainability assessments (Shah *et al*. 2020). Moreover, the data focus on banana farming, a key agricultural sector, thereby ensuring practical

relevance. By integrating environmental efficiency, economic viability, and social equity, the dataset is well-suited to advancing circularity metrics, fostering sustainable supply chain transitions in the agricultural sector. Several input and output variables are used to create the circularity index. For output values, it is assumed that bigger values imply higher circularity. Therefore, the original values are kept. For input values, however, it is assumed that smaller values imply higher circularity. As such, the values will need to be reversed to ensure consistency in direction. Once the circularity index for each of the 27 banana growers are calculated, they can be classified into categories based on certain criterion for comparison as shown below:

- High circularity (top 25% of scores)
- Medium circularity (middle 50%)
- Low circularity (bottom 25%)

FINDINGS

Using equal weights (0.2, 0.2, 0.2, 0.2, 0.2), judgement weights (0.3, 0.2, 0,2, 0,2, 0.1 and 0.1, 0.2, 0.3., 0.3, 0.1), and entropy-based weights (0.343, 0.157, 0.197, 0.160, 0.143) in the calculation, the circularity indices and the categories group by quartile (*i.e*., Q1- Low, Q2 and Q3 - Medium, Q4 - High) are shown in Table 2.

Table 2 Circularity indices comprising output and input variables calculated using entropy-based approach with different weighting methods.

Farm	Equal Weights (all 0.2)	Judgement Weights 1 (0.3, 0.2, 0.2, 0.2, 0.1)	Judgement Weights 2 (0.1, 0.2, 0.3, 0.3, 0.1)	Entropy-Based Weights
1	0.483 - Medium	0.431 - Low	0.471 - Low	0.477 - Medium
2	0.638 - Medium	0.595 - Medium	0.655 - Medium	0.590 - Medium
3	0.439 - Low	0.458 - Low	0.401 - Low	0.402 - Low
4	0.725 - High (7)	0.738 - High (6)	0.733 - High (5)	0.756 - High (5)
5	0.467 - Low	0.549 - Medium	0.514 - Medium	0.400 - Low
6	0.649 - Medium	0.683 - Medium	0.664 - Medium	0.623 - Medium
7	0.630 - Medium	0.599 - Medium	0.629 - Medium	0.616 - Medium
8	0.556 - Medium	0.539 - Medium	0.563 - Medium	0.513 - Medium
9	0.611 - Medium	0.654 - Medium	0.602 - Medium	0.631 - Medium
10	0.457 - Low	0.396 - Low	0.380 - Low	0.435 - Low
11	0.574 - Medium	0.602 - Medium	0.607 - Medium	0.501 - Medium
12	0.378 - Low	0.444 - Low	0.374 - Low	0.375 - Low
13	0.728 - High (6)	0.745 - High (5)	0.707 - High (7)	0.695 - High (7)
14	0.738 - High (5)	0.717 - High (7)	0.713 - High (6)	0.741 - High (6)
15	0.796 - High (2)	0.767 - High (3)	0.757 - High (2)	0.807 - High (3)
16	0.325 - Low	0.487 - Medium	0.412 - Low	0.292 - Low
17	0.647 - Medium	0.675 - Medium	0.684 - Medium	0.648 - Medium
18	0.291 - Low	0.286 - Low	0.291 - Low	0.257 - Low
19	0.407 - Low	0.413 - Low	0.431 - Low	0.332 - Low
20	0.953 - High (1)	0.959 - High (1)	0.962 - High (1)	0.963 - High (1)

21	0.523 - Medium	0.535 - Medium	0.556 - Medium	0.444 - Medium
22	0.507 - Medium	0.506 - Medium	0.490 - Medium	0.462 - Medium
23	0.517 - Medium	0.541 - Medium	0.500 - Medium	0.464 - Medium
24	0.627 - Medium	0.650 - Medium	0.649 - Medium	0.585 - Medium
25	0.529 - Medium	0.481 - Low	0.513 - Medium	0.510 - Medium
26	0.757 - High (4)	0.782 - High (2)	0.753 - High (3)	0.790 - High (4)
27	0.791 - High (3)	0.756 - High (4)	0.743 - High (4)	0.820 - High (2)
Mean	0.583	0.592	0.584	0.560
S.D.	0.157	0.150	0.153	0.177
Min	0.291	0.286	0.291	0.257
Max	0.953	0.959	0.962	0.963

Note: ( ) indicates the ranking based on the value of the circularity index.

The findings indicate only minor differences in the circularity index categories, limited to Farms 1, 5, 16, and 25, demonstrating the robustness of the approach. In the high circularity index category, the same seven farms (Farms 4, 13, 14, 15, 20, 26, and 27) consistently emerge, with Farm 20 ranking highest in all cases. This result aligns with the analysis using the traditional variable returns to scale (VRS) input-oriented data envelopment analysis (DEA) method, where eight farms (Farms 2, 9, 12, 13, 15, 17, 20, and 27) achieve a technical efficiency score of 1. Among these, Farm 20 serves as the top peer or benchmark for other farms to emulate (Lau *et al*. 2024). This alignment underscores the reliability of the circularity index, which offers a simpler and more accessible alternative to other efficiency benchmarking methods such as the DEA approach while yielding comparable results. Identifying the most efficient farms through the circularity index provides actionable insights for decision-makers at grower associations and government agencies, enabling the development of targeted extension services, workshops, and training programs to enhance the

Table 3 presents the average values of the variables by CI category alongside farm age. The Analysis of Variance (ANOVA) results indicate that, for all five variables, the mean of at least one group differs significantly from the others.

Table 3 Average values of input and output variables and age of farm by CI category.

CI Category	Number of Growers	Cartons Packed per Hectare	Wages ($ per Carton)	Fertiliser Costs ($ per Carton)	Packaging Costs ($ per Carton)	On-Costs ($ per Carton)	Age of Farm (Year)
Low	7	1590	3.96	3.34	2.99	4.33	2.7
Medium	13	2091	4.64	2.29	2.45	2.26	4.7
High	7	3191	3.16	1.61	2.29	1.93	5.0

DISCUSSION

The findings show that using the relevant input and output variables as indicators, such as wages, fertiliser costs, packaging costs, and on-costs in an agricultural supply chain, a relatively simple index can be developed to measure resource utilisation performance at farm level which can be used as an indirect measure of circularity, especially on the narrowing and closing pathways. For example, the regression results indicate that, among the four input variables, fertiliser and packaging costs, particularly packaging, exert the strongest influence on the circularity index, as reflected in their higher coefficients. This finding can be explained by the adoption of biofertilisers and biodegradable packaging materials, which possess high circularity

characteristics such as recyclability and reusability, thereby contributing to resource regeneration. Biofertilisers reduce dependence on synthetic fertilisers by enhancing nutrient availability and soil health, lowering virgin input intensity, and supporting nutrient cycling, thereby constituting a direct narrowing pathway for circular agriculture (Miranda *et al*. 2024; Samantaray *et al*. 2024). Likewise, biodegradable, recyclable, or reusable packaging reduces material leakage and waste, enabling circular material flows across production and post-harvest stages (Cheng *et al*. 2024; Zambujal-Oliveira and Fernandes 2024). Packaging innovations are thus critical to both narrowing and closing loops within agricultural supply chains. Taken together, these results suggest that strategies aimed at reducing fertiliser and packaging costs while maintaining output can substantially improve the efficiency and circularity of the banana supply chain.

Table 3 further shows that farms in the high circularity category achieve superior input efficiency, likely reflecting better farming practices and management. This is consistent with the Banana Enterprise Performance Comparison report by Horticulture Australia Limited (Comiskey 2011, p. 9), which notes "*significant differences in the farm management activities of individual growers which in turn are leading to a wide variation in business profitability*". Farm size and length of establishment may also be important factors. Although the absence of farm size data in this study limits confirmation, the longer operational history of farms in the high circularity group supports this postulation. Prior research reinforces these insights. Zhang *et al*. (2021) show that larger farms tend to have lower per-hectare agrochemical and energy intensities, as well as reduced greenhouse gas emissions, thereby supporting narrowing through lower virgin input use. Zhu *et al*. (2022) provide empirical evidence that farm size significantly influences fertilizer use efficiency. Duffy's (2009) review of economies of size further demonstrates that larger farms can achieve lower unit costs and altered input-use patterns. Similarly, Tauer (2017) finds that farmer age and experience shape productivity and efficiency outcomes. Collectively, these findings suggest that enhanced farming practices, accumulated experience, and long-term investment are key drivers of higher circularity performance.

This study offers contributions to both scholarship and practice. A review of existing circularity indices indicates that many are complex and highly data-intensive, limiting their applicability to agricultural supply chains. Consequently, developing a single index that simultaneously captures all three phases: narrowing, slowing, and closing, is impractical. To address this gap, a simpler index focused on benchmarking circularity performance within one phase, particularly the narrowing cycle, responds to the call for more practical and sector-agnostic measures (De Koning *et al*. 2024). From a practical perspective, the index's flexibility and modest data requirements make it easier to implement, enabling its use as an effective benchmarking tool. Government agencies and policymakers can employ it to design extension services, workshops, and training programs aimed at supporting growers in advancing circular practices at the farm level.

Owing to the lack of primary data in this study, it is not possible to relate the circularity practices of individual growers to their index values. As such, current circularity practices adopted by the agricultural sector are used as references and basis for recommendations. To enhance circularity while maintaining productivity, banana growers can implement circularity-embedded strategies that minimise input consumption and improve resource efficiency. These strategies include: (1) mechanisation and automation to reduce labour costs or task specialisation to improve skill efficiency; (2) sustainable fertiliser use through precision agriculture technologies and integration of organic fertiliser alternatives; (3) eco-friendly packaging solutions such as transition to biodegradable packaging and reusable crates; and (4) establishment of farmer co-operatives to share resources to reduce on-costs and improve farming practices. These strategies can help banana growers optimise input use, enhance circularity, and achieve sustainability goals while maintaining productivity. The circularity index can help identify benchmarks for other farms to learn from and pinpoint areas that need improvement. By promoting resource efficiency and knowledge sharing, these strategies and benchmarking insights can enhance the economic resilience and competitiveness of the banana industry while advancing its sustainability, positioning the Australian banana supply chain as a global model for sustainable agricultural practice.

CONCLUSION

This study develops a circularity index for the agricultural sector, focusing on input narrowing through a case study of the Australian banana supply chain. The objective was to provide an accessible benchmarking tool to identify efficient farms and promote peer learning in circularity improvement, particularly within the narrowing cycle. By incorporating labour wages, fertiliser costs, packaging costs, and farm on-costs as inputs, and applying an entropy-based weighting method, the index objectively identified the critical factors influencing circularity. The analysis shows that the proposed index is robust and reliable, yielding results comparable to the more sophisticated DEA approach. Its advantage lies in being easier to interpret, construct, and apply. The categorisation of growers into low, medium, and high circularity groups further enabled meaningful comparisons and highlighted best practices for enhancing efficiency and circularity. Circularity-embedded strategies were also proposed for each input to guide industry stakeholders in improving supply chain performance.

Compared with existing approaches, the method is more flexible, as the number of indicators can be adjusted according to data availability. It is also less constrained by data granularity and technical challenges in data capture. Nevertheless, the approach is not without limitations. The selection of indicators may involve a degree of arbitrariness, which can compromise comparability across contexts. Moreover, the indicators often serve as proxies rather than direct measures of circularity, exposing the index to potential criticism for oversimplification or subjectivity in design.

In the case of Australian banana growers, the lack of detailed data on farm size, cropping patterns, and environmental impacts restricts a more comprehensive assessment of factors shaping circularity. The focus on four inputs may also overlook other important variables, such as energy use and water consumption. Future research should therefore expand the set of indicators and integrate life-cycle assessment to better capture environmental outcomes. Longitudinal studies could further validate the effectiveness of the index and refine its application across diverse agricultural contexts. While this study primarily addresses the efficiency of resource use in the narrowing phase, future work should also explore the slowing and closing cycles, including reuse, recycling, and upcycling of crop loss or waste, to provide a fuller account of circularity in agricultural supply chains.

REFERENCES

Ahmed, R., He, Q. and Garza-Reyes, J.A. (2025), "The sustainable configuration of a circular economy in the agri-food supply chain: a case study of the sugar cane supply chain", *Management of Environmental Quality: An International Journal*, Vol. 36 No. 4, pp. 1013-1033.

Al-Dairi, M., Pathare, P.B., Al-Yahyai, R., Jayasuriya, H. and Al-Attabi, Z. (2023), "Postharvest quality, technologies, and strategies to reduce losses along the supply chain of banana: A review", *Trends in Food Science & Technology*, Vol. 134, pp. 177-191.

Alzate Acevedo, S., Díaz Carrillo, Á.J., Flórez-López, E. and Grande-Tovar, C.D. (2021), "Recovery of banana waste-loss from production and processing: a contribution to a circular economy", Molecules, Vol. 26 No. 17, p. 5282.

Ambler, K., De Brauw, A. and Godlonton, S. (2018), "Measuring postharvest losses at the farm level in Malawi", *Australian Journal of Agricultural and Resource Economics*, Vol. 62 No. 1, pp. 139-160.

Aminoff, A. and Kettunen, O. (2016), "Sustainable supply chain management in a circular economy—Towards supply circles", in Setchi, R., Howlett, R., Liu, Y. and Theobald, P. (Eds), *Sustainable Design and Manufacturing 2016*. *Smart Innovation, Systems and Technologies*, Vol. 5, Springer, Cham.

Australian Bureau of Statistics (ABS) (2025), "Australian agriculture: Horticulture – Statistics on the production and value of a range of horticultural crops", available at:

https://www.abs.gov.au/statistics/industry/agriculture/australian-agriculture-horticulture/latest-release.

(A complete reference list can be available from the author upon request.)

Revisiting Deserts, Empires, and Guilds: Historical Foundations of Frugal Supply Chains

Gilles Pache

Aix-Marseille University, France

ABSTRACT

In the context of geopolitical volatility and growing sustainability constraints, frugality emerges as a strategic approach for rethinking supply chain design and performance. Historical cases such as the Roman *cursus publicus*, trans-Saharan trade networks, and medieval guild systems demonstrate that reliable and coordinated flows can be maintained under severe resource limitations. Their operational effectiveness relied on mechanisms that remain central to contemporary operations management: disciplined resource allocation, process standardization, structured governance, coordinated stakeholder networks, and localized adaptation. These systems prioritized reliability, efficiency, and continuity of flows over resource-intensive or technologically complex solutions. Translating main principles to modern supply chains highlights the value of lean and resilient operational architecture capable of absorbing disruptions while optimizing existing assets and minimizing waste. Frugality, therefore, offers both a theoretical and practical framework for designing supply chains aligned with environmental performance objectives.

INTRODUCTION

Throughout history, people have braved sometimes hostile environments to exchange and circulate the resources essential to life and the economy. The vast expanses of the Sahara, the Roman imperial roads, and medieval trade networks are not merely vestiges of the past, but testimonies to ingenuity and resilience in contexts where access to resources was limited, distances immense, and climatic or political uncertainties constant. Yet, the actors in these supply chains were able to design efficient systems through cooperation, rigorous planning, and continuous adaptation to local constraints. According to Weyrauch and Herstatt (2017), frugality—understood as "doing more with less"—is defined by three criteria: a substantial reduction in costs, a focus on essential functions, and optimized performance. This strategic approach ensures the continuity and robustness of flows despite extreme conditions. The study of historical networks thus shows how human societies built lean supply chains long before the industrial era, revealing universal principles that remain applicable today.

Drawing inspiration from ancient practices allows us to re-examine contemporary supply chains as they face economic and geopolitical uncertainty, environmental constraints, and growing sustainability demands. From a methodological standpoint, this paper follows the *narrative tradition* which, as Diamond (2019) explains, relies on prose-based arguments and a small number of representative cases, without seeking statistical confirmation. Trans-Saharan caravans show how to optimize flows across arid and unpredictable territories; Roman relay stations illustrate the power of centralized planning combined with local adaptation; and medieval guilds underscore the importance of cooperation, minimal standardization, and secure trade. Taken together, these historical examples offer a compelling conceptual framework for thinking about frugality in modern logistics, where organizational ingenuity, resource sharing, and operational flexibility enable efficiency, resilience, and social responsibility without relying exclusively on costly technologies or abundant resources. Understanding and integrating lessons from the past thus provides a valuable guide for building sustainable, efficient, and robust supply chains in a rapidly changing world.

CONCEPTUAL FRAMEWORK

In a world marked by economic instability, resource constraints, and environmental challenges, organizations must rethink their operating methods to remain competitive. Efficiency no longer

depends solely on accumulating resources or deploying advanced technologies; it increasingly relies on the ability to coordinate activities creatively and to make optimal use of available assets. Achieving strategic objectives under these conditions requires reorganizing product flows, reducing waste, and fostering collaboration among stakeholders. Organizations also need to develop adaptability to operational and environmental fluctuations and anticipate potential disruptions. Examining models from diverse and resource-constrained contexts provides valuable insights into mechanisms that simultaneously enhance performance, sustainability, and resilience. By integrating lessons from historical and contemporary practices, it becomes possible to identify universal principles of frugality applicable to modern supply chains. These insights demonstrate that robust operational strategies rely as much on system design, coordination, and governance as on technological or resource-intensive solutions, providing guidance for efficiency, continuity, and reliability in complex and uncertain operational environments.

Frugality in Theory and Practice

The concept of frugality, often referred to as frugal innovation, arises from the need to generate value in contexts characterized by limited resources, economic pressures, and rising social and environmental demands. It aligns closely with the Indian practice of jugaad, emphasizing pragmatic, flexible, and low-cost solutions that maximize outcomes with minimal inputs (Prabhu, 2017). Beyond cost reduction, frugality provides a systemic lens for managing organizational processes, supporting waste reduction, streamlined flows, and lasting impact under resource constraints (Fulconis et al., 2019). Research highlights multiple applications: integrating frugal approaches with lean management to optimize logistics while reducing operational complexity (Rosca and Bendul, 2016), enhancing supply chain resilience and performance (Shibin et al., 2018), and enabling SMEs to operate effectively without high-cost technologies. Knizkov and Arlinghaus (2020) identify three archetypes of frugal supply chains, illustrating operational configurations that overcome constraints at every stage. Collectively, these insights position frugality not merely as a financial tactic but as a strategic principle guiding operations in complex environments.

Frugality extends beyond internal practices and is embedded in broader cultural, organizational, and institutional frameworks. Its effective adoption requires mindset shifts, alongside policy and regulatory support. Evidence from emerging supply chains during the COVID-19 pandemic highlights the critical role of government and local authority interventions in enabling low-cost, context-adapted solutions that ensure continuity and resilience (Dubey et al., 2022). Institutional support also facilitates sustainable production and distribution practices aligned with development objectives, enhancing resource efficiency and inclusivity (Al-Khatib, 2025). Frugality serves as a strategic lever, allowing executives to integrate agility, sustainability, and operational resilience. By fostering proactive decision-making, supporting cultural transformation, leveraging appropriate technologies, and coordinating internal and external stakeholders, frugal practices enhance performance, innovation, and social impact while improving organizational adaptability to dynamic market and environmental conditions.

Operationally, frugal innovation translates into practices that balance performance, cost efficiency, and sustainability across supply chains. Flexibility, supplier collaboration, and systematic flow optimization enable organizations to respond effectively to disruptions while minimizing waste and unnecessary costs. Digitalization and circularity support demand anticipation, flow reorganization, and sustainability objectives (Van Tuijl et al., 2024; Al-Khatib and Ramayah, 2025), while knowledge sharing strengthens collective performance and value creation (Li et al., 2020). Frugal logistics also reinforces resilience: micro-supply chains capable of independent operation safeguard global networks against shocks (Karroumi and Sedqui, 2022; Bapat and Malshe, 2024). Field studies in India show these approaches optimize costs, secure distribution, and maintain access to essential goods during crises, from contactless delivery during the pandemic (Bergi et al., 2021) to centralized management of humanitarian assets (Sengura et al., 2024; Natasha, 2025). Frugality thus emerges as both a theoretical framework and a practical driver of efficiency, innovation, and resilience, offering a comprehensive model for managing supply chains under uncertainty.

Value of Historical Insight

Although frugal innovation offers clear benefits, it also presents limitations that require careful long-term evaluation. Excessive simplification of processes can compromise product quality, robustness, and reliability (Knizkov and Arlinghaus, 2020). Much of the research focuses on SMEs or emerging markets, limiting the transferability of insights to larger or global supply chains. Regulatory constraints, strict standards, and environmental requirements often slow adoption, while conventional performance metrics fail to capture the full benefits of integrated, resource-conscious logistics (Prabhu, 2017; Fulconis et al., 2019). A superficial understanding of frugality may lead to implementation errors or counterproductive outcomes, reducing operational effectiveness. In this context, historical supply chains offer a valuable perspective, revealing how complex systems reconciled efficiency, resilience, and resource scarcity over extended networks. Studying these examples highlights transferable operational principles, including resource sharing, context-adapted planning, rigorous documentation, and stakeholder coordination. By analyzing past solutions, executives can extract lessons that complement contemporary research, which often emphasizes SMEs, emerging markets, or technology-centered approaches, providing a relevant framework for designing frugal operational practices in modern global supply chains.

Recent studies reinforce the practical value of historical insights by demonstrating their direct applicability to modern operations management. Frugal digitalization optimizes flow management for SMEs (Prasad and Krishna, 2025), while improvisation and adaptive problem-solving enhance circular supply chains (Zhang, 2025). Advanced analytics strengthen competitiveness and decision-making within frugal logistical systems (Al-Omoush et al., 2026). From this viewpoint, integrating the historical lessons allows organizations to avoid unnecessary reinvention and adopt solutions already proven effective in complex, resource-constrained contexts. Moreover, they illustrate the operational mechanisms that underpin resilience, flexibility, and efficiency in supply chains operating under uncertainty. By connecting historical principles to contemporary challenges, executives gain actionable guidance for designing robust, efficient, and sustainable logistical networks. This perspective ensures that frugal innovation is not merely conceptual but also grounded in measurable operational outcomes, offering a roadmap to manage resource scarcity, mitigate risks, and enhance overall supply chain performance in volatile, uncertain, complex, and ambiguous (VUCA) environments.

THREE HISTORICAL CASES

Over the centuries, the movement of goods, information, and resources has shaped societies and economies, highlighting the importance of organized and adaptable systems. Before industrialization, actors in these networks faced constraints now largely forgotten: vast distances, extreme weather, limited infrastructure, and security challenges. Success depended on the ability to coordinate transport, safeguard flows, and deploy scarce resources efficiently. Studying ancient supply systems reveals strategies that ensured continuity despite significant obstacles and provides insight into the principles of effective flow management, organizational resilience, and adaptability under constraints. By examining trans-Saharan networks, Roman logistics, and medieval guilds, recurring operational mechanisms emerge that continue to inform contemporary supply chain design. Understanding these historical examples allows managers to extract practical lessons in resource optimization, stakeholder coordination, and systemic flexibility, illustrating how frugal approaches sustained complex operations long before modern technologies and how these principles remain relevant for today’s global supply chains facing volatility, scarcity, and uncertainty.

Trans-Saharan Caravans

From antiquity, trans-Saharan trade relied initially on chariots, before the camel became central from the 1st century AD. Camels, capable of long journeys without water while carrying heavy loads, transformed mobility and commerce across the Maghreb, central Sahara, and Sudanese regions (Boahen, 1962). Caravan networks adapted routes to changing political and ecological conditions, reflecting sophisticated logistical planning. Leaders relied on detailed environmental knowledge—water sources, seasonal pastures, wind corridors, and hazards—to optimize routes.

Camel training complemented human expertise, while task allocation among free men and slaves maximized transport efficiency for essential commodities like salt, grain, and dates. Trade also depended on complex institutional structures. Written contracts under Islamic law ensured trust and coordination across vast distances, while groups such as the Berabish, Tuareg, and Kunta provided security and territorial regulation (McDougall, 1992; Lydon, 2008). These arrangements show that effective frugal logistics combined environmental awareness, social coordination, and resource optimization, allowing caravans to sustain flows across hostile terrain. Modern supply chains can draw lessons in anticipatory planning, local adaptation, and integrated risk management from these historical networks.

Caravan operations combined strategic planning, local adaptation, and institutional support to maintain continuous trade across expansive deserts. Optimizing animal and human resources, anticipating climatic, political, or economic fluctuations, and leveraging contracts and shared responsibilities reinforced network stability (McDougall, 1992; Lydon, 2008). Security provided by clans and governance mechanisms ensured reliable exchanges, demonstrating that operational efficiency depended on social and political coordination as much as on resource allocation. Trans-Saharan networks illustrate the principles of resilient logistics: systemic optimization, stakeholder cooperation, flexible decision-making, and integration of local constraints into broader strategies. The durability of these networks, which persisted well into the 19th century despite the introduction of motorized vehicles, underscores the long-term effectiveness of frugal practices. Contemporary managers can apply these lessons by designing supply chains that balance efficiency with adaptability, secure flows in uncertain contexts, and optimize limited resources while maintaining continuity across complex operational environments.

Roman Empire

The Roman transport and communication system exemplifies a centralized supply chain supporting imperial administration and territorial control. The *cursus publicus*, established under Augustus and expanded in the 1st century AD, was designed to facilitate official communications, administrative travel, and transport of strategic goods (Kolb, 2012). Its efficiency rested on a hierarchical network of relay stations—*mutationes* for changing horses and *mansiones* for lodging—linked by roads, bridges, and depots that connected provinces to Rome (Kolb, 2014; Scheidel, 2014). Standardized procedures and formal permits ensured controlled access, enabling reliable operations over long distances. Simulations indicate couriers averaged 67 km per day using multiple transport modes, prioritizing consistency over speed (Scheidel, 2014). Local populations contributed animals, vehicles, and labor to maintain operations, reinforcing resilience across the system (Kolb, 2012, 2014). Villas near key nodes supplied provisions and equipment, supporting uninterrupted service (Popova, 2020). These practices illustrate that frugal logistics depended on coordination, adaptation to territorial constraints, and resource optimization. Roman supply chains highlight principles of centralized planning combined with localized responsiveness, foreshadowing modern approaches emphasizing operational efficiency, flexibility, and resilience in complex networks.

Roman logistics integrated infrastructure, community engagement, and institutional regulation to secure consistent operations. Relay stations, waterways, and storage facilities facilitated the movement of officials, armies, and goods across a vast territory, demonstrating how structured networks can maintain continuity under challenging conditions (Roth, 1999). Permit systems and hierarchical access ensured prioritization and resource control, while local labor contributions supported operational reliability. The combination of standardized practices, auxiliary facilities, and strategic mobilization created a robust, lean system capable of adapting to variations in demand, terrain, and administrative requirements. Lessons from the *cursus publicus* underscore the importance of anticipating constraints, coordinating multiple actors, and integrating infrastructure with operational planning. Contemporary supply chain managers can draw from Roman practices by combining centralized oversight with local flexibility, emphasizing reliable processes, resource optimization, and resilience in the face of uncertainty.

Medieval Guilds

In medieval Europe, merchant guilds formed the backbone of extensive logistical networks supporting long-distance trade. Their responsibilities went beyond corporate representation, encompassing regulation of exchanges, financing expeditions, securing routes, and ensuring product quality. Standardized weights, measures, and production processes reduced uncertainty and facilitated the circulation of essential goods, including salt, grain, cloth, and wine (Richardson, 2008; Ogilvie, 2011). For instance, Hanseatic guilds across the North and Baltic Seas coordinated warehouses, fleets, and transport systems, optimizing resource use in politically, economically, and climatically challenging contexts. These arrangements relied on collective expertise, governance stability, and institutional coordination, demonstrating that frugal logistics arose from social organization, cooperation, and local adaptation rather than advanced technology. Medieval guilds ensured continuity and resilience, highlighting that effective medieval trade depended on reliable processes and structured coordination rather than speed or technical sophistication.

Medieval guilds also played a pivotal role in infrastructure and flow management. In northern Europe and England, they financed and maintained roads, bridges, river quays, and marketplaces, reinforcing economic integration. The Hanseatic League illustrates their operational capacity, combining port warehouses, merchant fleets, transport coordination, standardized documentation, and diplomatic efforts to maintain continuous trade in regions with political rivalries. Medieval guilds adapted routes and modes of transport to manage risks such as piracy, tolls, or seasonal conditions, demonstrating advanced operational flexibility (Ogilvie, 2011). They also used financial instruments like merchant loans and futures contracts to reduce transaction costs and share risk. By integrating mutual protection, planning, information sharing, and institutional adaptation, medieval guilds implemented frugal supply chains that foreshadow contemporary sustainable logistical strategies. These historical examples offer enduring insights into cooperation, resource efficiency, and resilience applicable to modern supply chain management.

DISCUSSION AND CONCLUSION

Examining historical logistical practices provides valuable insights for modern supply chain management. Human societies have long faced extreme constraints, including vast distances, scarce infrastructure, limited resources, and environmental or geopolitical risks. To cope with these challenges, stakeholders developed sophisticated methods to organize, protect, and optimize flows of goods and information. Ancient supply chains reveal recurring strategies based on adapting to multi-level constraints, ensuring continuity while enhancing resilience in the face of disruptions. These lessons extend beyond historical interest, offering foundational principles for contemporary logistics, where cost pressures, sustainability, and agility remain critical. By analyzing trans-Saharan caravans, the Roman *cursus publicus*, and medieval guilds, one can identify practical applications of frugality that inform managerial decision-making. These practices strengthen efficiency, robustness, and social responsibility, demonstrating that effective supply chains rely on coordinated operations, intelligent resource allocation, and flexible adaptation to complex environments. History thus provides a blueprint for frugal and resilient supply chains.

Lessons from History

Trans-Saharan caravans, the Roman *cursus publicus*, and medieval guilds reveal enduring principles of logistical frugality. Efficiency arose not only from resource availability but from the capacity to organize, pool, and deploy resources intelligently under constraints. Caravans allocated camels, provisions, and labor strategically to ensure safe and reliable desert crossings despite extreme conditions (Boahen, 1962; McDougall, 1992). Roman networks combined centralized planning, standardization, and local adaptation through relay stations and *villae rusticae*, maintaining dependable communications over long distances (Kolb, 2012; Lemcke, 2016). Medieval guilds demonstrated that collective regulation, shared financing, and coordinated merchant networks could sustain flows despite political instability or environmental hazards (Ogilvie, 2011). Across all three cases, frugal logistics depended on clear rules,

collaboration, and careful optimization of scarce resources. These historical systems illustrate that resilience and efficiency emerge not from abundance, but from structured coordination, anticipation of disruptions, and flexible management of human, material, and institutional resources.

Historical practices offer lessons directly applicable to contemporary supply chains navigating uncertainty. Resource pooling—whether infrastructure, vehicles, personnel, or information—is a consistent theme in caravans, Roman posts, and medieval guild networks, forming a lever for cost reduction and resilience. Standardization combined with local adaptation allowed these systems to adjust to environmental, political, or economic variability: caravans modulated convoy composition and transport animals according to desert conditions or terrain, while Roman authorities adjusted transport speeds and relay schedules based on available resources. Medieval guilds similarly optimized storage, transport, and trade coordination across multiple cities and regions. Historical practices also provide insight into the long-term relevance of integrated logistical networks. Kidd and Stumm (2005) highlight differences in European and Indian ports and hinterlands, showing that coordinated planning, standardized operations, and strategic resource allocation remain essential for connecting complex supply networks. Today, flexible production, distribution, and routing systems reflect the same logic, ensuring responsiveness to disruptions and demonstrating that frugality is a strategic, system-wide approach strengthening robustness, agility, and sustainability.

Implications for Modern Frugal Supply Chains

Historical examples provide concrete guidance for enhancing strategic frugality in contemporary supply chains. Resource optimization emerges as a core principle: Sahelian caravans rationed water, food, and cargo to maintain continuous trade across harsh deserts, demonstrating how careful management of limited resources directly supported resilience and reliability (Lovejoy, 1984). The Roman logistics illustrates how centralized planning, standardized infrastructure, and strategic deployment of relay stations reduced excess and ensured consistent long-distance transport (Roth, 1999). Medieval guilds highlight the benefits of institutional coordination: shared documentation, collective financing, and cooperative governance strengthened the security of trade flows, reduced transaction costs, and facilitated risk-taking in politically and environmentally volatile regions (Müller-Boysen, 1990; Marczinek et al., 2025). These examples show that frugality arises not from scarcity alone but from intelligent allocation of resources, careful planning, and continuous adaptation to evolving conditions, providing a model for managing modern supply chains under constraints and uncertainty.

Equally important is balancing standardization with flexibility. Roman trading posts followed repeatable layouts that ensured reliability while adapting to local conditions, whereas caravans and medieval guilds adjusted routes, transport volumes, and schedules in response to environmental, economic, or political changes (McDougall, 1992; Scheidel, 2014). Historical caravan networks, for instance, selected transport animals according to terrain, elevation, and cargo, and adapted their seasonal itineraries to natural conditions such as climate cycles or rainfall patterns (Haksöz and Uşar, 2011; Mohan, 2021). Modern supply chains can adopt similar strategies: standardized core operations ensure consistency, while local flexibility allows rapid response to disruptions, variable demand, or unforeseen risks. These examples also emphasize the importance of organizational culture, strategic foresight, and collaboration among stakeholders. The discipline, ingenuity, and cooperative practices observed across historical systems demonstrate that frugality is a strategic approach, enabling adaptive, resilient, and resource-efficient supply chains capable of generating value while minimizing waste and supporting long-term sustainability.

References

Al-Khatib, A.-W. (2025). Toward achieving the sustainable development goals: The roles of digital human capital, circular supply chain practices, frugal innovation, and the moderating effect of relational capital. *Sustainable Development*, *33*(6), 7974-7991.

Al-Khatib, A.-W., & Ramayah, T. (2025). Artificial intelligence-based dynamic capabilities and circular supply chain: Analyzing the potential indirect effect of frugal innovation in retailing firms. *Business Strategy & the Environment, 34*(1), 830–848.

Al-Omoush, K.-S., Fernández-Caparrós, M.-R., Lassala, C., & Ribeiro-Navarrete, S. (2026). Unleashing supply chain innovation and frugal innovation: Examining the interaction between institutional pressures and supply chain analytics adoption. *Management Decision*, forthcoming.

Bapat, S., & Malshe, A. (2024). Bio-inspired frugal engineering strategies for resilient supply chains. *Procedia CIRP, 125*, 10–15.

Bergi, M., Kamarudeen, N., & Sundarakani, B. (2011). Frugal innovation: Contact-less last mile delivery as resilient business model. *Proceedings of the 11th Annual International Conference on Industrial Engineering & Operations Management*, Singapore, 3002–3018.

Boahen, A. (1962). The caravan trade in the nineteenth century. *Journal of African History, 3*(2), 349–359.

Cartwright, M. (2019). The salt trade of ancient West Africa. *World History Encyclopedia*. Article 1342.

Diamond, J. (2019). *Upheaval: How nations cope with crisis and change*. Boston (MA): Little, Brown & Company.

Dubey, R., Bryde, D., Foropon, C., Tiwari, M., & Gunasekaran, A. (2022). How frugal innovation shapes global sustainable supply chains during the pandemic crisis: Lessons from COVID-19. *Supply Chain Management: An International Journal, 27*(2), 295–311.

Fulconis, F., Paché, G., & Reynaud, E. (2019). Frugal supply chains: A managerial and societal perspective. *Society & Business Review, 14*(3), 228–241.

Haksöz, C., & Uşar, D.-D. (2011). Silk road supply chains: A historical perspective. In C. Haksöz, S. Seshadri and A. Iyer (Eds.), *Managing supply chains on the silk road: Strategy, performance, and risk* (pp. 3–26). Boca Raton (FL): CRC Press.

Karroumi, B., & Sedqui, A. (2022). Resilient supply chain built on frugal innovations, and how this relation can be created? *Proceedings of the 14th LOGISTIQUA Colloquium*, El Jadida, 1–6 (CD-rom).

Kidd, J., & Stumm, M. (2005). From pre-medieval to post-modern times: Logistics routes and their modalities have not changed much. *Management Decision*, *43*(9), 1249–1261.

Knizkov, S., & Arlinghaus, J. C. (2020). Frugal processes: An empirical investigation into the operations of resource-constrained firms. *IEEE Transactions on Engineering Management, 68*(3), 667–684.

Kolb, A. (2012). Transport and communication in the Roman State: The *cursus publicus*. In C. Adams and R. Laurence (Eds.), *Travel and geography in the Roman Empire* (pp. 95–105). London: Routledge.

Kolb, A. (2014). Communications and mobility in the Roman Empire. In C. Bruun and J. Edmondson (Eds.), *The Oxford handbook of Roman epigraphy* (pp. 649–670). Oxford: Oxford University Press.

Le, P.-B. (2023). Determinants of frugal innovation for firms in emerging markets: The roles of leadership, knowledge sharing and collaborative culture. *International Journal of Emerging Markets, 18*(9), 3334–3353.

Lemcke, L. (2016). *Evectiones* and *tractoriae*: Identifying the permits for the *cursus publicus* in the 4th century. *Byzantinische Zeitschrift, 109*(2), 769–784.

Li, Z., Zhang, H., & Gao, R. (2020). Frugal innovation in supply chain cooperation considering e-retailer's platform value. *Soft Computing, 24*(20), 15373–15387.

Lovejoy, P. (1984). Commercial sectors in the economy of the nineteenth-century Central Sudan: The trans-Saharan trade and the desert-side salt trade. *African Economic History, 13*, 85–116.

Lydon, G. (2008). Contracting caravans: Partnership and profit in nineteenth- and early twentieth-century trans-Saharan trade. Journal of Global History, 3(1), 89–113.

Marczinek, M., Maurer, S., & Rauch, F. (2025). Networks in trade–Evidence from the legacy of the Hanseatic League. *Journal of International Economics, 157*, Article 104102.

McDougall, A. (1992). Salt, Saharans, and the Trans-Saharan slave trade: Nineteenth century developments. *Slavery & Abolition, 13*(1), 61–88.

Mohan, B. (2021). Managing flows and risks in supply chains–A page from ancient Silk Route. *SCMS Journal of Indian Management*, *18*(2), 67–77.

Müller-Boysen, C. (1990). *Kaufmannsschutz und Handelsrecht im frühmittelalterlichen Nordeuropa*. Hamburg: Wachholtz.

Natasha, S. (2025). Frugal business model innovation in an Indian emerging market: A multiple case study. *Asia Pacific Journal of Innovation & Entrepreneurship, 19*(2), 167–185.

Ogilvie, S. (2011). *Institutions and European trade: Merchant guilds, 1000–1800*. Cambridge: Cambridge University Press.

Popova, D. (2020). An architectural reassessment of a "Villa Rustica" near Serdica. *Tractus Aevorum, 7*(2), 143–162.

Prabhu, J. (2017). Frugal innovation: Doing more with less for more. *Philosophical Transactions of the Royal Society A: Mathematical, Physical & Engineering Sciences, 375*(2095), Article 20160372.

Prasad, C., & Krishna, S. (2025). Small business, big solutions: Leveraging frugal innovation for MSME digitalization. In R. Manna and A. Singh (Eds.), *Frugal innovation in entrepreneurship* (pp. 177–212). Hershey (PA): IGI Global.

Richardson, G. (2004). Guilds, laws, and markets for manufactured merchandise in late-medieval England. *Explorations in Economic History, 41*(1), 1–25.

Rosca, E., & Bendul, J. (2016). Frugal and lean engineering: A critical comparison and implications for logistics processes. In M. Freitag, H. Kotzab and J. Pannek (Eds.), *Dynamics in logistics* (pp. 335–345). Cham: Springer.

Roth, J. (1999). *The logistics of the Roman army at war: 264 B.C.–A.D. 235*. Leiden: Brill.

Scheidel, W. (2014). The shape of the Roman world: Modelling imperial connectivity. *Journal of Roman Archaeology, 27*, 7–32.

Shibin, K.-T., Dubey, R., Gunasekaran, A., Luo, Z., Papadopoulos, T., & Roubaud, D. (2018). Frugal innovation for supply chain sustainability in SMEs: Multi-method research design. *Production Planning & Control, 29*(11), 908–927.

Sengura, J.-D., Mu, R., & Zhang, J. (2024). Towards frugal innovation capability in emerging markets within the digitalization epoch: Exploring the role of strategic orientation and organizational ambidexterity. *Journal of Theoretical & Applied Electronic Commerce Research, 19*(3), 2000–2029.

van Tuijl, E., Intriago Zambrano, J.-C., & Knorringa, P. (2024). Digitalization, frugal innovation, and sustainable development in the global south: Opportunities and challenges of a frugal smart water pump. In M. Ertz, U. Tandon, S. Sun, J. Torrent-Sellens and E. Sarigöllü (Eds.), *The Palgrave handbook of sustainable digitalization for business, industry, and society* (pp. 63–81). Cham: Palgrave Macmillan.

Weyrauch, T., & Herstatt, C. (2017). What is frugal innovation? Three defining criteria. *Journal of Frugal Innovation, 2*, Article 1.

Zhang, P. (2025). Implementing circular supply chain in Chinese SMEs: The role of bricolage capability, frugal innovation, and entrepreneurial leadership. *International Review of Economics & Finance, 103*, Article 104526.

Does Digital Transformation Enhance Supply Chain Resilience Capabilities? Evidence from the Vietnamese Seafood Industry

Thi Tham Tran, Vinh Van Thai, Truong Ton Hien Duc

RMIT,Australia

INTRODUCTION

The rapid expansion of global connectivity, enabled by advances in communication technologies and transportation infrastructure, has led to increasingly complex and highly interconnected supply chain networks. While such interconnectedness improves efficiency, it also amplifies vulnerability to disruptions due to geographic dispersion, heightened interdependence among partners, and limited supply chain visibility (Patel, 2023). Recent large-scale disruptive events, notably the US–China trade war and the COVID-19 pandemic, have exposed these vulnerabilities, resulting in substantial operational and financial losses, including reduced productivity, service failures, and increased supply chain costs (Baldwin & Freeman, 2022). According to the Business Continuity Institute (BCI, 2024), 78.6% of organisations reported productivity losses arising from such disruptions, underscoring the urgent need to enhance supply chain resilience, particularly in globally dispersed networks (Azadegan et al., 2020).

In this connection, supply chain resilience capabilities (SRC) refer to a supply chain's ability to anticipate disruptions, identify emerging risks, and reconfigure resources and operations to withstand and recover from adverse events while sustaining performance (Wang et al., 2022). These capabilities enable organisations to sense environmental changes, prepare proactively, and adapt their resource allocation and operational processes in response to uncertainty (Duchek, 2020). As a result, SRC not only support organisational survival during disruptions but also contributes to competitive advantage in volatile environments (Chen et al., 2021).

Prior research increasingly recognises digital transformation (DT) as a critical enabler of SRC. By facilitating advanced data analytics, real-time information sharing, and end-to-end supply chain visibility, DT enhances organisations' ability to sense disruptions, anticipate risks, and respond flexibly to fluctuations in supply and demand (Yin, 2023). Moreover, digital integration across supply chain partners strengthens collaboration, trust, and coordinated decision-making, thereby enabling more effective responses during and after disruption events (Li et al., 2022). Accordingly, effective DT deployment (DTD) is increasingly viewed as essential for strengthening SRC (Yuan et al., 2024). However, the successful deployment of DT is contingent upon organisational readiness, encompassing leaders' cognition, strategy, organisational culture, finance, infrastructure, digitally skilled human resources, operational procedure and collaborative partnerships (Lokuge et al., 2019; Pingali et al., 2023). Inadequate readiness can undermine DT implementation efforts and limit their potential to enhance supply chain resilience. Moreover, the effectiveness of DT in strengthening SRC is inherently context-dependent and shaped by industry-specific structural and institutional conditions. Examining this relationship within the Vietnamese seafood industry, an export-oriented sector characterised by high environmental uncertainty, resource constraints, and mounting digitalisation pressures, therefore provides a particularly salient empirical context to investigate how organisational readiness and DTD jointly contribute to supply chain resilience.

In Vietnam, the seafood industry represents a vital pillar of the national economy, contributing approximately 4–5% of gross domestic product (GDP), and generating USD 10 billion of export value in 2024 (VASEP, 2024). Beyond its economic significance, the industry plays a critical role in ensuring national and global food security. Notably, Vietnam ranked as the world's third-largest seafood exporter in 2024 (VASEP, 2024), thereby imposing additional expectations regarding its capacity to withstand, respond to, and recover from disruptions. Recent global crises, most notably the COVID-19 pandemic, have exposed structural vulnerabilities within Vietnam's seafood supply chains and underscored the urgent need to strengthen SRC (Hong, 2021). In response, DT has emerged as a key strategic approach for enhancing supply chain resilience.

While the seafood sector is among those actively advancing DT, evidenced by the adoption of IoT-enabled aquaculture monitoring systems, blockchain-based traceability platforms, and digital marketing tools (VMPI, 2023), these DT initiatives remain fragmented and insufficiently aligned with a coherent strategic roadmap. As a result, many firms fail to realise expected performance gains, with challenges especially acute among small and medium-sized enterprises (SMEs), which dominate the industry but face persistent constraints in financial resources, digital capabilities, and managerial expertise (VMPI, 2023). Together, these conditions raise two critical questions: to what extent can seafood manufacturers effectively capitalise on DTD, and how can successful DTD be leveraged to strengthen SRC in an increasingly dynamic and uncertain global market?

Accordingly, this study investigates the relationships among DT readiness (DTR), DTD, and SRC in the Vietnamese seafood industry through the following research questions:

RQ1: What is the relationship between DTR and DTD?

RQ2: What is the relationship between DTD and SRC?

RQ3: How does DTR affect SRC via the mediating role of DTD?

The remainder of this paper is structured as follows. The next section reviews the relevant literature, followed by a description of the research methodology. The subsequent section presents the empirical results. Finally, the paper concludes by outlining the key contributions of the study and acknowledging its limitations.

LITERATURE REVIEW

DT readiness (DTR)

DTR refers to the extent to which an organisation is prepared and willing to initiate, implement, and sustain digital initiatives in pursuit of its strategic objectives (Gfrerer et al., 2021). It represents a foundational stage in the DT process, signalling organisational openness to digitalisation and establishing the preconditions for effective transformation (Bican & Brem, 2020). DTR is underpinned by interconnected managerial, strategic, and cultural dimensions, including leaders' digital cognition and commitment, the clarity and alignment of digital strategies with organisational and supply chain goals, and shared values that promote collaboration, learning, and innovation (Lokuge et al., 2019; Hortovanyi et al., 2023). Beyond these core dimensions, DTR is further strengthened by financial capacity, digital infrastructure, human resource capabilities, digitally enabled operational procedures, and supply chain integration, which collectively enable organisations to mobilise resources, embed digital technologies into workflows, and collaborate effectively with partners (Min & Kim, 2024). Taken together, these interrelated determinants constitute a comprehensive foundation for the effective and sustainable implementation of digital transformation initiatives.

DT deployment (DTD)

DTD involves adopting and integrating digital technologies within organisational processes and across supply chain networks to enhance efficiency, responsiveness, and value creation (Zhang et al., 2022). Within organizations, DT is applied across core functions such as procurement, demand management, production, delivery, financial management, and customer engagement, leveraging technologies like big data analytics, AI, machine learning, CRM systems, and digital document management to optimize decision-making, forecast demand, streamline workflows, and improve service quality (Li et al., 2022; Yin, 2023). In production and delivery, real-time data enables dynamic scheduling, route optimisation, and enhanced operational responsiveness (Zhang et al., 2022). Across supply chains, DTD facilitates information sharing, transparency, and visibility through technologies such as Blockchain and IoT, allowing firms to monitor resources, detect bottlenecks, and anticipate disruptions, thereby strengthening resilience and operational continuity (Faruquee et al., 2021). Overall, DTD is a holistic, value-driven process that integrates technological, operational, and interorganizational dimensions to enable sustainable business transformation.

Supply chain resilience capabilities (SRC)

SCR refers to a supply chain's capability to withstand disruptions, respond effectively, and recover to its original or an improved state (Ali et al., 2017). SCR comprises three interrelated dimensions: anticipation, coping, and adaptation (Hosseini et al., 2019). Anticipation represents the first line of defence and involves proactively monitoring internal and external environments, forecasting risks, and preparing preventive measures such as redundancy and supplier diversification to mitigate potential disruptions (Duchek, 2020; Ali et al., 2023). Coping and adaptation capabilities constitute the subsequent lines of defence in SCR. Coping refers to the ability to react swiftly and effectively once disruptions occur, encompassing problem-solving, resource reallocation, and operational adjustment to stabilise supply chain activities under uncertainty (Ma & Zhang, 2022). Adaptation focuses on post-disruption learning and long-term adjustment, enabling supply chains to improve through experience. This includes learning from past disruptions, developing contingency strategies, reconfiguring processes and structures, and, when necessary, transforming business models to better withstand future risks (Zhao et al., 2023). Together, anticipation, coping, and adaptation form an integrated resilience framework that enables supply chains not only to survive disruptions but also to evolve and strengthen their competitive position.

CONCEPTUAL MODEL AND HYPOTHESIS DEVELOPMENT

Relationship between DTR and DTD

Organisational readiness theory (ORT) conceptualises readiness as comprising both a shared commitment to change (change valence) and collective confidence in the organisation's capability to implement change (change efficacy), underpinned by adequate financial, human, and knowledge resources (Lokuge et al., 2019). Readiness is further conditioned by contextual factors, including organisational culture, strategic orientation, and inter-organisational partnerships. Building on this theoretical foundation, prior studies consistently identify digital readiness as a critical prerequisite for the successful adoption and institutionalisation of DT initiatives (Gfrerer et al., 2021).

Given the complexity and path-dependent nature of DT pathways, change efficacy, particularly in terms of managerial cognition and workforce digital capabilities, emerges as a key antecedent of effective DT implementation (Mancha & Shankaranarayanan, 2021). More broadly, organisational readiness shapes implementation outcomes by facilitating alignment among organisational culture, operational processes, and strategic objectives (Halpern et al., 2021). Furthermore, the clarity and effective communication of digital strategies (Halpern et al., 2021), together with digital supply chain integration readiness that promotes trust, coordination, and collaboration among supply chain partners (Schneider & Kokshagina, 2021), constitute essential enablers of DT. Accordingly, higher levels of DTR enhance an organisation's capacity to deploy digital initiatives effectively and to achieve sustainable DT outcomes. Accordingly, the following hypothesis is put forward:

H1: DTR has a significantlypositive impact on DTD.

Relationship between DTD and SRC

Dynamic capabilities refer to a firm's ability to purposefully integrate, build, and reconfigure internal and external resources and competencies in order to adapt effectively to rapid changes in the external environment (Teece, 2018). From this perspective, dynamic capability theory (DCT) provides a robust theoretical lens for explaining how DTR and DTD contribute to the development of SRC (Li et al., 2022; Zhao et al., 2023). Within DCT framework, the value of DTD does not reside in digital technologies per se, but in their effective integration with core supply chain processes and operations (Zhao et al., 2023). Such integration facilitates the development of dynamic capabilities, enabling firms to sense, seize, and reconfigure resources in response to environmental turbulence. First, DTD enables organisations to leverage advanced data analytics to improve demand forecasting accuracy and to better navigate market uncertainty, thereby enhancing decision-making and enabling more effective product and service provision relative to competitors (Yuan & Li, 2022). Second, DTD strengthens collaboration, trust, and flexibility across the supply chain ecosystem by facilitating information sharing and

coordination among partners. This integration of complementary resources across firm boundaries enhances collective responsiveness and supports superior product and service delivery during and after disruption events (Hanelt et al., 2021; Li et al., 2022). Third, DTD enhances supply chain visibility and transparency, allowing firms to proactively identify disruptions and operational anomalies. This capability supports timely corrective actions, thereby reducing recovery time and associated costs (Belhadi et al., 2022).

Through the effective execution of DTD, firms can achieve higher levels of disruption preparedness and improve their responsiveness in the post-disruption phase. Hence, the following hypotheses were developed:

H2: DTD has a significantly positive impact on SRC.

Relationship between DTR and SRC

Beyond actual deployment, organisational readiness represents a foundational enabling capability that determines a firm's capacity to effectively mobilise, integrate, and orchestrate digital resources (Lokuge et al., 2019). These capabilities collectively enhance the firm's ability to sense environmental changes, proactively allocate resources, and coordinate adaptive responses (Hanelt et al., 2021).

From a dynamic capability perspective, DTR can therefore be conceptualised as an antecedent capability that underpins sensing, seizing, and reconfiguring processes (Belhadi et al., 2022). By establishing the structural and managerial conditions necessary for adaptation, DTR strengthens organisational agility and enhances resilience capacity. Consequently, firms with higher levels of DT readiness are better positioned to anticipate disruptions, mobilise internal and external resources efficiently, and reconfigure supply chain processes in response to unexpected disruptions. Accordingly, the following hypothesis is proposed:

H3: DTR has a significantly positive impact on SRC.

Drawing upon the theoretical foundation established through the *literature* review, Figure 1 presents a conceptual model for evaluating the interrelationships between DTR, DTD, and SRC.

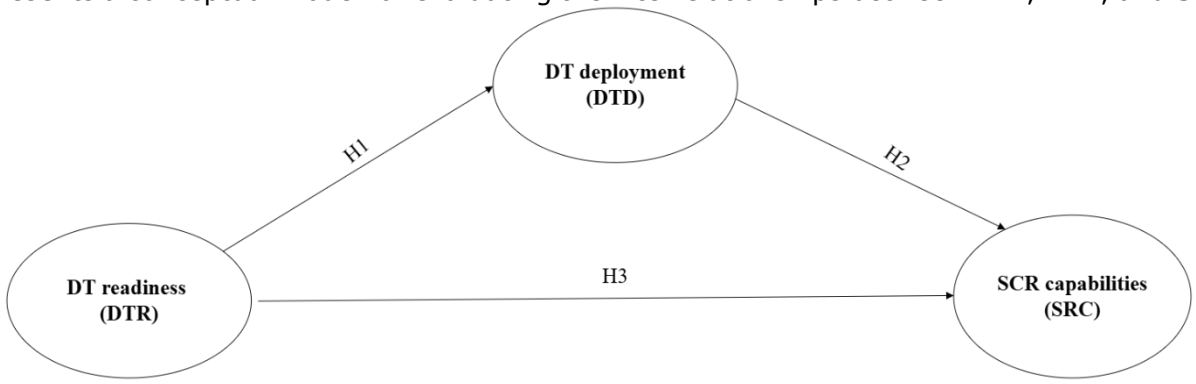


Figure 1. Conceptual model

(Source: Author's own work)

METHODOLOGY

This study adopted a survey-based research design to examine the relationships proposed in the conceptual model. The target population comprised Vietnamese seafood manufacturing firms, which are central actors in the seafood supply chain. The sampling frame was developed using official databases from the Ministry of Industry and Trade, the Vietnam Chamber of Commerce and Industry, the Ministry of Planning and Investment, and the Vietnam Association of Seafood Exporters and Producers (VASEP).

The survey instrument was developed from validated constructs in the literature and consisted of four sections: firm demographics, DTR, DTD, and SRC. All items were measured using a five-point Likert scale (1 = strongly disagree; 5 = strongly agree). The final set of measurement items is presented in the Appendix. To ensure linguistic and conceptual equivalence, the questionnaire underwent a forward–backward translation procedure (Panuwatwanich & Nguyen,

2017), followed by pre-testing with 10 academic staff and 5 managers from the Vietnamese Seafood industry to assess item clarity and wording. The pilot testing is then conducted with 52 managers from the same industry to further evaluate the reliability. The final Vietnamese version was administered electronically via company email addresses using the Qualtrics platform.

FINDINGS

Data examination

A total of 988 email invitations with a Qualtrics survey link were sent to potential participants, yielding 353 responses. After screening for missing data, outliers, non-normality, and multicollinearity, 248 valid responses were retained for analysis. Non-response bias was assessed using an independent-samples *t*-test, comparing early (n = 104) and late (n = 144) respondents under the assumption that late respondents resemble non-respondents. No significant differences were found ($p > 0.05$), suggesting non-response bias was not a concern. In this study, common method bias was also evaluated using the common latent factor approach. A confirmatory factor analysis (CFA) of all items showed satisfactory fit (IFI = 0.952, TLI = 0.949, CFI = 0.952, RMSEA = 0.024). Adding a common method factor yielded comparable fit (IFI = 0.947, TLI = 0.944, CFI = 0.946, RMSEA = 0.025), with changes below recommended thresholds, indicating that common method bias is unlikely to threaten the validity of the findings.

Measurement model

The measurement model results show that all items loaded strongly onto their respective constructs, with factor loadings above 0.5 (see the Appendix). Reliability analysis indicated that Cronbach's alpha values exceeded 0.7, confirming internal consistency (Hair et al., 2018). CFA demonstrated satisfactory model fit: CMIN/*df* = 1.144 (≤3), RMR = 0.038, RMSEA = 0.024, and incremental fit indices IFI = 0.952, CFI = 0.952, TLI = 0.949. Convergent validity was supported, with AVE > 0.50 and CR > 0.70 for all constructs, while discriminant validity was confirmed as each construct's AVE square root exceeded its correlations with others (see Table 1). Overall, the measurement model exhibits adequate reliability and validity, supporting its use in subsequent structural analysis.

Table 1. Construct validity of the full CFA measurement model

	CR	AVE	MSV	MaxR(H)	SRC	DTR	DTD
SRC	0.802	0.594	0.577	0.821	0.771		
DTR	0.869	0.538	0.429	0.884	0.661	0.734	
DTD	0.751	0.563	0.501	0.752	0.597	0.609	0.750

Structural model

The hypotheses were tested using structural equation modelling (SEM). The results indicate that the model exhibits a satisfactory fit to the data, such as $\chi^2/df = 1.149$, IFI = 0.953, CFI = 0.952, and RMSEA = 0.025 (Hu & Bentler, 1999). In addition to testing the three hypotheses, this study examines the indirect effect of DTR on SRC through DTD in order to address the third research question. The standardised path coefficients for the hypothesised relationships are reported in Table 2.

Table 2. Summary of the results

Hypothesis	Relationship	Standardised regression weight	*p* value	Results
H1	DTR à DTD	0.837	***	Supported
H2	DTR à SRC	0.299	0.125	Not supported
H3	DTD à SRC	0.552	0.010	Supported
Indirect relationship	DTR à DTD à SRC	0.462	0.021	Fully mediated

(Source: Author's own work)

The results indicate a strong positive relationship between DTR and DTD (β = 0.837, $p < 0.001$), providing robust support for H1 and suggesting that higher DTR enables more effective deployment. DTD also positively impacts SRC (β = 0.552, $p = 0.01$), supporting H3, while the direct effect of DTR on SCR was not significant ($p > 0.05$), thus H2 is unsupported. Mediation analysis showed that DTD fully mediates the relationship between DTR and SRC (β = 0.462, $p = 0.021$), highlighting that DTR enhances SRC primarily through effective DTD. The results of the structural model testing are presented in the Appendix.

DICUSSIONS

Relationship between DTR and DTD

The findings indicate that organisations with higher levels of DTR are better positioned to deploy DT initiatives effectively. This relationship is consistent with ORT, which conceptualises readiness as a critical precondition for change, encompassing behavioural, cognitive, and psychological preparedness to support organisational transformation (Weiner, 2020). A high level of DTR enhances organisational flexibility, coordination, and collective commitment, thereby enabling firms to translate strategic intent into effective DTD. Prior empirical studies further corroborate this relationship, highlighting the pivotal role of organisational readiness in achieving DT outcomes across diverse organisational and industry contexts (Halpern et al., 2021; Huang et al., 2025; Lokuge et al., 2019).

The salience of DTR is particularly critical in the Vietnamese context, where SMEs account for approximately 98% of all firms and frequently face strategic, financial, and human capital constraints (Hai et al., 2021). Many SMEs lack coherent DT strategies and adequate financial resources, with fewer than 40% able to support moderate- to large-scale DT initiatives, while persistent shortages of digital skills further impede implementation efforts (Minh et al., 2024). These constraints are especially evident in export-oriented seafood firms, where effective DTR requires not only general digital competencies but also industry-specific technical expertise and regulatory knowledge (Nga & Tam, 2025). Taken together, these contextual conditions underscore DTR as a fundamental prerequisite for the effective planning, implementation, and scaling of DT initiatives.

Relationship between DTD and SRC

This finding confirms that DTD positively influences SRC, consistent with prior empirical evidence (Zhao et al., 2023; Yuan et al., 2024). Li et al. (2022), based on survey data from 162 Chinese manufacturing firms, demonstrate that deeper DTD significantly enhances firm resilience capabilities.

This finding is also consistent with the DCT perspective, in that DT enhances organisational agility by strengthening firms' ability to sense environmental changes, anticipate disruptions, and proactively mitigate supply chain risks (Annarelli et al., 2021). Through real-time data collection and analytics, DT improves demand forecasting, reduces uncertainty, and enhances supply chain visibility, enabling early disruption detection and timely responses (Yuan & Li, 2022). In addition, DT fosters internal integration and cross-functional collaboration while strengthening coordination and trust among supply chain partners, thereby improving collective response capabilities during disruptions (Hanelt et al., 2021; Li, 2022). By supporting business model innovation and operational reconfiguration, DT further contributes to agile and adaptable supply chain networks, reinforcing SRC in volatile environments (Ye et al., 2022).

This relationship is especially salient in the Vietnamese seafood industry, which is highly export-oriented and with stringent international regulatory requirements, and exposure to frequent external shocks such as climate variability, disease outbreaks, and trade policy changes. In this context, DTD enables seafood manufacturing firms to improve real-time traceability, quality monitoring, and compliance with food safety and sustainability standards across upstream aquaculture and downstream distribution activities (Nhu-Mai and Duc-Son, 2025). Digital technologies such as data analytics, IoT-based monitoring, and integrated information systems enhance supply chain visibility and coordination, allowing firms to respond more rapidly to

disruptions in raw material supply, logistics delays, and demand fluctuations in export markets (Dey et al., 2024).

The mediating role of DTD on the relationship between DTR and SRC

The findings indicate that although DTR does not have a direct effect on SRC, its influence is realised indirectly through DTD. This mediating effect highlights the critical role of translating organisational preparedness into actionable and embedded digital practices. The practice-based view (PBV) suggested by Bromiley & Rau (2014) offers a robust theoretical explanation for this mechanism, as it emphasises that sustained performance advantages arise not merely from the possession of resources or favourable readiness conditions, but from the effective enactment of organisational practices within routine operations.

In the context of Vietnamese seafood firms, this result can be attributed to the industry's highly fragmented supply chain structure, in which individual firms' DTR is often insufficient to directly influence end-to-end supply chain activities. Readiness at the firm level does not automatically extend to upstream and downstream partners, such as farmers, logistics providers, and exporters. Consequently, DTR must be operationalised through concrete DTD practices that reflect both the breadth and depth of digital technology utilisation. Specifically, DTD breadth captures the extent to which firms conduct interactions with supply chain partners through digital platforms, as indicated by the proportion of partners engaged digitally, the proportion of transactions executed through digital technologies, and the proportion of other partner interactions carried out via digital platforms. DTD depth in primary activities refers to the extent to which digital technologies are embedded in core value chain processes, including inbound logistics, production management, outbound logistics, and marketing, sales, and service. This may encompass applications such as digital traceability systems, real-time monitoring of raw material sourcing and processing activities, and data-driven demand forecasting. DTD depth in support activities captures the extent to which digital technologies are utilised in procurement and partner selection and management, human resource management, and other managerial functions.

Through the effective DTD, Vietnamese seafood firms can develop the adaptive, absorptive, and reconfiguration capabilities required to enhance SCR. These capabilities enable firms to respond more effectively to industry-specific disruptions, such as supply variability, logistics delays, and abrupt changes in export regulations, thereby transforming DTR into SRC (Dey et al., 2024). This finding reinforces the argument that readiness alone is insufficient; SRC emerges only when digital preparedness is translated into sustained and coordinated digital practices.

CONCLUSION

This study examines the roles of DTR and DTD in strengthening SRC. The findings demonstrate that higher levels of DTR significantly facilitate more effective DTD, which in turn exerts a positive and significant impact on SRC. Importantly, DTD mediates the relationship between DTR and SRC, indicating that organisational readiness contributes to supply chain resilience primarily through the effective implementation and integration of digital initiatives rather than through direct effects.

This study contributes to both theory and practice. From a theoretical perspective, it extends ORT by clarifying how multidimensional readiness conditions, spanning cognitive, strategy, culture, financial, infrastructure, human, operational procedure, and supply chain integration, serve as critical antecedents to effective DTD. It also advances DCT by demonstrating how DTD enables firms to sense, seize, and reconfigure resources in response to supply chain disruptions, thereby underpinning SRC. In addition, the study extends the practice-based view by elucidating DTD as a mediating mechanism through which DTR is transformed into SRC. By conceptualising DTR and DTD as multidimensional constructs that capture both the breadth and depth of digital deployment across primary and support activities, the study offers a more comprehensive understanding of how digital practices contribute to SCR. From a practical perspective, the findings provide actionable guidance for managers in Vietnamese seafood manufacturing firms, particularly in SME-dominated and resource-constrained environments. The results underscore

the importance of prioritising effective DTD, rather than readiness in isolation, to enhance supply chain visibility, coordination, and adaptability.

Notwithstanding these contributions, this study has several limitations. Its focus on a single industry and national context may limit the generalisability of the findings, while the cross-sectional research design constrains causal inference and the examination of dynamic DT processes over time. Future research could address these limitations by adopting longitudinal designs or cross-industry and cross-country comparative studies to further validate and extend the proposed framework.

REFERENCES

Ali, A., Mahfouz, A., & Arisha, A. (2017). Analysing supply chain resilience: integrating the constructs in a concept mapping framework via a systematic literature review. Supply chain management: An International Journal, 22(1), 16-39.

Ali, I., Sadiddin, A., & Cattaneo, A. (2023). Risk and resilience in agri-food supply chain SMEs in the pandemic era: a cross-country study. International Journal of Logistics Research and Applications, 26(11), 1602-1620.

Annarelli, A., Battistella, C., Nonino, F., Parida, V., & Pessot, E. (2021). Literature review on digitalisation capabilities: Co-citation analysis of antecedents, conceptualization and consequences. Technological Forecasting and Social Change, 166, 120635.

Azadegan, A., Mellat Parast, M., Lucianetti, L., Nishant, R., & Blackhurst, J. (2020). Supply chain disruptions and business continuity: An empirical assessment. Decision Sciences, 51(1), 38-73.

Baldwin, R., & Freeman, R. (2022). Risks and global supply chains: What we know and what we need to know. Annual Review of Economics, 14, 153-180.

Belhadi, A., Kamble, S. S., Venkatesh, M., Jabbour, C. J. C., & Benkhati, I. (2022). Building supply chain resilience and efficiency through additive manufacturing: An ambidextrous perspective on the dynamic capability view. International Journal of Production Economics, 249, 108516.

Bican, P. M., & Brem, A. (2020). Digital business model, digital transformation, digital entrepreneurship: Is there a sustainable "digital"?. Sustainability, 12(13), 5239.

Bromiley, P., & Rau, D. (2014). Towards a practice-based view of strategy. Strategic Management Journal, 35(8), 1249–1256.

Business Continuity Institute_BCI (2024). Supply Chain Resilience Report 2024: Available at https://www.thebci.org/resource/bci-supply-chain-resilience-report-2024.html (accessed 08 January 2026).

Chen, R., Xie, Y., & Liu, Y. (2021). Defining, conceptualizing, and measuring organisational resilience: A multiple case study. Sustainability, 13(5), 2517.

Chwiłkowska-Kubala, A., Cyfert, S., Malewska, K., Mierzejewska, K., & Szumowski, W. (2023). The impact of resources on digital transformation in energy sector companies. The role of readiness for digital transformation. Technology in Society, 74, 102315.

Dey, P. K., Chowdhury, S., Abadie, A., Vann Yaroson, E., & Sarkar, S. (2024). Artificial intelligence-driven supply chain resilience in Vietnamese manufacturing small-and medium-sized enterprises. International Journal of Production Research, 62(15), 5417-5456.

Duchek, S. (2020). Organisational resilience: a capability-based conceptualization. Business research, 13(1), 215-246.

Faruquee, M., Paulraj, A., & Irawan, C. A. (2021). Strategic supplier relationships and supply chain resilienceSCR: is digital transformation that precludes trust beneficial?. International Journal of Operations & Production Management, 41(7), 1192-1219.

Gfrerer, A., Hutter, K., Füller, J., & Ströhle, T. (2021). Ready or not: Managers' and employees' different perceptions of digital readiness. California Management Review, 63(2), 23-48.

Hai, H., Xuan, N., Thao, T., & Hien, P. (2021). The effects of strategy and market orientation on the performance of Vietnamese startups. Management Science Letters, 11(4), 1357-1366.

Hair, J.F., Babin, B.J. and Anderson, R.E. (2018), Multivariate Data Analysis, Cengage, Mason, OH.

Halpern, N., Mwesiumo, D., Suau-Sanchez, P., Budd, T., & Bråthen, S. (2021). Ready for digital transformation? The effect of organisational readiness, innovation, airport size and ownership on digital change at airports. Journal of Air Transport Management, 90, 101949.
Hanelt, A., Bohnsack, R., Marz, D., & Antunes Marante, C. (2021). A systematic review of the literature on digital transformation: Insights and implications for strategy and organisational change. Journal of Management Studies, 58(5), 1159-1197.
Hong, D. N. (2021). Post COVID-19: opportunities and challenges for the fishery supply chain in Vietnam. Social Science Research, 3(1), 116-124.
Hortovanyi, L., Morgan, R. E., Herceg, I. V., Djuricin, D., Hanak, R., Horvath, D., ... & Szabo, R. Z. (2023). Assessment of digital maturity: the role of resources and capabilities in digital transformation in B2B firms. International Journal of Production Research, 61(23), 8043-8061.
Hosseini, S., Ivanov, D., & Dolgui, A. (2019). Review of quantitative methods for supply chain resilience analysis. Transportation research part E: logistics and transportation review, 125, 285-307.
Hu, L.T. and Bentler, P.M. (1999), "Cutoff criteria for fit indexes in covariance structure analysis: conventional criteria versus new alternatives", Structural Equation Modeling: A Multidisciplinary Journal, 6(1), 1-55.
Huang, J., Raja Yusof, R.N., Abd Rahman, A. and Ab Rahman, R. (2025), "Determinants of digital technology adoption and its impact on firm performance in manufacturing firms", Journal of Manufacturing Technology Management, 36(5), 1003–1025.
Li, L. (2022). Digital transformation and sustainable performance: The moderating role of market turbulence. Industrial Marketing Management, 104, 28-37.
Lokuge, S., Sedera, D., Grover, V., & Dongming, X. (2019). Organisational readiness for digital innovation: Development and empirical calibration of a construct. Information & Management, 56(3), 445-461.
Ma, B., & Zhang, J. (2022). Tie strength, organisational resilience and enterprise crisis management: An empirical study in pandemic time. International Journal of Disaster Risk Reduction, 81, 103240.
Mancha, R., & Shankaranarayanan, G. (2021). Making a digital innovator: antecedents of innovativeness with digital technologies. Information Technology & People, 34(1), 318-335.
Min, S., & Kim, B. (2024). Adopting artificial intelligence technology for network operations in digital transformation. Administrative Sciences, 14(4), 70.
Minh, L. N., Tan, N. N., Toan, D. V., Thao, T. D., Huyen, N. T., & Hoài, N. T. (2024). Digital transformation in Vietnam: A case study of Hanoi SMEs. International Journal of Advanced and Applied Sciences, 11(4), 207-215.
Nga, L. P., & Tam, P. T. (2025). Impacting Digital Transformation of Human Resource Management on Enterprise Competitive Capacity: A Case Study in Vietnam. Qubahan Academic Journal, 5(2), 129-155.
Nhu-Mai Thi, N. O. N. G., & Duc-Son, H. A. (2025). Enhance Competitive Advantage of Vietnamese Enterprises: The Role of Digital Technology and Resilient Supply Chain. Journal of Distribution Science, 23(4), 49-60.
Panuwatwanich, K., & Nguyen, T. T. (2017). Influence of organisational culture on total quality management implementation and firm performance: evidence from the Vietnamese construction industry. Management and Production Engineering Review, 8(1), 5-15.
Patel, K. R. (2023). Enhancing Global Supply Chain Resilience: Effective Strategies for Mitigating Disruptions in an Interconnected World. BULLET: Jurnal Multidisiplin Ilmu, 2(1), 257-264.
Pingali, S. R., Singha, S., Arunachalam, S., & Pedada, K. (2023). Digital readiness of small and medium enterprises in emerging markets: The construct, propositions, measurement, and implications. Journal of Business Research, 164, 113973.
Schneider, S., & Kokshagina, O. (2021). Digital transformation: What we have learned (thus far) and what is next. Creativity and Innovation Management, 30(2), 384-411.
Teece, D. J. (2018). Dynamic capabilities as (workable) management systems theory. Journal of Management & Organisation, 24(3), 359-368.
Vietnam Association of Seafood Exporters and Producers (2024). Overview of vietnam's aquaculture industry, https://vasep.com.vn/gioi-thieu/tong-quan-nganh.
Vietnamese Ministry of Planning and Investment (2023). Readiness level in digital transformation of Vietnamese enterprises.https://digital.business.gov.vn/wp-content/uploads/2023/02/Annual-DXReport_Final_Public.pdf

Wang, J., Chen, R., & Zhang, S. (2022). The Mediating and Moderating Effect of Organisation Resilience on Competitive Advantage: Evidence from Chinese Companies. Sustainability, 14(21), 13797.
Weiner, B. J. (2020). A theory of organisational readiness for change. In Handbook on implementation science (pp. 215-232). Edward Elgar Publishing.
Ye, F., Liu, K., Li, L., Lai, K. H., Zhan, Y., & Kumar, A. (2022). Digital supply chain management in the COVID-19 crisis: An asset orchestration perspective. International Journal of Production Economics, 245, 108396.
Yin, W. (2023). Identifying the pathways through digital transformation to achieve supply chain resilience: an fsQCA approach. Environmental Science and Pollution Research, 30(4), 10867-10879.
Yuan, Y., & Li, W. (2022). The effects of supply chain risk information processing capability and supply chain finance on supply chain resilience: a moderated and mediated model. Journal of Enterprise Information Management, 35(6), 1592-1612.
Yuan, Y., Tan, H., & Liu, L. (2024). The effects of digital transformation on supply chain resilience: A moderated and mediated model. Journal of Enterprise Information Management, 37(2), 488-510.
Zhang, T., Shi, Z. Z., Shi, Y. R., & Chen, N. J. (2022). Enterprise digital transformation and production efficiency: Mechanism analysis and empirical research. Economic research-Ekonomska istraživanja, 35(1), 2781-2792.
Zhao, N., Hong, J., & Lau, K. H. (2023). Impact of supply chain digitalisation on supply chain resilience and performance: A multi-mediation model. International Journal of Production Economics, 259, 108817.

APPENDIX

Table 1. Measurement scaling reliability

Items	**Coding**	**Loading**
DT readiness (DTR)		
Digital infrastructure readiness (IR) (Cronbach's α =0.774)		
In our firm, IT infrastructure resources are ready for all departments to implement DT.	IR1	0.727
In our firm, IT infrastructure resources are regularly upgraded to implement DT.	IR2	0.711
In our firm, database is equipped with security features to protect sensitive information during the DT process.	IR3	0.686
Digital human resource readiness (HR) (Cronbach's α =0.789)		
In our firm, "digitally fluent" talents are attracted through special policies for implementing DT.	HR1	0.759
In our firm, human resources are allocated for DT right from the start.	HR2	0.750
In our firm, human resources from existing business areas are flexibly reallocated for DT when required.	HR3	0.736
In our firm, training in digital competencies (knowledge, skills, and mindset) is provided to staff.	HR4	0.745
In our firm, employees' business initiatives that leverage digital technology are appropriately rewarded.	HR5	0.756

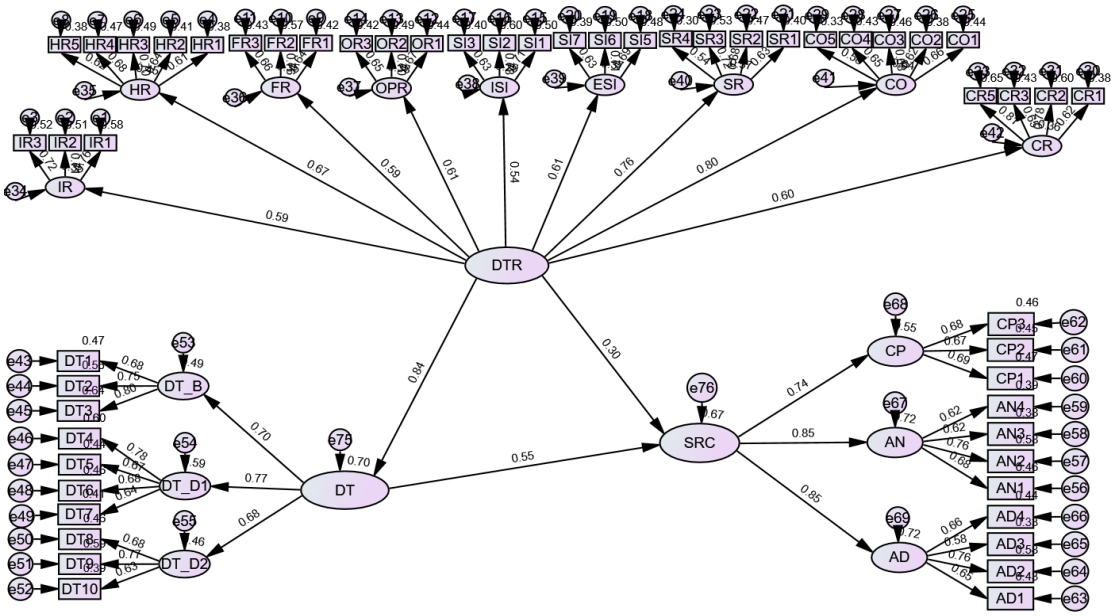
Digital financial readiness (FR) (Cronbach's α =0.730)		
In our firm, budgets are allocated for DT right from the start.	FR1	0.675
In our firm, financial resources from existing business areas are flexibly reallocated for DT when required.	FR2	0.589
Our firm actively seeks additional external financial resources for DT in case of budget shortages.	FR3	0.666
Digital operational procedure readiness (OR) (Cronbach's α =0.717)		
In our firm, the manual workflows are ready for DT.	OR1	0.602
In our firm, the information flow is ready for DT.	OR2	0.640
In our firm, the documentation flow is ready for DT.	OR3	0.641
Internal digital supply chain integration readiness (ISI) (Cronbach's α =0.736)		
In our firm, a digital platform is actively used to integrate and share information.	SI1	0.639
In our firm, we strive to collaborate through a digital platform to achieve multiple objectives.	SI2	0.594
In our firm, a digital platform is promoted for making joint decisions to optimize benefits.	SI3	0.724
External digital supply chain integration readiness (ESI) (Cronbach's α = 0.713)		
In our firm, a digital platform is actively used to integrate and share information.	SI5	0.641
In our firm, we strive to collaborate through a digital platform to achieve multiple objectives.	SI6	0.572
In our firm, a digital platform is promoted for making joint decisions to optimize benefits.	SI7	0.658
Digital strategy readiness (SR) (Cronbach's α = 0.745)		
In our firm, DT is communicated as one of the goals of our strategies.	SR1	0.687
In our firm, the roadmap for DT is integrated into our strategic planning.	SR2	0.671
In our firm, the strategic goals regarding DT are clear to all employees.	SR3	0.659
In our firm, the roles and responsibilities of all participants are clearly defined within DT processes.	SR4	0.725
Digital cognitive readiness (CO) (Cronbach's α = 0.775)		
In our firm, top managers regularly discuss and identify new digital technologies to integrate them into our business model.	CO1	0.731
In our firm, top managers understand the opportunities and threats enabled by DT.	CO2	0.740

In our firm, top managers are consistently focused on creating customers' value through digital solutions.	CO3	0.718
In our firm, top managers have a commitment to implement DT.	CO4	0.732
In our firm, top managers always prioritise DT.	CO5	0.749
Digital cultural readiness (CR) (Cronbach's α = 0.807)		
We have a culture of sharing ideas regarding DT within our firm.	CR1	0.788
We have a culture of sharing ideas regarding DT between our firm and supply chain partners.	CR2	0.744
Our firm has a culture of continuous learning regarding DT.	CR3	0.778
Our firm has a culture of being willing to take risks with regard to DT.	CR5	0.719
DT deployment (DTD)		
Breadth (DTD_B) (Cronbach's α = 0.781)		
The proportion of the total number of partners with whom our firm has interacted through digital platforms.	DT1	0.751
The proportion of the total number of partner interactions (transactions) conducted through DT.	DT2	0.710
The proportion of the total number of other interactions with partners carried out through digital platforms.	DT3	0.652
Depth_primary activities (DTD_D1) (Cronbach's α = 0.785)		
The extent to which DTs are used in inbound logistics activities in our firm.	DT4	0.707
The extent to which DTs are used in production management in our firm.	DT5	0.737
The extent to which DTs are used in outbound logistics activities in our firm.	DT6	0.739
The extent to which DTs are used in marketing, sales, and service in our firm.	DT7	0.745
Depth_support activities (DTD_D2) (Cronbach's α = 0.730)		
The extent to which DTs are used in procurement management, including partner selection and management in our firm.	DT8	0.646
The extent to which DTs are used in human resource management in our firm.	DT9	0.587
The extent to which DTs are used in other management activities in our firm.	DT10	0.688
Supply chain resilience capabilities (SRC)		
Anticipation (AN) (Cronbach's α = 0.740)		
Supply chain disruptions and their impacts are always understood in our firm's supply chain.	AN1	0.673

Prospective risks that may lead to supply chain disruptions are always monitored by our firm's supply chain.	AN2	0.638
Supply chain disruptions and their impacts are always accurately forecasted in our firm's supply chain.	AN3	0.701
Unexpected supply chain disruptions are always effectively prepared for in our firm's supply chain.	AN4	0.707
Coping (CP) (Cronbach's α = 0.700)		
Solutions to cope with supply chain disruptions are always effectively developed in our firm's supply chain.	CP1	0.586
Existing resources in our firm's supply chain are always utilised effectively to cope with supply chain disruptions.	CP2	0.574
The operational processes in our firm's supply chain are always successfully adjusted in response to disruptions.	CP3	0.670
Adaptation (AD) (Cronbach's α = 0.756)		
The experiences learned from past crises of our firm's supply chain are always used for supply chain disruptions in the future.	AD1	0.707
Contingency plans and solutions for future supply chain disruptions are always effectively developed in our firm's supply chain.	AD2	0.672
The existing production systems in our firm's supply chain are always capable of reconfiguring to adapt to disruption impacts.	AD3	0.741
Business models in our firm's supply chain are always adjusted to respond to disruptions.	AD4	0.676

(Source: Author's own work)

Figure 1. Structural model



(Source: Author's own work)

SUPPLY CHAIN ANALYTICS

Inside The Mind of an AMR: A Demonstrator for Slam-Based Navigation in Logistics Education

Luca Reck[1], Sara Perotti[2], Luca Cannava[2], Peik Bremer[1]

1: Technical University of Applied Sciences Würzburg-Schweinfurt, Germany; 2: Politecnico di Milano, Italy

INTRODUCTION

The contemporary industrial landscape is experiencing ongoing transformation driven by human-centricity, digitalization and sustainability (Jefroy et al., 2022; Pacher et al., 2023). While Industry 4.0 has largely focused on full automation and cyber-physical integration, the emerging Industry 5.0 paradigm shifts attention toward collaboration between humans and intelligent systems (Golovianko et al., 2023).

This industrial evolution toward human-machine collaboration is profoundly reshaping industrial processes and redefining the competencies required in science, technology, engineering and mathematics (STEM) fields (Pacher et al., 2023). Within this transformation, logistics represents a particularly critical domain due to its central role in supply chains and its labour-intensive nature (Jefroy et al., 2022). The sector exemplifies the Industry 5.0 shift from pure automation toward human-centric technological integration, where robotics serves not to replace human operators but to enhance their capabilities in warehousing and intralogistics operations (Grosse et al., 2023).

Recent research on smart logistics confirms this transition, highlighting increasing interaction between humans and technology through collaborative systems and human-robot cooperation (Jefroy et al., 2022). Among the technologies shaping intralogistics, Autonomous Mobile Robots (AMRs) have emerged as transformative enablers of intelligent and flexible warehouse operations (Turhanlar et al., 2024). AMRs are mobile robots capable of autonomously navigating complex environments without requiring pre-installed infrastructure, distinguishing them from traditional automated guided vehicles (AGVs) (Prasad et al., 2025). These capabilities position AMRs as enablers in logistics and intralogistics operations, particularly in material handling, where they enhance warehouse efficiency (Turhanlar et al., 2024) while reducing human workload in repetitive transport tasks (Alves et al., 2023).

Advances in autonomous robot development have intensified research on navigation systems. Simultaneous Localization and Mapping (SLAM) has become a key technology enabling robots to perceive environments, build real-time maps and determine their position within these maps. Thereby SLAM provides the foundation for robotic perception, spatial awareness and autonomous navigation (Saleem et al., 2023). Traditional SLAM-techniques rely on geometric model-based methods that perform effectively in static environments but face significant limitations in dynamic or complex settings (Pu *et al.*, 2023; Wang *et al.*, 2024). To overcome these constraints, recent studies have advanced toward semantic enhancement through deep learning techniques, enabling robots to integrate contextual and object-level understanding into the SLAM system, substantially improving robustness and precision of the localization (Tang et al., 2023; Wang et al., 2024). The integration of semantic segmentation into SLAM represents a major step forward, enabling robots not only to recognize spatial structures but also to intelligently interact with human counterparts (Pu et al., 2023).

This technological progress re-emphasizes the educational imperative to understand the underlying principles of robotic perception and decision-making. This need extends beyond logistics, as mobile robots are gaining relevance across domains such as healthcare, research and education (Sousa et al., 2025). Consequently, education models must evolve to prepare future engineers for collaboration with such intelligent systems. In response, scholars have called for innovative educational tools that systematically equip engineers to address these challenges

(Jiménez López et al., 2022) and for transdisciplinary learning approaches that highlight human-machine interaction (Gürdür Broo et al., 2022).

Despite these insights in engineering pedagogy, a notable gap in implementation remains. Existing systems deliver robust geometric SLAM, mapping and planning (Chen *et al.*, 2022), effectively teach sensor fusion, odometry and loop-closure (Jin et al., 2019). However, performing complex tasks such as autonomous payload transport in warehouses requires semantic understanding that extends beyond basic geometric mapping (Kulkarni et al., 2021). While research demonstrates integration of object detection via convolutional neural networks to enable these domain-specific applications, they focus primarily on system validation, neglecting pedagogical accessibility (Kulkarni et al., 2021). Consequently, there remains a lack of systems that integrate neural network-based semantic SLAM or provide interactive visualization. Moreover, none of the existing approaches directly address the educational context.

This study aims to address this gap by developing an immersive educational demonstrator that fuses geometric SLAM with neural network semantic outputs and allows students to interactively explore the perception processes of AMRs. The demonstrator builds on vision-based perception, as camera-driven approaches offer a practical balance between accessibility and computational efficiency, providing an inexpensive and pedagogically suitable use-case.

The remainder of this paper is organised as follows. First, the literature review synthesises the technological and educational foundations relevant to this study. The methodology section then describes the research design and development approach. Subsequently, the conceptual design section introduces the structure and components of the proposed demonstrator, followed by the demonstrator application section, which details its educational use and implementation.

LITERATURE REVIEW

Technological Perspective: SLAM-based systems in Logistics

Intralogistics - responsible for organising, executing and optimising internal flows of materials and information (Krenczyk et al., 2020) - has become a key domain for robotics, reflecting the technological and organisational transformation of modern automation. This evolution is compelled by market dynamics, such as e-commerce, mass customization, omni-channel models and just-in-time practices (Custodio and Machado, 2020; Merschformann et al., 2019; Turhanlar et al., 2024), as well as labor shortages (Ponis and Efthymiou, 2020). These developments require a shift away from maximising economies of scale through bundled transport volumes (Scholz et al., 2017) toward handling smaller batch sizes with higher transport frequency (Schuhmacher and Hummel, 2018). As technological innovation creates new ways to reorganise material-handling processes (Dharmasiri et al., 2020), automation has been increasingly applied in warehouses; however, this does not necessarily translate into greater flexibility (Custodio and Machado, 2020). In practice, most automation systems rely on centralised, hierarchically organised architectures, limiting their responsiveness to dynamic operational condition (Schuhmacher and Hummel, 2018). In this context, autonomous robots represent one viable approach to ensure efficient and flexible internal transport (Scholz et al., 2017), because they operate without reliance on a central control system and incorporate their own intelligence (Schuhmacher and Hummel, 2018). Consequently, intralogistics has become a proving ground where AMRs can enhance productivity while reducing the physical workload for human workers (Srinivas and Yu, 2022).

Autonomous operation fundamentally depends on the robot’s ability to perceive and interpret its surrounding environment (Cadena et al., 2016; Tang et al., 2023). Autonomous robot architectures typically consist of four interdependent modules: perception, localisation and mapping, planning and decision-making, and motion control (Jiang, 2025; Liu and Xu, 2025). Among these, the perception module provides the essential input for all subsequent operations, as it captures and interprets environmental data to extract meaningful information (Jin et al., 2019). To act effectively and achieve their objectives, autonomous robots must understand their surroundings rather than merely sense them (Al-Tawil et al., 2024). While sensing provides raw environmental data, autonomous robots must transform these sensory inputs into geometric

and semantic representations of the environment to interpret and interact effectively with their surroundings (Lai, 2022). The criticality of this perceptual capability extends to higher-level tasks such as path planning and decision-making to avoid obstacles (Han, 2023).

SLAM supports this process by enabling robots to achieve the spatial awareness required for safe and purposeful motion (Han, 2023). SLAM is described as the task of building a map of an unfamiliar environment while estimating the robot's position within it (Smith and Cheeseman, 1986), a capability essential for AMRs that operate autonomously without depending on prebuilt maps (Al-Tawil et al., 2024; S. Chen et al., 2022). At the architectural level, SLAM is commonly described as comprising a front-end and a back-end (Cadena et al., 2016). The front-end processes raw sensor measurements and converts them into models suitable for estimation. The back-end performs inference on this abstracted information to produce a globally consistent trajectory and map (Cadena et al., 2016)**.** These functions are operationalised through five components: data acquisition, visual odometry, back-end optimisation, loop closure detection and mapping (Cai et al., 2024; Pu et al., 2023; Xiang et al., 2024). A defining strength of SLAM is its ability to resolve accumulated trajectory drift through loop-closure detection (Cadena et al., 2016). In this process, the robot recognises that it has returned to a previously visited location and uses this information to correct the drift (Cai et al., 2024; Kim et al., 2024), which distinguishes it from odometry-only approaches (Cadena et al., 2016).

Depending on the sensors employed for data acquisition, scholars distinguish between laser SLAM and visual SLAM (W. Chen et al., 2022; Pu et al., 2023). vSLAM relies on camera inputs to detect and track visual features, whereas laser SLAM uses laser sensors to measure distances and construct spatial representations (Dau et al., 2025). Due to their low cost and ability to capture rich visual information, vSLAM methods have become increasingly attractive for mobile robotics (Dau et al., 2025; Rostum and Vásárhelyi, 2025). Traditional vSLAM focuses on geometric reconstruction but cannot support tasks that require object understanding (W. Chen et al., 2022; Lai, 2022). These constraints have motivated research toward semantic enrichment, where deep learning modules augment geometric mapping with object-level information (W. Chen et al., 2022). By assigning semantic labels and constructing high-level maps, robots gain a human-centred understanding of their environment (W. Chen et al., 2022; Lai, 2022). These benefits come at the cost of increased computational demand, including higher requirements for real-time processing, data fusion and algorithmic robustness (Cai et al., 2024; Gan et al., 2024; Wang et al., 2024). Nonetheless, state-of-the-art deep learning models such as You Only Look Once (YOLO) have been integrated into vSLAM frameworks to enhance scene understanding, identify dynamic objects and improve robustness in complex environments (Tang et al., 2023).

As Pfeiffer et al. (2017) note, a persistent challenge in robotics is ensuring that robots behave in ways human operators desire. Achieving this requires understanding about how autonomous systems perceive and interpret their environment. Because vSLAM relies on image-based perception that closely mirrors human visual understanding (W. Chen et al., 2022), it provides an intuitive basis for visualising these perceptual processes and making robotic "thinking" accessible to learners.

Educational Perspective: Immersion & Experiential Learning

The ongoing transition toward Industry and Society 5.0 is reshaping engineering practice and, consequently, the competencies required of future engineers (Pacher et al., 2023). Advances in digital transformation and the convergence of previously distinct disciplines have increasingly blurred traditional disciplinary boundaries, giving rise to more transdisciplinarity in established models of engineering education (Gürdür Broo et al., 2022). As a result, engineers are expected to combine deep technical expertise with transversal competencies (Pacher et al., 2023). Despite these developments, engineering education largely retains traditional instructional patterns centred on passive lectures and time-based metrics such as credit hours (Gürdür Broo et al., 2022). Moreover, STEM knowledge is frequently taught in discipline-specific isolation, contradicting the integrated way in which students encounter technology in real-world contexts (Thibodeaux et al., 2025). Consequently, graduates are often insufficiently prepared to translate technological knowledge into operational solutions and to manage complex, interconnected systems - capabilities increasingly central to contemporary engineering practice (Gürdür Broo et

al., 2022). Against this backdrop, a transition toward technology-enhanced immersive and interactive learning appears essential to equip future engineers with the transdisciplinary fluency and practical competencies demanded by digitalised, human-centred industrial systems.

Immersive and interactive technologies are increasingly recognised as effective means of addressing limitations in traditional engineering education by strengthening the link between theory and practice (Sabraz Nawaz et al., 2025). By reducing the separation between physical and virtual environments, such technologies enable active engagement with complex content and have been shown to enhance participation, collaboration and learner engagement (Romero-Robles and Iturbe-Ek, 2023). This aligns with experiential learning perspectives, which emphasise hands-on interaction as a key driver of deep understanding and knowledge retention (Sabraz Nawaz et al., 2025). The relevance of these approaches is particularly pronounced in STEM education, where many concepts require practical exposure that conventional teaching formats struggle to provide (Pathania and Kumar, 2025). Interactive learning environments have therefore been adopted to make abstract principles more accessible and to support the integration of conceptual instruction with applied understanding (Pathania and Kumar, 2025). Taken together, immersive and interactive technologies offer a viable pathway toward experiential learning formats that better reflect the transdisciplinary and practice-oriented skill demands of digitally transformed, human-centred engineering contexts.

Logistics constitutes a critical interface domain that naturally integrates diverse engineering fields and further exemplifies the convergence of different disciplines within the Industry 5.0 paradigm (Gürdür Broo et al., 2022). This transdisciplinarity, combined with the growing symbiosis of human and machine intelligence in smart logistics operations (Jefroy et al., 2022), renders intralogistics a particularly suitable context for experiential learning approaches that connect abstract theory with operational reality. Recent educational frameworks for autonomous systems, such as the modular platforms proposed by Mehrtash et al. (2024), demonstrate the value of hands-on engagement with sensors, software architectures and localisation and mapping modules. However, a gap remains in making the perceptual processes directly observable and intuitively understandable, particularly for learners without deep prior expertise in robotics or artificial intelligence. In this context, the visualisation of SLAM outputs provides an effective means of exposing the robot’s perceptual and localisation processes. By adopting SLAM for educational purposes, learners can directly relate complex algorithmic principles to visible system behaviour. Consequently, the approach of this paper shifts the educational focus from system construction to perceptual transparency, enabling a transparent learning experience that lowers entry barriers while preserving technical authenticity.

METHODOLOGY

Starting from the research gaps identified in the integrative literature review, this study aims to develop an immersive demonstrator that enables students and instructors in logistics and engineering to understand SLAM-based perception and its enhancement through artificial intelligence. To achieve this research objective, the methodological approach was structured into three sequential phases, as illustrated in **Fig. 1**.

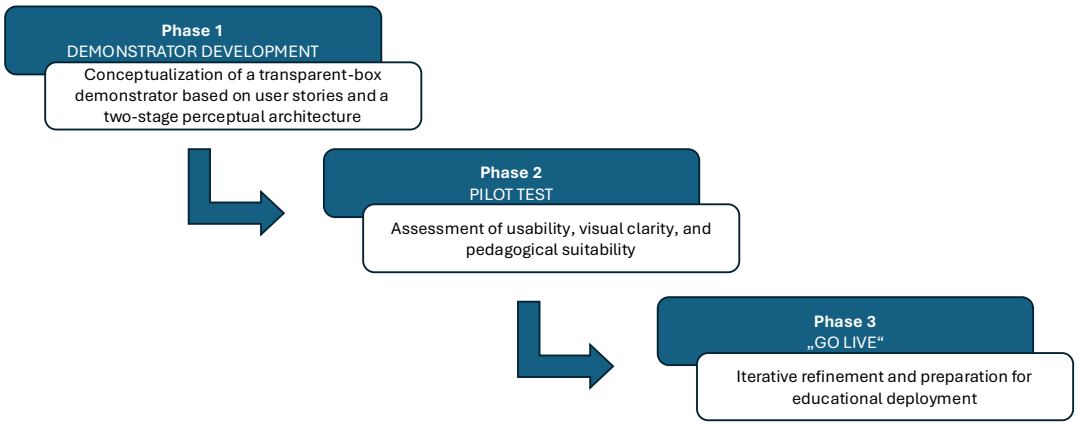


Fig. 5: Three-phase methodology for the development and educational deployment of the immersive SLAM-demonstrator

Demonstrator Development

The development phase is grounded in the distinction between black-box and transparent-box simulators introduced by Machuca (2000). While black-box approaches expose learners only to system outputs, transparent-box approaches reveal the internal mechanisms generating system behaviour. Although originally proposed in the context of management education, the pedagogical principle is equally relevant for engineering contexts involving processes like SLAM. In the context of AMRs, showing what robots accomplish in intralogistics corresponds to the black-box view, whereas meaningful learning also requires insight into how autonomous behaviour emerges. Accordingly, this study adopts a transparent-box approach by making the robot's perceptual processes visible throughout the demonstrator. Building on this principle, the development process adopts a user-centred requirements approach grounded in the User Story method. User stories offer a lightweight and structured way of expressing system requirements from the user's perspective (Amna and Poels, 2022; Zacharias et al., 2019). Their concise, goal-oriented format supports the decomposition of complex systems into comprehensible components (Fancott et al., 2012; Tona et al., 2022). Requirements were elicited through discussions and iterative feedback sessions with instructors who may incorporate the demonstrator into their teaching (Amna and Poels, 2022; Brockenbrough et al., 2025). This process ensured alignment between the demonstrator's functionality and pedagogical needs.

The demonstrator itself was implemented as a two-stage perceptual system that incrementally exposes the principles of robotic perception. In the first stage, a real-time geometric SLAM map is generated by moving the camera through the environment, introducing and visualizing fundamental concepts of localisation, mapping, and structural perception. In the second stage, a pretrained YOLOv8 model augments the geometric map with object-level semantic information, illustrating how neural networks extend vSLAM toward context-aware perception. Both stages are presented visually on an external monitor, enabling not only the person carrying the camera to simulate the AMR but also all observing participants to follow the robot's perceptual processes in real time. This setup operationalises the transparent-box principle by progressively revealing how AMRs perceive, interpret and represent their surroundings.

Pilot Test and Go Live

A pilot test with a small group of instructors assessed usability, clarity of visualisation and pedagogical relevance. Feedback from this phase informed iterative refinements, resulting in a final demonstrator version that is aligned with educational objectives.

CONCEPTUAL DESIGN

The low-cost demonstrator is designed to make the perceptual and localisation processes of an AMR transparent while remaining modular and easily replicable. Consistent with the transparent-box perspective outlined in the methodology, the conceptual focus lies on the AMR's perspective - how it perceives and interprets the exemplary intralogistics scenario. To ensure applicability across institutions with varying resources and constraints, the demonstrator is built from configurable components, allowing the setup to be adapted to different spatial, technical and educational contexts.

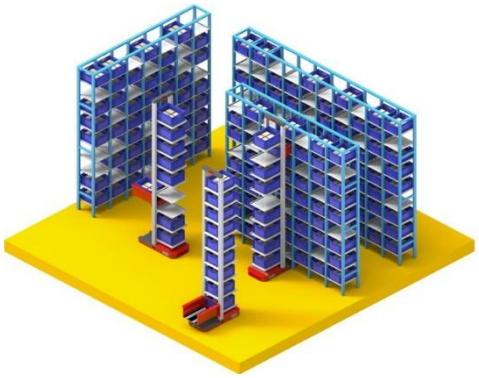


Fig. 6: Illustrative multi-tote storage and retrieval (MTSR) AMR, adapted from Dossier Logistica

To avoid a purely abstract representation of robotic behaviour, the demonstrator reproduces the core functionality of tote-handling AMRs, as analysed in the literature (Castellucci et al., 2025; Qin et al., 2024) and illustrated in **Fig. 2**. These AMRs autonomously navigate warehouse aisles and perform both vertical and horizontal movements to retrieve and transport totes, reflecting the e-commerce driven shift from pallet- to tote-level handling driven by rising stock keeping units (SKUs) and smaller order sizes (Hu and Chang, 2010; Lam et al., 2023). The demonstrator focuses specifically on the replenishment process, which links the storage area - where large stock quantities are stored - with the picking level, where smaller quantities are held for rapid order fulfilment (Walter et al., 2013)

Physical Layout

The process is implemented in an illustrative warehouse layout consisting of a single storage rack and a picking station (**Fig. 3**). The rack comprises multiple shelf levels holding both neutral and colour-labelled totes, while a table positioned a few metres away serves as the picking station and destination for retrieved totes.

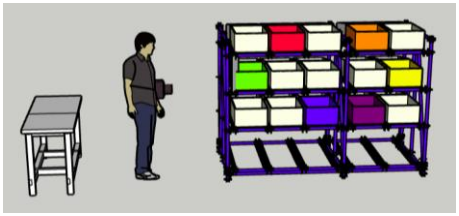


Fig. 7: Physical Layout

Within this environment, participants simulate a tote-handling AMR that autonomously navigates the aisle, retrieves a tote from a designated shelf level, transports it across the defined distance to the picking station and deposits it at the target location. The distance between racks and the picking station can be scaled to the available space, and all physical components - racks, totes, station elements - may be adapted to institutional resources. Furthermore, no additional infrastructure such as guiding tape is required, as the scenario reflects AMR navigation independent of fixed guidance systems. This layout offers a realistic yet resource-efficient environment for demonstrating automated material-handling processes.

Technical Environment

The demonstrator's perceptual pipeline begins with an OAK-D-S2-AF camera, mounted at chest height, supplying depth and RGB data to an Intel NUC11PAHi5 integrated into a wearable carrier system and powered by a mobile power bank. Building on this hardware layer, the open-source Robot Operating System (ROS) serves as middleware for data streaming, device communication and the integration of the vSLAM framework (Al-Tawil et al., 2024). A ROS–Unity bridge transmits vSLAM and camera data to Unity, which runs on a separate notebook. For educational purpose, the visualisation can be projected to an external monitor to improve visibility. Semantic perception is realised using a pretrained YOLOv8 model deployed on the OAK-D's onboard compute resources, enriching geometric SLAM output with contextual labels. To ensure stable real-time operation, live perception visualisation and global map inspection were decoupled into two dedicated Unity instances, preventing performance degradation during extended use. **Fig. 4** illustrates the layered hardware–middleware–software architecture and the corresponding data flows.

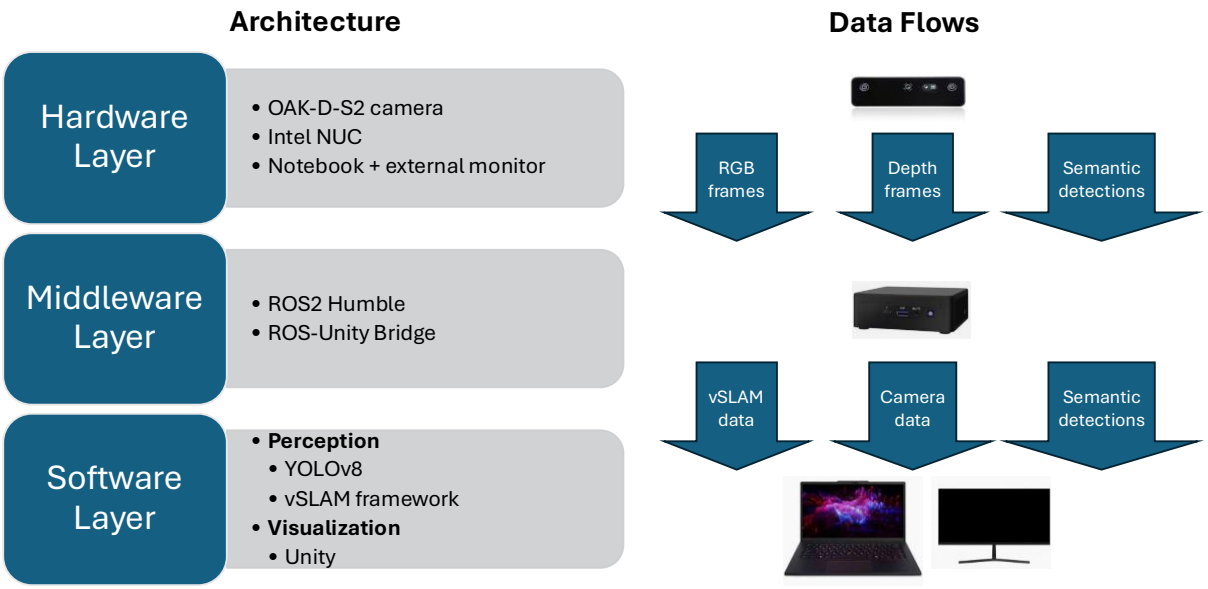


Fig. 8: System architecture and data flows

DEMONSTRATOR APPLICATION

Fig. 5: Pilot Test in the lab environment

The demonstrator application is guided by a user-centred learning scenario derived from a User Story developed in cooperation with potential academic users. The User Story frames the demonstrator from the perspective of logistics students and defines the intended learning outcomes as the ability to visually and experientially understand how an AMR perceives its environment, builds a map, detects obstacles and interprets semantic information in real time, thereby linking theoretical principles of SLAM to practical logistics operations. In line with the transparent-box approach, students do not merely observe system outputs but actively simulate an AMR by carrying the camera mounted to a chest harness through the physical intralogistics environment (**Fig. 5**).

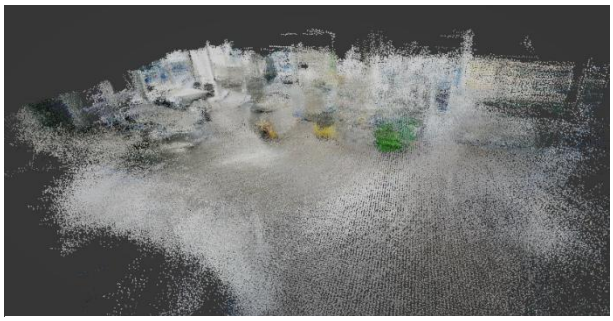


Fig. 6: Generated SLAM Map of the lab environment visualised in Unity

Stage 1 introduces geometric perception by first inviting participants to share their expectations regarding how an AMR perceives its surroundings and how such perception could be represented as a spatial map. Participants then physically simulate an AMR by moving through the environment with the camera, while the vSLAM pipeline generates a geometric map in real time. The evolving map is rendered in Unity using a camera-following view that allows participants and observers to directly experience how localisation and mapping emerge incrementally as the environment is explored. After the exploration phase, the accumulated SLAM output can be examined as a global map (**Fig. 6**). By switching to a bird's-eye view and interactively zooming within the 3D scene, students can analyse the map structure and spatial consistency. This stage establishes a foundational understanding of vSLAM without semantic augmentation.

Stage 2 builds on this understanding by embedding the perception process within a realistic logistics task and initially inviting participants to articulate their expectations on how semantic information - such as object detection - might augment the geometric map. Participants then continue to simulate an AMR as semantic perception is incorporated into the demonstrator workflow. The pretrained YOLOv8 network deployed on the camera is trained on the Common Objects in Context (COCO) dataset, which is a large-scale dataset comprising 80 object classes designed for training and benchmarking object detection models (Chatterjee et al., 2024). As not all these classes are relevant to the demonstrator scenario, a subset was deliberately selected and used as representative goods. These objects plausibly occur in totes and are commonly available across institutional contexts, supporting both didactic clarity and high replicability of the setup. Detected objects are visualised in Unity using distinct colour-coded bounding boxes, with each colour uniquely representing a specific object class. For illustrative purposes (**Fig. 7**), representative items were positioned openly at the picking station, as semantic object detection relies on visual features captured by the camera.

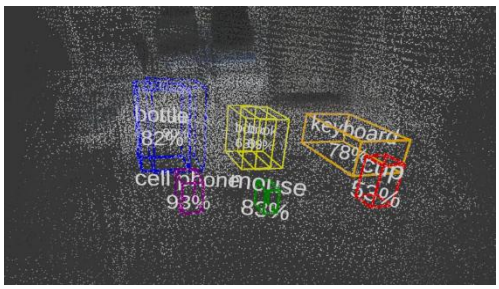


Fig. 7: Object detection visualised in Unity

Within this second stage, semantic perception is operationalised through a structured replenishment workflow. Students receive a digital retrieval list on a tablet (**Fig. 8**) specifying object classes and their associated colours and are tasked with retrieving the corresponding totes from the shelves and transporting them to the picking station. The physical totes are labelled using the same colour scheme as the digital visualisation, reinforcing the direct correspondence between semantic perception and real-world interaction. Upon successful delivery to the picking station, participants confirm task completion directly in the retrieval list interface and are subsequently able to analyse the final map in Unity. Throughout this task, participants and observers can follow how semantic information enhance geometric mapping and supports task-oriented understanding of the environment.

Tote Retrieval List

Item	Tote Colour	Storage Location	Number of Totes	Target	Retrieved
Bottle	Blue	Rack 1 / Level 0 / Position B	1	Picking Station	☐
Keyboard	Orange	Rack 1 / Level 2 / Position C	1	Picking Station	☐
Book	Yellow	Rack 1 / Level 1 / Position C	1	Picking Station	☐

Fig. 8: Exemplary tote retrieval list

CONCLUSION

This paper presented a transparent-box demonstrator designed to make SLAM-based perception in AMRs observable and intelligible within a logistics education context, including for learners without prior expertise in robotics or artificial intelligence. By combining geometric vSLAM with neural network–based semantic perception and real-time visualisation, the demonstrator addressed a gap between advanced robotic navigation technologies and their pedagogical accessibility. Anchored in a transparent-box pedagogical approach, the demonstrator shifts the educational focus from system construction toward perceptual understanding. Situated within a realistic intralogistics replenishment scenario, it enables students to observe how robots perceive and semantically interpret their environment, thereby linking abstract algorithmic concepts to operational reality. This approach aligns with calls for experiential, transdisciplinary learning formats that prepare future engineers for human-centred, intelligent systems in the context of Industry 5.0 (Gürdür Broo et al., 2022; Jiménez López et al., 2022).

Several limitations of the current implementation should be acknowledged. Semantic perception relies on a pretrained YOLOv8 network trained on the COCO dataset, limiting object recognition to 80 predefined classes. Adapting the demonstrator to logistics-specific or additional categories would require domain-specific retraining or the integration of alternative neural network architectures. In addition, recognition accuracy can vary across objects and viewing conditions. In isolated cases, visually salient features influenced detection outcomes; for example, a book was not reliably recognised, while a Buddha depiction on its cover was classified as a person. Semantic object detection further depends on visual line-of-sight, meaning that objects must be

visible to the camera to be detected. Consequently, the use of transparent totes represents a practical design option to ensure continuous semantic perception in future deployments.

Despite these limitations, the demonstrator provides a modular foundation for future extensions. While the current implementation focuses on perception and localisation, subsequent work may incorporate additional autonomy layers such as navigation, decision-making and human–robot interaction. Extending the transparent-box concept to these modules would further support holistic understanding of autonomous systems and strengthen the demonstrator's role as a scalable platform for robotics and logistics education.

ACKNOWLEDGMENTS

This study is part of the research activities belonging to the HumanTech Project, Department of Management, Economics and Industrial Engineering at Politecnico di Milano (Italy). The HumanTech Project is financed by the Italian Ministry of University and Research (MUR) for the 2023-2027 period as part of the ministerial initiative "Departments of Excellence" (L. 232/2016). The initiative rewards departments that stand out for the quality of the research produced and funds specific development projects.

This study was conducted as part of the research activities of the Global.Labs initiative at the THWS Logistics Lab, Faculty of Business and Engineering. Global.Labs is a sub-project of THWS.Global and is funded by the German Academic Exchange Service (DAAD) within the HAW.International initiative (project ID 5782 5650) for the funding period 2026–2028.

REFERENCES

Al-Tawil, B., Hempel, T., Abdelrahman, A., Al-Hamadi, A., 2024. A review of visual SLAM for robotics: evolution, properties, and future applications. Frontiers in Robotics and AI 11, 1347985. https://doi.org/10.3389/frobt.2024.1347985

Alves, J., Lima, T.M., Gaspar, P.D., 2023. Is Industry 5.0 a Human-Centred Approach? A Systematic Review. Processes 11, 193. https://doi.org/10.3390/pr11010193

Amna, A.R., Poels, G., 2022. Systematic Literature Mapping of User Story Research. IEEE Access 10, 51723–51746. https://doi.org/10.1109/ACCESS.2022.3173745

Brockenbrough, A., Feild, H., Salinas, D., 2025. Exploring LLMs Impact on Student-Created User Stories and Acceptance Testing in Software Development, in: Proceedings of the 56th ACM Technical Symposium on Computer Science Education V. 2. Presented at the SIGCSE TS 2025: The 56th ACM Technical Symposium on Computer Science Education, ACM, Pittsburgh PA USA, pp. 1401–1402. https://doi.org/10.1145/3641555.3705183

Cadena, C., Carlone, L., Carrillo, H., Latif, Y., Scaramuzza, D., Neira, J., Reid, I., Leonard, J.J., 2016. Past, Present, and Future of Simultaneous Localization and Mapping: Toward the Robust-Perception Age. IEEE Trans. Robot. 32, 1309–1332. https://doi.org/10.1109/TRO.2016.2624754

Cai, D., Li, R., Hu, Z., Lu, J., Li, S., Zhao, Y., 2024. A comprehensive overview of core modules in visual SLAM framework. Neurocomputing 590. https://doi.org/10.1016/j.neucom.2024.127760

Castellucci, T., Tappia, E., Moretti, E., Melacini, M., 2025. Performance Analysis of Multi-Tote Storage and Retrieval Autonomous Mobile Robot Systems through Agent-Based Simulation. IFAC-PapersOnLine 59, 2533–2538. https://doi.org/10.1016/j.ifacol.2025.09.426

Chatterjee, N., Singh, A.V., Agarwal, R., 2024. You Only Look Once (YOLOv8) Based Intrusion Detection System for Physical Security and Surveillance, in: 2024 11th International Conference on Reliability, Infocom Technologies and Optimization (Trends and Future Directions) (ICRITO). Presented at the 2024 11th International Conference on Reliability, Infocom Technologies and

Optimization (Trends and Future Directions) (ICRITO), IEEE, Noida, India, pp. 1–5. https://doi.org/10.1109/ICRITO61523.2024.10522139

Chen, S., Zhou, W., Yang, A.-S., Chen, H., Li, B., Wen, C.-Y., 2022. An End-to-End UAV Simulation Platform for Visual SLAM and Navigation. Aerospace 9, 48. https://doi.org/10.3390/aerospace9020048

Chen, W., Shang, G., Ji, A., Zhou, C., Wang, X., Xu, C., Li, Z., Hu, K., 2022. An Overview on Visual SLAM: From Tradition to Semantic. Remote Sensing 14, 3010. https://doi.org/10.3390/rs14133010

Custodio, L., Machado, R., 2020. Flexible automated warehouse: a literature review and an innovative framework. The International Journal of Advanced Manufacturing Technology 106, 533–558. https://doi.org/10.1007/s00170-019-04588-z

Dau, B.A., Bingi, K., Ibrahim, R., Omar, M., 2025. Review of Autonomous SLAM Mapping and Navigation for Unknown Environment Exploration, in: 2025 IEEE International Conference on Automatic Control and Intelligent Systems (I2CACIS). Presented at the 2025 IEEE International Conference on Automatic Control and Intelligent Systems (I2CACIS), IEEE, Kuala Lumpur, Malaysia, pp. 196–201. https://doi.org/10.1109/I2CACIS65476.2025.11101177

Dharmasiri, P., Kavalchuk, I., Akbari, M., 2020. Novel implementation of multiple automatedground vehicles trafficreal time control algorithm forwarehouse operations: Djikstra approach. Operations and Supply Chain Management 13, 396–405. https://doi.org/10.31387/oscm0430279

Fancott, T., Kamthan, P., Shahmir, N., 2012. Implications of the social web environment for user story education. Electronic Journal of e-Learning 10, 44–59.

Gan, F., Xu, S., Jiang, L., Liu, Y., Liu, Q., Lan, S., 2024. Robust visual SLAM algorithm based on target detection and clustering in dynamic scenarios. Frontiers in Neurorobotics 18. https://doi.org/10.3389/fnbot.2024.1431897

Golovianko, M., Terziyan, V., Branytskyi, V., Malyk, D., 2023. Industry 4.0 vs. Industry 5.0: Co-existence, Transition, or a Hybrid, in: Procedia Computer Science. Presented at the 4th International Conference on Industry 4.0 and Smart Manufacturing, pp. 102–113. https://doi.org/10.1016/j.procs.2022.12.206

Grosse, E.H., Sgarbossa, F., Berlin, C., Neumann, W.P., 2023. Human-centric production and logistics system design and management: transitioning from Industry 4.0 to Industry 5.0. International Journal of Production Research 61, 7749–7759. https://doi.org/10.1080/00207543.2023.2246783

Gürdür Broo, D., Kaynak, O., Sait, S.M., 2022. Rethinking engineering education at the age of industry 5.0. Journal of Industrial Information Integration 25, 100311. https://doi.org/10.1016/j.jii.2021.100311

Han, Z., 2023. Multimodal intelligent logistics robot combining 3D CNN, LSTM, and visual SLAM for path planning and control. Frontiers in Neurorobotics 17. https://doi.org/10.3389/fnbot.2023.1285673

Hu, K.-Y., Chang, T.-S., 2010. An innovative automated storage and retrieval system for B2C e-commerce logistics. International Journal of Advanced Manufacturing Technology 48, 297–305. https://doi.org/10.1007/s00170-009-2292-4

Jefroy, N., Azarian, M., Yu, H., 2022. Moving from Industry 4.0 to Industry 5.0: What Are the Implications for Smart Logistics? Logistics 6, 26. https://doi.org/10.3390/logistics6020026

Jiang, S., 2025. Path Planning and Navigation Technologies for Autonomous Mobile Robots in Dynamic Indoor Environments. Highlights in Science, Engineering and Technology 147, 350–358. https://doi.org/10.54097/0869dc58

Jiménez López, E., Cuenca Jiménez, F., Luna Sandoval, G., Ochoa Estrella, F.J., Maciel Monteón, M.A., Muñoz, F., Limón Leyva, P.A., 2022. Technical Considerations for the Conformation of Specific Competences in Mechatronic Engineers in the Context of Industry 4.0 and 5.0. Processes 10, 1445. https://doi.org/10.3390/pr10081445

Jin, Z., Shao, Y., So, M., Sable, C., Shlayan, N., Luchtenburg, D.M., 2019. A Multisensor Data Fusion Approach for Simultaneous Localization and Mapping, in: 2019 IEEE Intelligent Transportation Systems Conference (ITSC). Presented at the 2019 IEEE Intelligent Transportation Systems Conference - ITSC, IEEE, Auckland, New Zealand, pp. 1317–1322. https://doi.org/10.1109/ITSC.2019.8916930

Kim, J.J.Y., Urschler, M., Riddle, P.J., Wicker, J.S., 2024. Attacking the Loop: Adversarial Attacks on Graph-Based Loop Closure Detection. Presented at the Proceedings of the International Joint Conference on Computer Vision, Imaging and Computer Graphics Theory and Applications, pp. 90–97. https://doi.org/10.5220/0012313100003660

Krenczyk, D., Kalinowski, K., Ćwikła, G., Kempa, W., Grabowik, C., Paprocka, I., 2020. The design and analysis of material handling systems using simulation. International Journal of Modern Manufacturing Technologies 12, 65–71.

Kulkarni, M., Junare, P., Deshmukh, M., Rege, P.P., 2021. Visual SLAM Combined with Object Detection for Autonomous Indoor Navigation Using Kinect V2 and ROS, in: 2021 IEEE 6th International Conference on Computing, Communication and Automation (ICCCA). Presented at the 2021 IEEE 6th International Conference on Computing, Communication and Automation (ICCCA), IEEE, Arad, Romania, pp. 478–482. https://doi.org/10.1109/ICCCA52192.2021.9666426

Lai, T., 2022. A Review on Visual-SLAM: Advancements from Geometric Modelling to Learning-Based Semantic Scene Understanding Using Multi-Modal Sensor Fusion. Sensors 22, 7265. https://doi.org/10.3390/s22197265

Lam, H.Y., Ho, G.T.S., Mo, D.Y., Tang, V., 2023. Responsive pick face replenishment strategy for stock allocation to fulfil e-commerce order. International Journal of Production Economics 264, 108976. https://doi.org/10.1016/j.ijpe.2023.108976

Liu, D., Xu, L., 2025. Robot path planning and obstacle avoidance algorithm based on visual perception. Neural Computing and Applications. https://doi.org/10.1007/s00521-025-11358-4

Machuca, J.A.D., 2000. Transparent-Box Business Simulators: An Aid to Manage the Complexity of Organizations. Simulation & Gaming 31, 230–239. https://doi.org/10.1177/104687810003100207

Mehrtash, M., Centea, D., Wanyama, T., 2024. Development of Experiential Learning Framework for Autonomous Vehicle Education. Presented at the Lecture Notes in Networks and Systems, pp. 117–124. https://doi.org/10.1007/978-3-031-65400-8_14

Merschformann, M., Lamballais, T., De Koster, M.B.M., Suhl, L., 2019. Decision rules for robotic mobile fulfillment systems. Operations Research Perspectives 6, 100128. https://doi.org/10.1016/j.orp.2019.100128

Pacher, C., Woschank, M., Zunk, B.M., 2023. The Role of Competence Profiles in Industry 5.0-Related Vocational Education and Training: Exemplary Development of a Competence Profile for Industrial Logistics Engineering Education. Applied Sciences 13, 3280. https://doi.org/10.3390/app13053280

Pathania, M., Kumar, K., 2025. Enhancing Practical Learning Through Augmented Reality: A Case Study in Virtual Labs, in: 2025 3rd International Conference on Communication, Security, and Artificial Intelligence (ICCSAI), Greater Noida, India, pp. 1143–1148. https://doi.org/10.1109/ICCSAI64074.2025.11064019

Pfeiffer, M., Schaeuble, M., Nieto, J., Siegwart, R., Cadena, C., 2017. From perception to decision: A data-driven approach to end-to-end motion planning for autonomous ground robots, in: 2017 IEEE International Conference on Robotics and Automation (ICRA). Presented at the 2017 IEEE International Conference on Robotics and Automation (ICRA), IEEE, Singapore, Singapore, pp. 1527–1533. https://doi.org/10.1109/ICRA.2017.7989182

Ponis, S.T., Efthymiou, O.K., 2020. Cloud and IoT Applications in Material Handling Automation and Intralogistics. Logistics 4. https://doi.org/10.3390/logistics4030022

Prasad, K.A., Kumar, H., Tiwari, U., 2025. A Systematic Review of Slam Techniques for AMRs in Warehouse Environments, in: 2025 International Conference on Cognitive Computing in Engineering, Communications, Sciences and Biomedical Health Informatics (IC3ECSBHI). Presented at the 2025 International Conference on Cognitive Computing in Engineering, Communications, Sciences and Biomedical Health Informatics (IC3ECSBHI), IEEE, Greater Noida, India, pp. 1270–1275. https://doi.org/10.1109/IC3ECSBHI63591.2025.10991180

Pu, H., Luo, J., Wang, G., Huang, T., Liu, H., Luo, J., 2023. Visual SLAM Integration With Semantic Segmentation and Deep Learning: A Review. IEEE Sensors Journal 23, 22119–22138. https://doi.org/10.1109/JSEN.2023.3306371

Qin, Z., Yang, P., Gong, Y., De Koster, R.B.M., 2024. Performance Analysis of Multi-Tote Storage and Retrieval Autonomous Mobile Robot Systems. Transportation Science 58, 1033–1055. https://doi.org/10.1287/trsc.2023.0397

Romero-Robles, L.E.R., Iturbe-Ek, J.I., 2023. Virtual Reality in Engineering Education: A Virtual Introduction to Unit Operations and Process Scaling. https://doi.org/10.1109/WEEF-GEDC59520.2023.10344291

Rostum, H., Vásárhelyi, J., 2025. Enhancing Machine Learning Techniques in VSLAM for Robust Autonomous Unmanned Aerial Vehicle Navigation. Electronics (Switzerland) 14. https://doi.org/10.3390/electronics14071440

Sabraz Nawaz, S.S., Mohamed Riyath, M.I.M., Nayak, R., Mohamed Najim, M.N.M., Alotaibi, B.A., Sanjeetha, M.B.F., Al Murshidi, G., 2025. Trends and Future Directions of Metaverse in Education: A Bibliometric Analysis. IEEE Access 13, 124333–124350. https://doi.org/10.1109/ACCESS.2025.3588007

Saleem, H., Malekian, R., Munir, H., 2023. Neural Network-Based Recent Research Developments in SLAM for Autonomous Ground Vehicles: A Review. IEEE Sensors J. 23, 13829–13858. https://doi.org/10.1109/JSEN.2023.3273913

Scholz, M., Serno, M., Franke, J., Schuderer, P., 2017. A Hybrid Transport Concept for the Material Supply of a Modular Manufacturing Environment. Procedia Manufacturing 11, 1448–1453. https://doi.org/10.1016/j.promfg.2017.07.275

Schuhmacher, J., Hummel, V., 2018. Development of a descriptive model for intralogistics as a foundation for an autonomous control method for intralogistics systems. Procedia Manufacturing 23, 225–230. https://doi.org/10.1016/j.promfg.2018.04.021

Smith, R.C., Cheeseman, P., 1986. On the Representation and Estimation of Spatial Uncertainty. The International Journal of Robotics Research 5, 56–68. https://doi.org/10.1177/027836498600500404

Sousa, R.B., Sobreira, H.M., Martins, J.G., Costa, P.G., Silva, M.F., Moreira, A.P., 2025. Integrating Multimodal Perception into Ground Mobile Robots, in: 2025 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC). Presented at the 2025 IEEE International Conference on Autonomous Robot Systems and Competitions (ICARSC), IEEE, Funchal, Portugal, pp. 104–111. https://doi.org/10.1109/ICARSC65809.2025.10970176

Srinivas, S., Yu, S., 2022. Collaborative order picking with multiple pickers and robots: Integrated approach for order batching, sequencing and picker-robot routing. International Journal of Production Economics 254, 108634. https://doi.org/10.1016/j.ijpe.2022.108634

Tang, Y., Zhao, C., Wang, J., Zhang, C., Sun, Q., Zheng, W.X., Du, W., Qian, F., Kurths, J., 2023. Perception and Navigation in Autonomous Systems in the Era of Learning: A Survey. IEEE Transactions on Neural Networks and Learning Systems 34, 9604–9624. https://doi.org/10.1109/TNNLS.2022.3167688

Thibodeaux, T., Jordan, S., Kemerly, S., 2025. Student perceptions of STEM camp experience and STEM career pathways: a mixed methods study. Discover Education 4. https://doi.org/10.1007/s44217-025-00645-w

Tona, C., Juárez-Ramírez, R., Jiménez, S., López, R.G.P., 2022. Toward Developing an Ontology for Assessing Quality of User Stories in Scrum Framework, in: 2022 10th International Conference in Software Engineering Research and Innovation (CONISOFT). Presented at the 2022 10th International Conference in Software Engineering Research and Innovation (CONISOFT), IEEE, Ciudad Modelo, San José Chiapa, Mexico, pp. 39–48. https://doi.org/10.1109/CONISOFT55708.2022.00016

Turhanlar, E.E., Ekren, B.Y., Lerher, T., 2024. Autonomous mobile robot travel under deadlock and collision prevention algorithms by agent-based modelling in warehouses. International Journal of Logistics Research and Applications 27, 1322–1341. https://doi.org/10.1080/13675567.2022.2138290

Walter, R., Boysen, N., Scholl, A., 2013. The discrete forward–reserve problem – Allocating space, selecting products, and area sizing in forward order picking. European Journal of Operational Research 229, 585–594. https://doi.org/10.1016/j.ejor.2013.02.047

Wang, Y., Tian, Y., Chen, J., Xu, K., Ding, X., 2024. A Survey of Visual SLAM in Dynamic Environment: The Evolution From Geometric to Semantic Approaches. IEEE Transactions on Instrumentation and Measurement 73, 1–21. https://doi.org/10.1109/TIM.2024.3420374

Xiang, Z., Guo, J., Meng, J., Meng, X., Li, Y., Kim, J., Wang, S., Lu, B., Chen, Y., 2024. Accurate localization of indoor high similarity scenes using visual slam combined with loop closure detection algorithm. PLOS ONE 19. https://doi.org/10.1371/journal.pone.0312358

Zacharias, I.C.S., Campese, C., Dos Santos, T.B., Da Cunha, L.P., Costa, J.M.H., 2019. User Stories Method and Assistive Technology Product Development: A New Approach to Requirements Elicitation, in: Proceedings of the Design Society: International Conference on Engineering Design. pp. 3781–3790. https://doi.org/10.1017/dsi.2019.385

GLOBALISATION OF SUPPLY CHAINS

Labor Supply Expansion and the Erosion of Social Sustainability: A System Dynamics Study of EU Trucking

Dhiraj Pal[1], Henrik Sternberg[1], Molly Hughes[2]

1: Iowa State University, United States of America; 2: West Virgnia University, United States of America

INTRODUCTION

Social sustainability has become a central concern in logistics and supply chain management (SCM)(Kim et al., 2022; Wiengarten et al., 2021). In particular trucking has become an area of growing concern, as cost pressure, subcontracting (Belzer & Thörnquist, 2020), and cross-border labor mobility increasingly strain working conditions (American Trucking Associations (ATA), 2025; van Gardingen & Atema, 2023).

In the European Union (EU), driver shortages and relaxed labor regulations have accelerated carriers' reliance on so-called third-country drivers (3CDs). In this context, a 3CD refers to a non-EU driver formally employed by a carrier registered in one EU member state, often in EU-13 countries such as Poland or Lithuania, while operating freight services in another EU country such as Sweden (Baranska & Picard, 2023; van Gardingen & Atema, 2023). From the perspective of the shipper, the carrier is legally established in a second EU country, while the driver originates from a third country outside the EU.

Over a relatively short period of time, more than 300,000 3CDs, primarily from countries such as India, Kazakhstan, and the Philippines, have entered EU trucking. Notably, between 2012 and 2022, the number of 3CDs in the EU increased by approximately 580%, from about 44,000 in 2012 (Pakulniewicz, 2024). Anecdotal evidence suggests these 3CD often face hardships and sometime outright exploitation (Baranska & Picard, 2023; van Gardingen & Atema, 2023), with the EU mobility package (regulation to improve driver working condition) being ineffectual.

Existing perspectives that conceptualize supply chains as adaptive systems assume that negative outcomes on supply chain environmental sustainability activate corrective responses through learning and reconfiguration (Wieland, 2021) . Applied to social sustainability, this logic implies that deteriorating working conditions should trigger balancing mechanisms that restore acceptable labor outcomes. However, we investigate why, in the presence of large-scale expansion of 3CDs, these adaptive mechanisms appear ineffective in supply chain social sustainability (SCSS). While SCM research investigated the effects of deregulation (Sternberg et al, 2020) and strain among drivers (Sternberg & Lantz, 2018), it does not explain why regulated and shortage-driven supply chains fail to self-correct when labor supply expands through 3CD expansion. Moreover, research has primarily examined SCSS in developing-country contexts (Tang, 2018). Accordingly, the purpose of this research is to explain and conceptualize how the expansion of third-country drivers reshapes adaptive mechanisms and SCSS outcomes in EU trucking.

To explore this gap, we combine a narrative literature review and explorative interviews. We present the findings as a causal loop diagram (CLD) (Sterman et al., 2015) to illustrate how the introduction of 3CDs impacts SCSS. By adopting a systems perspective, the study contributes to an underexplored area within SCM that examines supply chain labor outcomes and their drivers (Tokar & Swink, 2019).

METHODOLOGY

This study follows a two-stage qualitative research design. In the first stage, we conducted a narrative literature review to establish a baseline of what we know about how SCSS is impacted by regulation, subcontracting and labor supply in trucking, prior to the large-scale expansion of 3CD. These literature derived mechanism anchor the initial structure of the system dynamics model.

To understand how the expansion of 3CD impact SCSS, we examined their working and living conditions using semi-structured interviews and field observations. Participants were selected through purposive sampling, focusing on 3CDs working in the EU who had obtained work visas via EU-13 countries, a prevalent practice in the EU (Baranska & Picard, 2023). Data were collected in Belgium, Denmark, Germany and Sweden at locations where the presence of 3CDs had previously been reported by law enforcement agencies, media sources and social media.

Interviews were conducted primarily in English and Turkish, with occasional use of Russian, Uzbek, and Kyrgyz. Written informed consent was obtained in participants' native languages in accordance with ethical guidelines and the General Data Protection Regulation (GDPR). Interviews were transcribed in the original language and translated into English using AI-assisted tools, with translations reviewed by a researcher proficient in the relevant language. AI was also used to support transcription of languages beyond English and Turkish. Participants were offered a small gift only after completing the interview. Field notes were appended to the interviews to provide contextual insights, and all materials were de-identified prior to analysis to ensure confidentiality.

Interview data were analysed using thematic analysis following Braun & Clarke (2006). All transcripts were coded using Delve, a qualitative analysis tool. Insights from the interviews were used to identify additional mechanisms associated with 3CD expansion, which were incorporated into the CLD in Figure 1. The resulting system dynamics model integrates literature-based baseline structures with empirically grounded mechanisms, enabling an exploration of how the introduction of 3CD reshapes SCSS through interacting feedback processes (Größler et al., 2008; Sterman et al., 2015).

LITERATURE

Baseline Model of Social Sustainability in Trucking

The initial structure of the system dynamics model is represented by the *green links* in the CLD (Figure 1). Within trucking, regulatory strength and enforcement often constitute foundational drivers of labor and organizational outcomes (Baranska & Picard, 2023). Therefore, weak regulation and lax oversight are known to increase non-compliance with labor and safety standards (Nilsson et al., 2017), encouraging carriers to outsource or subcontract operations to reduce costs and shift risks (**Link 1**) (Hilal, 2008; Kim et al., 2022; Kudo & Belzer, 2019; Peoples & Talley, 2004; Sternberg & Lantz, 2018; Thörnquist, 2019). Such arrangements enable the externalization of labor and operational risks, resulting in the proliferation of owner-operator models and contributing to increased market fragmentation (**Links 2a**) (Belzer & Thörnquist, 2020; Peoples & Talley, 2004; Soro et al., 2025; Thörnquist, 2019; Viscelli, 2016).

As fragmentation deepens, reliance on layered subcontracting and intermediaries intensifies, further fragmenting market structures (**Link 2b and 2a**) (Belzer & Thörnquist, 2020; Kim et al., 2022; Soro et al., 2025; Thörnquist, 2019; Viscelli, 2016). This intensifies price competition among carriers, exerting downward pressure on wages, benefits, and overall remuneration and working conditions (**Link 3 and 4**) (Ju & Belzer, 2024; Kim et al., 2022; Peoples & Talley, 2004; Soro et al., 2025; Thörnquist, 2019). Conversely, effective regulation improves compliance with labor standards, leading to higher wages and better working conditions (**Link 5**) (Hilal, 2008; Ju & Belzer, 2024). It is well established that improved conditions increase the attractiveness of truck driving (**Link 6**), thereby increasing driver availability (**Link 7**) (Burks & Monaco, 2019; Ju & Belzer, 2024; Phares & Balthrop, 2022). Although, abundant labor supply can depress wages based on supply-demand economics (**Link 8**) (Azar et al., 2022; Burks & Monaco, 2019).

Another important mechanism concerns unpaid detention time, where weak enforcement again results in the avoidance of appropriate detention-time payments, particularly to small carriers and owner-operators (**Link 9**) (Kudo & Belzer, 2019; Soro et al., 2025). Unpaid detention reduces effective hourly earnings (**Link 10**) (Ju & Belzer, 2024; Peoples & Talley, 2004; Phares & Balthrop, 2022; Soro et al., 2025; Viscelli, 2016) and extends working hours, increasing fatigue and road safety risks (**Link 11**) (Ju & Belzer, 2024; Kudo & Belzer, 2019). This in turn drives job strain and fatigue, reinforcing safety risks and degrading working conditions, thereby perpetuating a vicious cycle of declining job quality (**Links 12a and 12b**) (Ju & Belzer, 2024; Kudo & Belzer, 2019; Soro et al., 2025; Sternberg & Lantz, 2018). Finally, weak regulatory environments lower entry barriers, sustaining fragmentation and owner-operator prevalence

(**Link 13**), and reinforcing labor precarity in trucking (Ellig, 2020; Hilal, 2008; Ju & Belzer, 2024; Peoples & Peteraf, 1999).

Thus, the baseline model, as identified in Table 1, features two reinforcing mechanisms *fragmentation–subcontracting* and *fatigue–safety degradation* and one balancing mechanism of *labor supply adjustment*. Strong regulation and enforcement can therefore enable social sustainability to prevail in the trucking (Belzer, 2000). However, under weak oversight, the negative mechanisms dominate, resulting in substandard working conditions, high driver attrition, and a persistent shortage (Burks & Monaco, 2019; Viscelli, 2016).

RESULTS

We now proceed to develop the new mechanism of social sustainability in trucking with large-scale expansion of 3CDs, represented as *red Links* in the CLD (Figure 1). Prior studies have shown that driver substitution in EU trucking initially occurred between, EU-14 (old member countries after Brexit) and EU-13 member states. However, more recent evidence, based on an analysis of driver attestation data for 2022 (Baranska & Picard, 2023), suggests that a similar substitution pattern may be emerging, with EU drivers increasingly being replaced by 3CD (**Link 18**), particularly as transport companies in EU-13 member states expand their reliance on them (Baranska & Picard, 2023). This also expands the overall labor supply (**Link 17**). Further, the insights are presented under following categories.

3CD Emigration and Passive Acceptance of Exploitation

Evidence indicates that economic incentives, particularly higher wages relative to origin countries and the ability to support families at home, are the primary drivers of 3CD migration. As one respondent explained, "*More money here. That's why I came*," highlighting how wage differentials between origin countries and the EU expand the available migrant labor pool (**Link 14)**.

Despite awareness of occupational risks, many drivers adapt to unfavourable conditions, prioritizing income stability over legal protections. One driver noted, "*we can't say no, because if we don't do what they say, they'll fine us*," illustrating how constrained agency contributes to the normalization of unfavourable conditions and reinforces downward pressure on working conditions. Most respondents reported remitting the majority of their income to family members, which further limited their willingness to question unfavourable conditions. This passive acceptance, driven by economic necessity, contributes to **Link 16**, whereby increased reliance on 3CDs exerts downward pressure on remuneration and working conditions.

Role of Carrier, Working and Living Conditions

The drivers reported remaining abroad for four to ten months between returning to their employer's operational centre. This practice directly contradicts EU regulations, which require carriers to "organize" drivers' work so that they can return to their place of residence at least once every four consecutive weeks (Article 1(6)(d) of Regulation (EU) 2020/1054). These accounts reveal a clear gap between formal requirements and their implementation in practice.

Experiences of regulatory compliance varied. While some drivers stated compliance with driving and rest-time rules, others openly described explicit or implicit pressure to exceed statutory limits, including salary deductions for delays when refusing. These accounts suggest lack of legal enforcement and uneven legal compliance across carriers, reinforcing earlier findings that lack of enforcement and legal loopholes enables the erosion of labor protections (Hilal, 2008).

Also, in one of the interview the respondent stated "*Not always in the accommodations. Sometimes, when we are waiting in the company and there is no cargo, we rest there — only in the truck. We need to go to an apartment because if the police catch us sleeping in the truck, there is a penalty. They fine us if they see we sleep there too often, even for the nine-hour rest*". Thus, Working and living conditions were closely intertwined. Although, there are formal policies and regulations provide for hotel accommodation during long rest periods, interviews and field observations revealed that drivers routinely slept in their trucks. Thus, carriers often did not provide information to the drivers about available accommodation and secure parking locations, contributing to drivers' acceptance of suboptimal living conditions.

Remuneration and Economic Uncertainty

Interviews also revealed fragmented and opaque remuneration structures. Although several respondents reported monthly earnings of approximately €2,000, these figures often combined base wages and daily allowances, obscuring actual salary levels. Pay progression was commonly tied to performance metrics such as fuel efficiency or contract renewal. Several drivers described delayed payments, fragmented disbursements, or deductions for fuel use, damages, or delays. One respondent noted: *"Look, I worked for four months… they only deposited 350 euros to me"* (Uzbek driver employed in Lithuania), revealing precarious conditions.

Carriers effectively exercised control by maintaining opacity around wage calculations, deductions, and payment schedules. Although some respondents reported transparent and timely payment systems, indicating that there is variation in the practice likely depending on factors such as language skills, experience, or peer support.

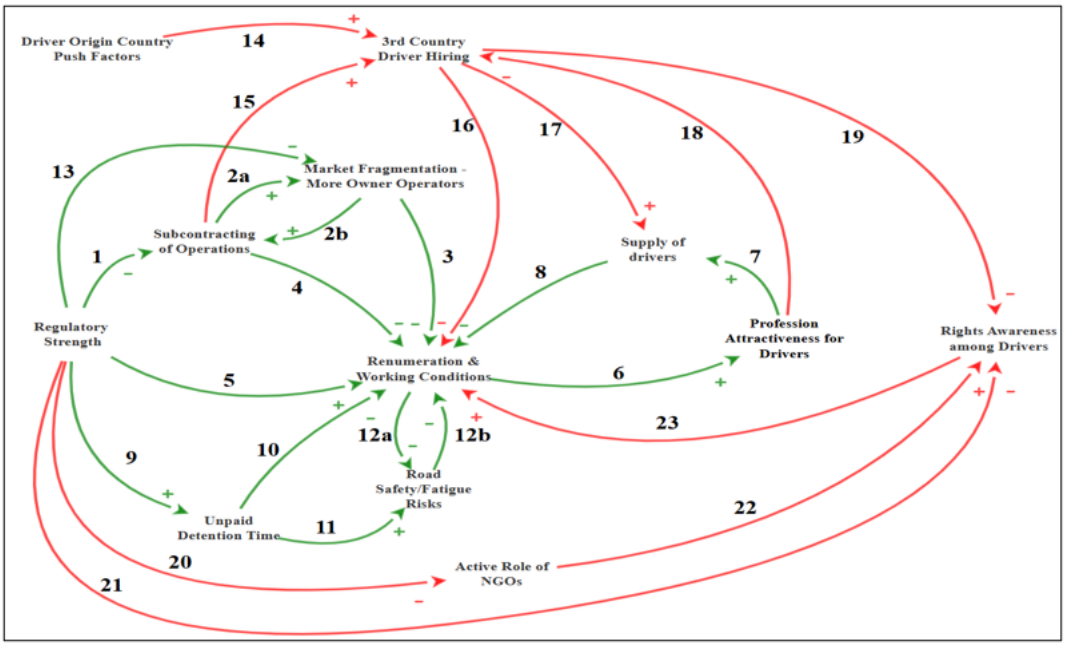
Awareness of Rights and Regulations

Our data points to 3CDs having a very low awareness of labor rights and regulatory protections. This information deficit strengthens carriers' bargaining power and reinforces **Link 15.** And, therefore carriers increasingly rely on 3CDs as a deliberate strategy to maintain low labor costs (Baranska & Picard, 2023). This pattern directly establishes **Link 19,** as increased reliance on economically dependent and legally unfamiliar 3CDs leads to overall legally unfamiliar workforce.

Another respondent mentioned, *"Sometimes they say, 'the load is important, keep going,' even when the driving time is finished. We cannot say no. If we refuse, they fine us when we come back to the office. So we just drive".* So, drivers expressed reluctance to report or refuse instructions to extend driving time or to challenge unfavourable working and living conditions. This dynamic is captured in **Link 23**. This limited rights awareness constrains drivers' ability to demand fair treatment. In addition, irregular access to benefits such as pensions, sickness insurance, and paid leaves reflects general ignorance, with several respondents reporting limited awareness of such entitlements or their absence in practice (**Link 19**).

These dynamics operate across the entire employment contract lifecycle. During recruitment, 3CDs are frequently required to sign contracts they do not fully understand due to language barriers and the selective absence of translations or explanations by carriers. Further, at the termination stage, drivers often report inconsistencies in final wage settlements and face significant barriers to legal redress after leaving the EU, including high costs and limited awareness of available remedies (Lee et al., 2022).

Figure 1: CLD of Macro-Level Working Conditions in EU Trucking



Governance Structure and Regulatory Context

Our data show that the employment of 3CDs often occurs against a backdrop of weak compliance and lax-enforcement of labor regulations. In-line with van Gardingen & Atema (2023) our data shows that non-compliance is an integral component of existing business practices in the trucking. Additionally, poor wages and working conditions are further reinforced by widespread outsourcing and multi-tier subcontracting. Under such arrangements, drivers rarely maintain a direct contractual relationship with the shipper and are instead hired through intermediaries or carriers, which deepen accountability gaps (van Gardingen & Atema, 2023). Together, these structural conditions underpin the causal pathways represented by **Link 1, 5, 9, 13** and **21** in the CLD (Figure 1).

Role of Non-Governmental Organizations (NGOs)

NGOs can play an active role to enhance 3CDs rights awareness and strengthen their capacity to seek redress, thereby establishing **Link 22**. But, weak regulatory enforcement and limited institutional capacity significantly constrain NGOs' ability to engage meaningfully in protection of 3CDs (**Link 20**) (Baranska & Picard, 2023).

CONCLUDING DISCUSSION

This study examined how the rapidly increasing employment of third-country drivers (3CDs) reshapes supply chain social sustainability in EU trucking. By combining a literature-based baseline with empirically grounded insights from interviews and observations, the system dynamics model (Figure 1) explains how labor immigration interacts with subcontracting, regulation, and labor market conditions. The key feedback loops summarized below in Table 1 show that the entry of 3CDs does not merely expand labor supply but activates reinforcing mechanisms that systematically affect wages, working conditions, and collective rights across the industry.

Table 1: Key Feedback Loops in CLD (Figure 1)

#	Causal Link	Stage	Loop Nomenclature (Nature)	Driving Mechanism
1	$6 \rightarrow 7 \rightarrow 8 \rightarrow 6$	Baseline	Labor Supply Adjustment (Balancing)	Poor remuneration reduces profession attractiveness, lowering supply of domestic drivers, which in turn eases downward pressure on wages and conditions
2	$2a \rightarrow 2b \rightarrow 2a$	Baseline	Fragmentation–Subcontracting (Reinforcing)	Subcontracting increases owner-operator prevalence and market fragmentation, which further increases reliance on subcontracting
3	$12a \rightarrow 12b \rightarrow 12a$	Baseline	Fatigue–Safety Degradation (Reinforcing)	Poor working conditions increase fatigue and safety risks, which further deteriorate working conditions
4	$6 \rightarrow 18 \rightarrow 16 \rightarrow 6$	3CD Expansion	Supply Expansion (Reinforcing)	Declining job attractiveness for domestic drivers increases reliance on 3CDs, expanding labor supply and sustaining low wages and poor conditions
5	$6 \rightarrow 18 \rightarrow 17 \rightarrow 8 \rightarrow 6$	3CD Expansion	Wage Suppression (Reinforcing)	3CD hiring increases labor supply, intensifying competition and exerting downward pressure on remuneration and conditions
6	$6 \rightarrow 18 \rightarrow 19 \rightarrow 23 \rightarrow 6$	3CD Expansion	Rights Suppression (Reinforcing)	Increased reliance on 3CD with lower rights awareness weakens collective pressure, reinforcing poor remuneration and working conditions

The main contribution to SCSS research lies in conceptualizing employment of 3CD as a structural mechanism that transforms industry dynamics, rather than as a short-term response to labor shortages. As illustrated by the reinforcing loops in Table 1, the availability of 3CDs weakens bargaining power and sustains cost competition, which in turn places downward pressure on remuneration and working conditions. These dynamics help explain, why the standard response to price signals by adjustments to driver supply (Burks & Monaco, 2019) fail to stabilize the system. While prior research shows that drivers enter the industry when pay and conditions are attractive and exit when they deteriorate, the expansion of financially completely dependent and legally unfamiliar workers dampens this balancing effect, allowing declining social sustainability to persist despite formal regulation.

The findings also highlight a clear policy trade-off. Allowing large-scale entry of 3CDs reduces transport costs and alleviates short-term driver shortages, as reflected in our model. At the same time, these same dynamics erode social sustainability by reinforcing wage suppression, fragmented employment structures, and legal unfamiliarity. Policy-makers therefore cannot simultaneously prioritize low transport costs through unrestricted labor immigration and expect social sustainability to improve without intervention. If preventing a race to the bottom in wages and working conditions is a policy objective, active measures are required given the increasing numbers. These include stronger enforcement, clearer allocation of responsibility across subcontracting chains, and limits on the ability to arbitrage labor and immigration regimes within the EU internal market.

For logistics and supply chain research, the study demonstrates the value of system dynamics for explaining social sustainability outcomes that emerge from interacting supply chain structures rather than isolated firm-level practices. As the scale of 3CD expansion continues to grow, understanding these feedback mechanisms becomes critical for both policymakers and industry actors seeking to balance efficiency with socially sustainable freight transport systems.

Future research

While the study uncovers systemic mechanisms impacting social sustainability in EU trucking amid the expansion of 3CDs, it remains limited by the absence of empirical validation. Nevertheless, the identified mechanisms offer a foundation for future researchers to validate the proposed causal links using administrative or firm-level data

REFERENCES

American Trucking Associations (ATA). (2025, September). *Cheaters Are Undercutting America's Trucking Industry. The Trump Administration Must Stop It.* https://www.trucking.org/news-insights/cheaters-are-undercutting-americas-trucking-industry-trump-administration-must-stop

Azar, J., Marinescu, I., & Steinbaum, M. (2022). Labor market concentration. *Journal of Human Resources*, *57*(S), S167–S199.

Baranska, P., & Picard, S. (2023). *Third-Country Drivers in European Road Transport* [Report]. European Transport Workers' Federation (ETF). https://www.etf-europe.org/wp-content/uploads/2025/04/ETF-ROAD-TRANSPORT-REPORT.pdf.pdf

Belzer, M. H. (2000). *Sweatshops on wheels: Winners and losers in trucking deregulation*. Oxford University Press.

Belzer, M. H., & Thörnquist, A. (2020). Economic Liberalisation of Road Freight Transport in the EU and the USA. In *The Regulation and Management of Workplace Health and Safety* (pp. 52–79). Routledge.

Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, *3*(2), 77–101.

Burks, S. V., & Monaco, K. (2019). Is the US labor market for truck drivers broken. *Monthly Lab. Rev.*, *142*, 1.
Ellig, J. (2020). *Forty Years after Surface Freight Deregulation*.
Größler, A., Thun, J.-H., & Milling, P. M. (2008). System dynamics as a structural theory in operations management. *Production and Operations Management*, *17*(3), 373–384.
Hilal, N. (2008). Unintended effects of deregulation in the European Union: The case of road freight transport. *Sociologie Du Travail*, *50*, e19–e29.
Ju, S., & Belzer, M. H. (2024). Follow the money: Trucker pay incentives, working time, and safety. *The Economic and Labour Relations Review*, *35*(1), 7–26.
Kim, S., Chae, S., Wagner, S. M., & Miller, J. W. (2022). Buyer abusive behavior and supplier welfare: An empirical study of truck owner–operators. *Journal of Supply Chain Management*, *58*(4), 90–111.
Kudo, T., & Belzer, M. H. (2019). Safe rates and unpaid labour: Non-driving pay and truck driver work hours. *The Economic and Labour Relations Review*, *30*(4), 532–548.
Lee, K.-H., Groschopf, W., & Mossyrsch, A. (2022). Modern Slavery and Working Conditions in the European Trucking Industry: A Growing Threat to Supply Chain Resilience. In *Supply Chain Resilience: Insights from Theory and Practice* (pp. 65–73). Springer.
Mindel, V., Overstreet, R. E., Sternberg, H., Mathiassen, L., & Phillips, N. (2024). Digital activism to achieve meaningful institutional change: A bricolage of crowdsourcing, social media, and data analytics. *Research Policy*, *53*(3), 104951.
Nilsson, F. R., Sternberg, H., & Klaas-Wissing, T. (2017). Who controls transport emissions and who cares? Investigating the monitoring of environmental sustainability from a logistics service provider's perspective. *The International Journal of Logistics Management*, *28*(3), 798–820.
Pakulniewicz, M. (2024, April 28). *The dark side of recruiting drivers from far afield: More and more cases are coming to light*. trans.info. https://trans.info/en/recruiting-drivers-from-abroad-385446
Peoples, J., & Peteraf, M. (1999). The effects of regulatory reform on company drivers and owner operators in the for-hire and private sectors. *Transportation Journal*, *38*(3), 5–17.
Peoples, J., & Talley, W. K. (2004). 9. Owner-operator truck driver earnings and employment: Port cities and deregulation. *Research in Transportation Economics*, *10*, 191–213.
Phares, J., & Balthrop, A. (2022). Investigating the role of competing wage opportunities in truck driver occupational choice. *Journal of Business Logistics*, *43*(2), 265–289.
Soro, W. L., Haworth, N., & Debnath, A. K. (2025). The relationships between financial performance and driver compensation and safety outcomes in the trucking industry: A systematic review. *Transport Reviews*, *45*(2), 239–258.
Sterman, J., Oliva, R., Linderman, K., & Bendoly, E. (2015). System dynamics perspectives and modeling opportunities for research in operations management. In *Journal of Operations Management* (Vol. 39, pp. 1–5). Elsevier.
Sternberg, H., & Lantz, B. (2018). Using crowdsourced data to analyze transport crime. *International Journal of Logistics Research and Applications*, *21*(2), 133–147.
Sternberg, H. S., Hofmann, E., & Overstreet, R. E. (2020). Perils of road freight market deregulation: Cabotage in the European Union. *The International Journal of Logistics Management*, *31*(2), 333–355.
Tang, C. S. (2018). Socially responsible supply chains in emerging markets: Some research opportunities. In *Journal of operations management* (Vol. 57, pp. 1–10). Elsevier.
Thörnquist, A. (2019). Truck drivers in the grey area between employment and self-employment: Swedish experiences. *Nordic Journal of Working Life Studies*, *9*.
Tokar, T., & Swink, M. (2019). Public policy and supply chain management: Using shared foundational principles to improve formulation, implementation, and evaluation. *Journal of Supply Chain Management*, *55*(2), 68–79.
van Gardingen, I., & Atema, E. (2023). *Widespread Exploitation in the EU Road Transport Industry: The Case of Central Asian Truck Drivers* [Report]. Road Transport Due Diligence (RTDD). https://www.rtdd.org/wp-content/uploads/2024/01/REPORT-Widespread-Exploitation-in-the-EU-Road-Transport-Industry.pdf
Viscelli, S. (2016). *The big rig: Trucking and the decline of the American dream*. Univ of California Press.

Wieland, A. (2021). Dancing the supply chain: Toward transformative supply chain management. *Journal of Supply Chain Management*, *57*(1), 58–73.
Wiengarten, F., Pagell, M., Durach, C. F., & Humphreys, P. (2021). Exploring the performance implications of precarious work. *Journal of Operations Management*, *67*(8), 926–963.

HUMANITARIAN SUPPLY CHAINS

CSR Legitimacy or Greenwashing? A Multi-Theoretical Framework for Analysing Corporate Social Responsibility in PNG's Extractive Industries

Alphonse Kona, David M. Herold, Erica French

Queensland University of Technology, Australia

INTRODUCTION

Extractive industries are among the most contested sites of corporate social responsibility globally. Mining and petroleum organisations operate in environments where economic benefit and environmental destruction are structurally intertwined, and where CSR initiatives are simultaneously demanded by affected communities, required by institutional actors, and routinely suspected of being cosmetic responses designed primarily to maintain a social licence to operate (Slack, 2012; Viveros, 2016). The question of whether CSR in extractive industries represents genuine sustainability commitment or strategic greenwashing is not merely empirical — it is fundamentally theoretical. The answer depends on which framework is used to interpret organisational motivation and behaviour.

This question is especially acute in Papua New Guinea (PNG), where extractive industries contribute substantially to national GDP yet have caused extensive environmental degradation, social disruption, and governance failures (Mudd, Jebb, & Ward, 2020; Yamarak & Parton, 2021). PNG's institutional context — characterised by customary land ownership, under-regulation, weak enforcement, and communities whose cultural identity, food security, and spiritual wellbeing are inseparable from the land being extracted — creates analytical conditions that render standard CSR frameworks, developed largely in Western institutional contexts, structurally insufficient (Tilt, 2016; Visser, 2008).

This paper responds to this challenge by developing a multi-theoretical conceptual framework that integrates legitimacy theory, stakeholder theory, and institutional theory to analyse CSR legitimacy in PNG's extractive industries. The framework makes two contributions: first, a theoretical argument for the analytical necessity — not merely the convenience — of multi-theoretical integration in complex developing-country contexts; and second, a conceptual model that operationalises this integration and distinguishes genuine sustainability from greenwashing in a theoretically grounded and empirically tractable way. The paper proceeds as follows: Section 2 reviews the core literature on CSR, sustainability, and greenwashing; Section 3 situates the analysis in the PNG extractive industry context; Section 4 develops and integrates the three theoretical lenses; Section 5 presents the conceptual model; and Section 6 discusses implications and directions for future research.

CSR, SUSTAINABILITY, AND THE GREENWASHING PROBLEM

The evolution of CSR: from philanthropy to strategic tool

Corporate social responsibility has evolved from philanthropic obligation to strategic corporate practice. Carroll's (1991) influential CSR pyramid organises corporate responsibilities into four hierarchical layers — economic, legal, ethical, and philanthropic — with economic responsibility at the base and philanthropy at the apex. While widely adopted, the model has attracted sustained criticism for its implicit assumption of developed-country institutional contexts. Visser (2006, 2008) demonstrated that in developing countries the pyramid is effectively inverted: philanthropic and economic responsibilities dominate, while legal and ethical responsibilities are deprioritised. This inversion reflects institutional realities of countries where regulatory enforcement is weak, community expectations of direct material benefit are strong, and the rule of law cannot be assumed. Subsequent frameworks — including the triple bottom line (TBL) and environmental, social, and governance (ESG) reporting — have broadened the conception of corporate responsibility beyond purely economic metrics (Elkington, 1997). However, these frameworks were predominantly developed and validated in Western institutional environments,

limiting their transferability to contexts such as PNG where the social, cultural, and environmental dimensions of responsibility are constituted very differently (Tilt, 2016).

Greenwashing and the limits of CSR

A central tension in CSR scholarship concerns the distinction between substantive and symbolic CSR — between genuine commitment to sustainability and what has come to be called greenwashing. Greenwashing is defined as the practice of organisations falsely portraying their social and environmental performance to appear more responsible than they actually are (de Freitas Netto, Sobral, Ribeiro, & Soares, 2020; Torelli, Balluchi, & Lazzini, 2020; Uyar, Karaman, & Kilic, 2020). The term was coined by biologist Jay Westerveld in 1986, who accused the hotel industry's promotion of towel reuse as misleading given its poor environmental policies in other areas of operation (Seele & Gatti, 2017). In extractive industry contexts in developing countries, the problem is acute. Research in Chile (Viveros, 2016), Africa (Bezzola, Günther, Brugger, & Lefoll, 2022), and Nigeria (Akporiaye & Webster, 2022) consistently finds that CSR programs are frequently reactive — implemented to mitigate conflict or appease regulators rather than address root causes of harm. In PNG, the road-building programme of Ok Tedi Mining Limited (OTML) — constructed using contaminated river gravel from the already-polluted Ok Tedi River — offers a striking example of CSR that demonstrably worsened the sustainability outcomes it ostensibly addressed (Kepore, Higgins, & Goddard, 2013). Distinguishing genuine sustainability contribution from symbolic greenwashing requires analytical frameworks capable of capturing the institutional, stakeholder, and legitimacy dynamics that shape these organisational decisions.

THE PNG EXTRACTIVE INDUSTRY CONTEXT

Economic significance and institutional distinctiveness

Papua New Guinea is heavily dependent on extractive industries, which account for the majority of its export earnings and a substantial share of government revenue (EITI, 2023). Mining operations — including Ok Tedi, Lihir Gold, and Porgera — and major petroleum projects, including the ExxonMobil Papua New Guinea Liquefied Natural Gas (PNGLNG) project, are among the most economically significant in the Pacific region. Extractive industries in PNG operate within a distinctive regulatory framework. The Mining Act 1992 and the Oil and Gas Act 1998 vest ownership of all minerals and petroleum in the State (Mining Act 1992, s.5; Oil and Gas Act 1998, s.6), while customary land remains with indigenous landowners. This legal bifurcation — separating surface rights from sub-surface resource rights — is a fundamental and persistent source of conflict between extractive organisations, communities, and the state, with no structural equivalent in the institutional environments from which most CSR theory has been derived. PNG's broader governance context compounds this tension. Despite constitutional provisions requiring that natural resources be used for the collective benefit of citizens and preserved for future generations (Constitution of PNG, Goal 4), the regulatory environment is widely regarded as under-enforced (Sing, 2015), and international frameworks such as EITI and the UN SDGs apply only unevenly.

Environmental and social impacts: the inseparability problem

The environmental and social consequences of extractive operations in PNG have been extensively documented. Waste disposal, chemical contamination, habitat destruction, and greenhouse gas emissions have directly undermined the livelihoods, food security, and cultural wellbeing of affected communities (Kepore & Imbun, 2011; Mudd et al., 2020; Yamarak & Parton, 2021). Deep-sea tailings disposal from Lihir Gold Mine has damaged coral reefs and depleted fish stocks; chemical contamination around Ramu Nickel Mine has caused seawater discolouration, coral bleaching, and crop destruction; and oil seepage near Kutubu has contaminated Lake Kutubu, a critical food and freshwater resource (Dambacher et al., 2007; Kuo, 2020). These environmental impacts are inseparable from social impacts in the PNG context. As Banks (2002, p. 41) observes, Melanesian environmental consciousness "is more holistic, and fuses the social, cultural, political, economic, and environmental aspects of landscapes in a way that does not occur in the developed world." Destruction of sacred sites, rivers, and sea environments severs connections to cultural heritage, ancestral identities, and spiritual wellbeing (Bainton, Ballard, Gillespie, & Hall, 2011; Jacka, 2018). The extreme

expression of this dynamic was the decade-long Bougainville conflict (1989–1998), triggered substantially by the environmental and social devastation of the Panguna mine, which cost an estimated 20,000 lives (Allen, 2020; Mudd et al., 2020). This environmental-social inseparability is itself a theoretical problem: standard CSR frameworks treat environmental and social dimensions as analytically distinct, but in PNG they must be understood as one.

CSR in PNG's extractive industries: contested legitimacy

Extractive organisations in PNG have implemented CSR programs across education, healthcare, infrastructure, and community development (Imbun, 2007; Kepore & Imbun, 2011; Oil Search Limited, 2014; Ok Tedi Mining Limited, 2024). However, the authenticity and effectiveness of these initiatives remain heavily contested. CSR programs in PNG's extractive sector have been characterised as strategic responses to stakeholder pressure designed to maintain legitimacy and secure social licence to operate, rather than genuine commitments to sustainable development (Dunn, 2012; Kaia, 2015). Despite millions of dollars reportedly spent on CSR activities, environmental degradation continues, conflicts persist, and affected communities frequently report that CSR benefits do not match the scale of harm caused (Duarte & Imbun, 2016; Yamarak & Parton, 2021). This persistent gap between CSR rhetoric and on-the-ground sustainability outcomes defines the theoretical problem that this paper addresses: what analytical framework can adequately distinguish substantive from symbolic CSR in this context?

TOWARDS A MULTI-THEORETICAL FRAMEWORK

Legitimacy theory

Legitimacy theory holds that organisations do not possess an unconditional right to operate; they must secure and maintain societal approval by acting in ways consistent with the norms, values, and expectations of the society in which they function (Suchman, 1995). Legitimacy is defined as "a generalized perception or assumption that the actions of an entity are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs, and definitions" (Suchman, 1995, p. 574). The mechanism through which organisations secure legitimacy is the social contract — the implicit and explicit expectations between the organisation and its social environment — of which social licence to operate (SLO) is the most operationally significant form in the extractive industries context (Lacey & Lamont, 2014; Prno & Slocombe, 2014). Applied to CSR, legitimacy theory explains why extractive organisations engage in CSR activities: not necessarily out of intrinsic ethical commitment, but because CSR functions as a tool to gain, maintain, or regain legitimacy in the face of environmental and social harm (Yongvanich & Guthrie, 2007). This opens the theoretical space for greenwashing — CSR initiatives that are symbolic rather than substantive, deployed for legitimation rather than genuine sustainability. Legitimacy theory alone, however, does not explain whose expectations organisations respond to, nor the specific institutional forces that shape what kinds of CSR are perceived as legitimate.

Stakeholder theory

Stakeholder theory argues that organisations must create value for all stakeholders — not merely shareholders — because a diverse range of individuals and groups can affect, or be affected by, the organisation's activities (Freeman, 1984; Freeman, 2023). The theory emphasises that sustainable performance requires identifying, engaging, and responding to a broad stakeholder constituency, and that the salience of particular stakeholders — defined by their power, legitimacy, and urgency — shapes how organisations set priorities (Mitchell, Agle, & Wood, 1997). In PNG's extractive industry context, stakeholder theory draws attention to the distinctive position of landowner groups and indigenous communities. Unlike most developed-country contexts where landowners are primarily economic actors, in PNG customary landowners are simultaneously those most directly harmed by extractive operations, the cultural custodians of the land, and — given the legal ambiguity between surface and sub-surface ownership — powerful sources of social licence. The theory raises a critical question: do CSR initiatives by extractive organisations in PNG genuinely engage these stakeholders in decision-making, or does engagement remain superficial — designed to secure operational consent without genuine accountability (Duarte & Imbun, 2016)? Stakeholder theory alone, however, cannot explain why

CSR programs tend to converge on similar forms across very different organisational contexts, or why organisations respond differently to stakeholders with apparently similar salience.

Institutional theory

Institutional theory explains how organisations are shaped by the broader social, cultural, and institutional environments in which they operate (DiMaggio & Powell, 1983; Scott, 2014). Central to the theory is institutional isomorphism — the tendency of organisations in similar environments to become more alike over time through three constraining processes. Coercive isomorphism arises from formal regulatory requirements and informal pressures from powerful stakeholders such as governments, international bodies, and community groups. Mimetic isomorphism refers to the imitation of practices of organisations perceived as successful or legitimate, particularly under conditions of uncertainty. Normative isomorphism reflects the diffusion of professional norms and industry standards through education, professional associations, and industry guidelines (DiMaggio & Powell, 1983). In PNG's extractive industries, each operates distinctively. Coercive pressures include the Mining Act 1992, the Oil and Gas Act 1998, the Environmental Act 2000, and international agreements including the Paris Accord and EITI standards — but enforcement is weak and informal community pressures frequently matter more. Mimetic pressures lead PNG organisations to adopt the CSR reporting and sustainability disclosure practices of international peers, raising the question of whether these are genuine adaptations or symbolic isomorphism — reproducing the form of global CSR norms without their substance. Normative pressures are transmitted through industry associations such as the International Council on Mining and Metals (ICMM) and through the professional training of corporate sustainability managers. Critically, however, whether the resulting CSR practices are substantive or symbolic — genuine sustainability or greenwashing — cannot be determined by examining any single institutional mechanism in isolation.

The case for integration

Each of the three theories illuminates a distinct dimension of CSR in PNG's extractive industries. Legitimacy theory explains the motivation for CSR engagement and the social contract logic of greenwashing. Stakeholder theory identifies the actors whose expectations matter and demands genuine accountability. Institutional theory explains the systemic forces — coercive, mimetic, and normative — that shape what kinds of CSR are adopted and how they are presented. Taken together, the three theories are not competing but complementary: what Fernando and Lawrence (2014) call "systems theories" because of their interdependence and interrelatedness. Chen and Roberts (2010, p. 652) observe that all three assume that "any organisation is influenced by the society in which it operates, and, in turn, the organisation also influences society." No prior study identified in the PNG extractive industries literature has applied all three theoretical lenses simultaneously — a significant gap. The institutional complexity of PNG — where formal and informal regulatory regimes coexist, customary land rights intersect with state resource ownership, cultural identity is constituted through environmental connection, and organisations must navigate international legitimacy demands alongside local community expectations — cannot be adequately analysed through a single theoretical lens. Legitimacy theory alone cannot explain which stakeholders' expectations shape CSR design. Stakeholder theory alone cannot explain why CSR programs converge on similar forms. Institutional theory alone cannot explain the strategic legitimation logic through which symbolic CSR maintains social licence. Integration of the three lenses is therefore analytically necessary, not merely methodologically convenient.

THE CONCEPTUAL MODEL

The conceptual model (Figure 1) provides a visual representation of how the three theories are integrated to explain the relationship between institutional and stakeholder pressures, CSR decision-making, and sustainability outcomes in PNG's extractive industries. The model is structured around four analytical columns.

Figure 11: The Conceptual Model

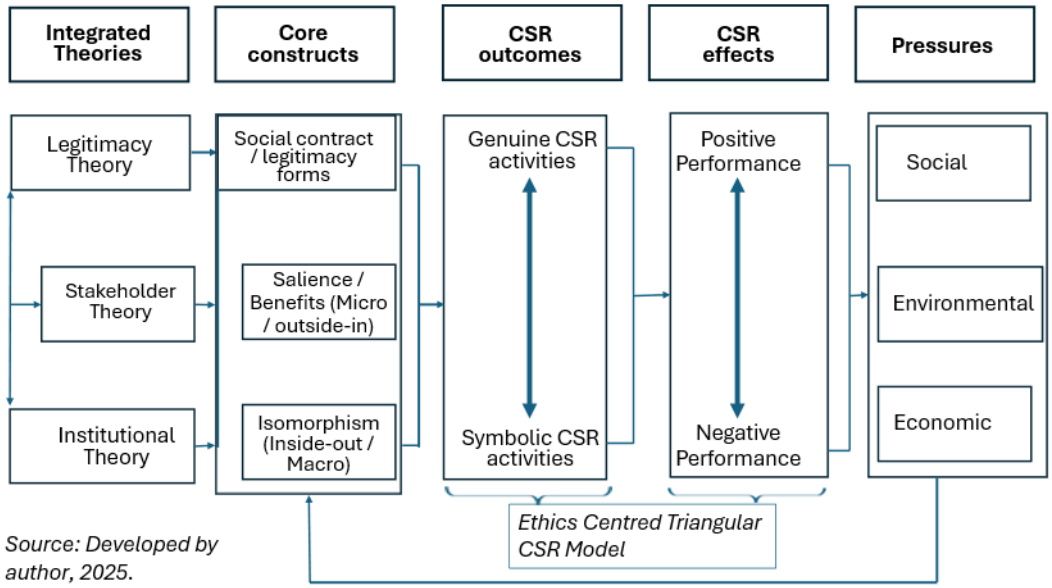


Figure 1: Multi-Theoretical Conceptual Framework for CSR Legitimacy in PNG's Extractive Industries

The first column captures the institutional and stakeholder pressures operating on extractive organisations: coercive pressures (regulatory requirements, community demands, international agreements), mimetic pressures (imitation of CSR leaders), and normative pressures (industry standards and professional norms), alongside stakeholder salience — the extent to which landowners, government agencies, NGOs, and international investors exert influence. The second column represents the organisation's CSR decision-making, shaped by its perceived legitimacy needs and social contract obligations. The third column distinguishes between two types of CSR outcome: genuine or substantive CSR, characterised by real environmental and social improvement, meaningful stakeholder participation, and contributions to sustainable development; and symbolic or greenwashing CSR, characterised by selective disclosure, tokenistic community engagement, and the appearance of responsibility without substantive change. The fourth column captures CSR effects on economic, social, and environmental dimensions, and critically includes a feedback loop through which the effects of CSR — whether positive or negative — generate new pressures back through the institutional and stakeholder environment, driving further CSR decisions.

Connected analytically to the outcomes column is a revised ethics-centred CSR typology, adapted from Carroll's (1991) pyramid to reflect the developing-country critique of Visser (2006): economic, legal, ethical, and philanthropic responsibilities, reordered and contextualised to reflect the PNG institutional reality in which philanthropic and ethical responsibilities often precede legal ones in community expectations. This adaptation is itself a theoretical contribution, recognising that the normative hierarchy of CSR responsibilities is institutionally contingent rather than universal.

The model as a whole provides a diagnostic framework. By analysing the nature of pressures acting on an organisation, the quality of stakeholder engagement in CSR design, the transparency of CSR reporting, and observed environmental and social outcomes on the ground, researchers and practitioners can assess whether an organisation's CSR program falls on the substantive or symbolic end of the continuum. This operationalises the distinction between genuine sustainability and greenwashing in a manner that is theoretically grounded and empirically tractable.

DISCUSSION AND IMPLICATIONS

This paper makes three principal theoretical contributions. First, it argues for and demonstrates the analytical necessity of multi-theoretical integration for understanding CSR in complex

developing-country contexts. The specific configuration of institutional conditions in PNG makes any single-theory analysis structurally incomplete. Second, it develops a conceptual model that operationalises the integration of legitimacy theory, stakeholder theory, and institutional theory in a way that generates testable propositions — specifically, that the relationship between institutional isomorphism and CSR design will determine whether the resulting CSR is substantive or symbolic, moderated by stakeholder salience and organisational legitimacy threat. Third, it contextualises and critiques Carroll's CSR pyramid in a developing-country context, contributing to the growing literature calling for institutional-contextual adaptation of canonical CSR frameworks (Visser, 2006, 2008; Frynas & Yamahaki, 2016).

For practitioners, the framework provides a diagnostic checklist for distinguishing genuine CSR from greenwashing in PNG's extractive industries: Does the CSR program address actual causes of environmental and social harm rather than their symptoms? Are affected landowners and communities genuinely involved in CSR design and evaluation, or merely informed after the fact? Does CSR reporting reflect observable on-the-ground outcomes, or merely disclose inputs and intentions? Are CSR commitments maintained even when they conflict with short-term economic interests? For policymakers and regulatory bodies, the framework highlights the importance of strengthening coercive isomorphic pressures — not merely through more legislation, but through consistent enforcement — while simultaneously developing normative institutional mechanisms that embed genuine sustainability standards in professional practice within PNG's extractive sector.

As a conceptual paper, the framework awaits empirical validation. The propositions derived from the integrated model will be tested in a forthcoming qualitative case study examining two mining organisations and two petroleum organisations in PNG, drawing on semi-structured interviews with company representatives, landowner groups, government officials, and NGOs, as well as analysis of CSR disclosure reports and secondary documentation. Future research should also examine the extent to which the framework is transferable to other resource-rich developing countries — including those in sub-Saharan Africa, Latin America, and Southeast Asia — where similar configurations of institutional complexity, customary land tenure, and extractive industry CSR contestation are present.

CONCLUSION

The question of whether CSR in extractive industries represents genuine sustainability contribution or strategic greenwashing is one of the most consequential in contemporary CSR scholarship. In PNG — a resource-rich developing country where extractive industries deliver economic benefits at enormous environmental and social cost, and where communities' identities, livelihoods, and spiritual wellbeing are inseparable from the lands being extracted — this question has urgency beyond academic interest. This paper has argued that answering it requires a multi-theoretical framework integrating legitimacy theory, stakeholder theory, and institutional theory, because the institutional complexity of PNG's context makes single-theory analysis structurally inadequate. The conceptual model developed here provides an analytical tool for future empirical research and a contribution to the broader project of developing CSR theory that is genuinely fit for purpose in developing-country contexts. The legitimacy of CSR in PNG's extractive industries cannot be assumed — it must be demonstrated, and the framework proposed here provides the means to do so.

REFERENCES

Akporiaye, A., & Webster, N. (2022). CSR and the extractive industries in Nigeria: Legitimacy, greenwashing, and community expectations. Resources Policy, 78, 102851.

Allen, M. G. (2020). Resource extraction and rural development: Towards a research agenda on agrarian change in Melanesia. Journal of Agrarian Change, 20(1), 142–159.

Bainton, N. A., Ballard, C., Gillespie, K., & Hall, N. (2011). Stepping stones across the Lihir islands: Developing cultural heritage management in Papua New Guinea. International Journal of Cultural Property, 18(1), 81–110.

Banks, G. (2002). Mining and the environment in Melanesia: Contemporary debates reviewed. The Contemporary Pacific, 14(1), 39–67.

Bezzola, M., Günther, I., Brugger, F., & Lefoll, E. (2022). Does CSR reduce conflicts in the extractive sector? Evidence from Africa. World Development, 158, 105985.

Carroll, A. B. (1991). The pyramid of corporate social responsibility: Toward the moral management of organizational stakeholders. Business Horizons, 34(4), 39–48.

Chen, J. C., & Roberts, R. W. (2010). Toward a more coherent understanding of the organization–society relationship: A theoretical consideration for social and environmental accounting research. Journal of Business Ethics, 97(4), 651–665.

Constitution of Papua New Guinea. Goal 4: Natural Resources and Environment, National Goals and Directive Principles.

Dambacher, J. M., Brewer, D. T., Dennis, D. M., Macintyre, M., & Foale, S. (2007). Qualitative modelling of gold mine impacts on livelihoods and social-ecological systems around Lihir Island, Papua New Guinea. Environmental Science & Policy, 10(7–8), 584–598.

de Freitas Netto, S. V., Sobral, M. F. F., Ribeiro, A. R. B., & Soares, G. R. L. (2020). Concepts and forms of greenwashing: A systematic review. Environmental Sciences Europe, 32, 19.

DiMaggio, P. J., & Powell, W. W. (1983). The iron cage revisited: Institutional isomorphism and collective rationality in organizational fields. American Sociological Review, 48(2), 147–160.

Duarte, C., & Imbun, B. (2016). The paradox of food security and the oil and gas industry in Papua New Guinea. Extractive Industries and Society, 3(3), 655–663.

Dunn, A. K. (2012). Legitimacy, identity and narrative: The case of Tullow Oil in Africa. Social & Cultural Geography, 13(4), 409–427.

EITI. (2023). Papua New Guinea EITI Report 2021. Oslo: Extractive Industries Transparency Initiative.

Elkington, J. (1997). Cannibals with Forks: The Triple Bottom Line of 21st Century Business. Oxford: Capstone.

Fernando, S., & Lawrence, S. (2014). A theoretical framework for CSR practices: Integrating legitimacy theory, stakeholder theory and institutional theory. Journal of Theoretical Accounting Research, 10(1), 149–178.

Freeman, R. E. (1984). Strategic Management: A Stakeholder Approach. Boston: Pitman.

Freeman, R. E. (2023). Stakeholder theory: The state of the art. Academy of Management Annals, 17(1), 1–30.

Frynas, J. G., & Yamahaki, C. (2016). Corporate social responsibility: Review and roadmap of theoretical perspectives. Business Ethics: A European Review, 25(3), 258–285.

Imbun, B. Y. (2007). Cannot manage without the "significant other": Mining, corporate social responsibility and local communities in Papua New Guinea. Journal of Business Ethics, 73(2), 177–192.

Jacka, J. K. (2018). The anthropology of mining: The social and environmental impacts of resource extraction in the mineral age. Annual Review of Anthropology, 47, 61–77.

Kaia, J. (2015). Mining and petroleum as drivers of Papua New Guinea's economic development. In B. Imbun & P. Hogan (Eds.), Mining in Papua New Guinea. Waigani: University of Papua New Guinea Press.

Kepore, K. P., Higgins, J., & Goddard, M. (2013). Mining and community relations in Papua New Guinea: Challenges and emerging issues. Pacific Economic Bulletin, 28(1), 27–44.

Kepore, K. P., & Imbun, B. Y. (2011). Mining and stakeholder engagement in a Papua New Guinea context. Corporate Social Responsibility and Environmental Management, 18(1), 30–46.

Kuo, C. (2020). Ramu Nickel Mine and coastal pollution in Papua New Guinea. Pacific Geographies, 53, 14–21.

Lacey, J., & Lamont, J. (2014). Using social contract to inform social licence to operate: An application in the Australian coal seam gas industry. Journal of Cleaner Production, 84, 831–839.

Mining Act 1992 (Papua New Guinea).

Mitchell, R. K., Agle, B. R., & Wood, D. J. (1997). Toward a theory of stakeholder identification and salience: Defining the principle of who and what really counts. Academy of Management Review, 22(4), 853–886.

Mudd, G. M., Jebb, M., & Ward, J. (2020). Mining impacts in Papua New Guinea: Critical overview and implications for sustainability. Resources Policy, 68, 101803.

Oil and Gas Act 1998 (Papua New Guinea).

Oil Search Limited. (2014). Sustainability Report 2014. Port Moresby: Oil Search Limited.

Ok Tedi Mining Limited. (2024). 2023 Sustainability Report. Tabubil: Ok Tedi Mining Limited.

Prno, J., & Slocombe, D. S. (2014). A systems-based conceptual framework for assessing the determinants of a social licence to operate in the mining industry. Environmental Science & Policy, 41, 54–65.

Scott, W. R. (2014). Institutions and Organizations: Ideas, Interests, and Identities (4th ed.). Thousand Oaks: SAGE.

Seele, P., & Gatti, L. (2017). Greenwashing revisited: In search of a typology and accusation-based definition incorporating legitimacy strategies. Business Strategy and the Environment, 26(2), 239–252.

Sing, N. (2015). Regulatory governance of the mining sector in Papua New Guinea. Pacific Economic Bulletin, 30(1), 42–58.

Slack, K. (2012). Mission impossible? Adopting a CSR-based business model for extractive industries in developing countries. Resources Policy, 37(2), 179–184.

Suchman, M. C. (1995). Managing legitimacy: Strategic and institutional approaches. Academy of Management Review, 20(3), 571–610.

Tilt, C. A. (2016). Corporate social responsibility research: The importance of context. International Journal of Corporate Social Responsibility, 1, 1–9.

Torelli, R., Balluchi, F., & Lazzini, A. (2020). Greenwashing and environmental communication: Effects on stakeholders' perceptions. Business Strategy and the Environment, 29(2), 407–421.

Uyar, A., Karaman, A. S., & Kilic, M. (2020). Is corporate social responsibility reporting a tool of signaling or greenwashing? Evidence from the worldwide logistics sector. Journal of Cleaner Production, 253, 119997.

Visser, W. (2006). Revisiting Carroll's CSR pyramid: An African perspective. In E. R. Pedersen & M. Huniche (Eds.), Corporate Citizenship in Developing Countries (pp. 29–56). Copenhagen: Copenhagen Business School Press.

Visser, W. (2008). Corporate social responsibility in developing countries. In A. Crane et al. (Eds.), The Oxford Handbook of Corporate Social Responsibility (pp. 473–499). Oxford: Oxford University Press.

Viveros, H. (2016). Examining stakeholders' perceptions of mining impacts and corporate social responsibility. Corporate Social Responsibility and Environmental Management, 23(1), 50–64.

Yamarak, L., & Parton, K. A. (2021). Impacts of mining projects in Papua New Guinea on livelihoods and poverty in indigenous mining communities. Mineral Economics. https://doi.org/10.1007/s13563-021-00284-1

Yongvanich, K., & Guthrie, J. (2007). Legitimation strategies in Australian mining extended performance reporting. Journal of Human Resource Costing & Accounting, 11(3), 156–177.

SUPPLY CHAIN SKILLS, TRAINING AND EDUCATION

Applications and Implications of Gamification in Warehousing

Jörg M. Ries, Naoum Tsolakis

1: City St George's, University of London, United Kingdom; University of Cambridge, United Kingdom

INTRODUCTION

Gamification has emerged as a significant concept in human–computer interaction (HCI), organisational behaviour, and operations management. It originated in industry around 2008 and gained widespread traction after 2010, when technology firms began incorporating game-inspired techniques into digital services and workplace systems. The academic foundations of gamification are typically traced to the influential work of Deterding et al. (2011), who defined gamification as "*the use of game design elements in non-game contexts*." Game elements include interface, mechanics, principles, models, and methods directly inspired by games (Seaborn and Fels, 2015). The academic literature highlights that the motivational potential of gamification stems from human engagement patterns observed in digital games, where carefully structured feedback, progression, and challenge–reward cycles sustain user involvement over long periods (Deterding et al., 2011). Over the past decade, gamification has been increasingly explored in labour-intensive operational settings, including logistics and warehousing. Warehouses face persistent challenges, including labour shortages, high turnover, increasing process complexity, and pressure to fulfil orders rapidly, driven by e-commerce (Boysen et al., 2019). Industry analyses show that these labour dynamics are now among the most significant constraints on operational performance. Recent forecasts by Gartner (2026) predict that 40% of large warehouse operations will adopt gamification tools by 2028, driven by the need to motivate, retain, and upskill workers in environments where staffing gaps are chronic. Gamification in warehouses typically applies game design principles—points, badges, leaderboards, performance dashboards, and adaptive challenges—to operational tasks to improve performance, enhance training effectiveness, and increase engagement (Bahr et al., 2022).

The relevance of gamification to modern warehousing is multifaceted. First, warehouse roles are increasingly dynamic and technologically mediated (cf. Perotti et al., 2025). Digital technologies such as Cyber-Physical Systems, Collaborative Robots, Cognitive and Physical Assistance Systems provide natural integration points for real-time feedback, challenges, and performance tracking. Gartner's research notes that many organisations are embedding gamified modules directly into these operational systems, enabling individualised or team-based challenges linked to real-time performance data. This integration allows gamification to move beyond superficial reward mechanisms toward more substantive tools for capability development and operational learning. Second, gamification addresses pressing human-resource concerns. Warehouses are struggling with high turnover and difficulty attracting younger workers who expect meaningful feedback, opportunities for progression, and engaging work environments. According to Gartner analysts, employees, especially those from younger generations, seek "*meaningful work experiences and opportunities to succeed*," and gamification can operationalise these expectations by combining recognition, skill-building, and transparent progression pathways. Gamified training tools, such as simulations or interactive quizzes, can reduce time-to-competency for new or seasonal employees, making them valuable in settings with fluctuating labour demands. Third, gamification contributes to operational consistency and continuous improvement. Performance dashboards, progress indicators, and feedback loops provide workers with real-time visibility into their accuracy, productivity, safety compliance, or learning achievements. This mirrors the high-frequency feedback systems that make digital games engaging and help foster a culture of accountability and self-improvement. Industry insights suggest that such transparency not only motivates employees but can also strengthen managerial decision-making by providing richer data on worker performance trends.

Taken together, these trends highlight why gamification has become strategically relevant for contemporary warehousing. As facilities grapple with productivity pressures and labour constraints, gamification offers a promising, human-centred approach to fostering engagement,

improving performance, and supporting workforce development. This study, therefore, aims to develop a conceptual framework for identifying and assessing applications and implications of gamification in warehousing. The framework is supported by a systematic review and classification of the literature based on warehouse processes: receiving, storage, order picking, packing and shipping, production logistics, and cross-docking. It enables the systematic evaluation of existing research, taking into account gamification applications and their performance implications. The remainder of this paper is structured as follows: Section 2 proposes a conceptual framework; Section 3 outlines the methodology and presents descriptive results; Section 4 discusses key findings; and Section 5 concludes.

CONCEPTUAL FRAMEWORK

Warehousing plays a central role in modern supply chains by providing the intermediate storage and handling of materials and goods, thereby bridging discrepancies in timing, quantity, and assortment and supporting value-added activities (Gu et al., 2007). Warehouses are generally characterised by their design and operations. While design includes the selection of storage systems, determination of layout, infrastructure, and the overall principles shaping material flows (Rouwenhorst et al., 2000; Gu et al., 2010), operations refer to activities performed as goods move through the warehouse (de Koster, 2007). The conventional warehousing process follows a sequence of receiving, storage, order picking, packing, and shipping, with production logistics or cross-docking serving as a specialised alternatives (Baker & Canessa, 2009).

The receiving process involves unloading goods, inspecting deliveries for quality and quantity deviations, and updating inventory systems (Rouwenhorst et al., 2000; de Koster, 2007). Although historically under-researched (Gu et al., 2007), receiving remains essential for ensuring the accuracy and integrity of subsequent operations (Richards, 2018). Following receipt, storage activities move items to designated warehouse locations, which may include repackaging or consolidation tasks (de Koster et al., 2007). Storage also involves placing goods in appropriate reserve or forward picking areas, with zones selected to optimise space utilisation and material accessibility (Rouwenhorst et al., 2000; Gu et al., 2007). Efficient storage aims to balance space constraints with retrieval speed, often requiring careful coordination between inventory policies, material handling equipment, and replenishment cycles (Gunasekaran et al., 1999). Subsequently, items are retrieved from warehouse locations to fulfil customer orders though order picking (de Koster et al., 2007; Richards, 2018). This includes order scheduling, item assignment, routing, and sorting (de Koster et al., 2007). Because picking performance directly affects flow times and service levels (Grosse et al., 2015), it is a major target for optimization through both technological and human-factors interventions. Packing consolidates, verifies, and secures items for shipment, ensuring product protection and compliance with distribution requirements (Hellström & Saghir, 2007). Shipping involves staging outbound goods, loading them onto transport vehicles, and updating shipment information to internal and external stakeholders (Rouwenhorst et al., 2000). These activities typically conclude the order-fulfilment cycle. Cross-docking, performed either in dedicated facilities or hybrid warehouses, moves goods directly from inbound to outbound flows without intermediate storage, reducing inventory costs and shortening cycle times (de Koster et al., 2007). In manufacturing environments, intermediate warehousing activities integrate with production logistics, which encompass material transport, inventory management, and production feeding to ensure supply reliability at minimal cost (Klumpp et al., 2019). The warehouse process dimension captures how gamification can be aligned with the operational flow of goods as they move through receiving, storage, order picking, packing, and shipping. These processes constitute the established structure of warehouse operations and have been widely described in the logistics literature (Rouwenhorst et al., 2000; de Koster, 2007). By mapping gamification to these well-defined warehouse stages, the framework accounts for the distinct cognitive and physical demands of each process and highlights targeted opportunities to influence behaviour and operational performance.

As a second dimension, the framework incorporates the gamification elements deployed across the warehouse processes. These gamification elements include points, badges, and leaderboards that make performance visible; status, levels, and roles that structure skill progression; and real-time feedback systems such as progression and rewards (Seaborn and Fels, 2015) integrated into existing warehouse management technologies such as wearables or handheld

devices. Narrative elements, such as themed tasks or shared team goals, may also be applied to strengthen motivation and foster a sense of community among workers.

The third dimension of the framework concerns the outcomes that gamification seeks to influence. These outcomes include psychological elements (e.g., motivation, committment), behavioral elements (e.g., participation, persistence), operational elements (e.g., productivity, quality), as well as organizational outcomes (e.g., inclusion , retention) (Koivisto and Hamari, 2019). These elements help to improve accuracy and productivity in tasks such as receiving, picking, and packing; enhance motivation and engagement across repetitive or physically demanding activities; increase adherence to safety protocols through hazard-awareness challenges; and more effective learning during onboarding and training. In addition, team-based gamification mechanics can reinforce collaboration, particularly in environments where synchronised coordination is essential.

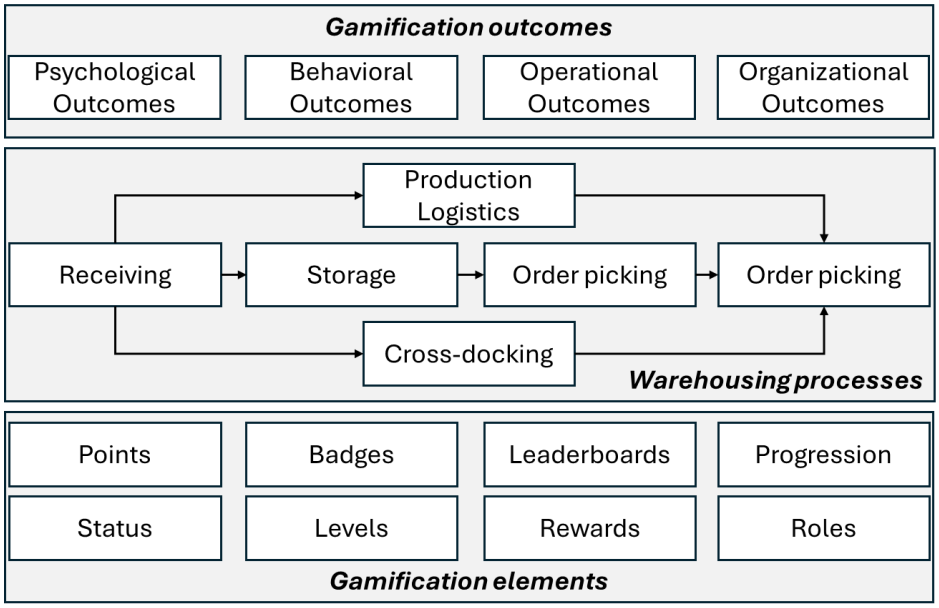


Figure 1: Conceptual Framework

This conceptual framework positions gamification as a structured, process-aligned approach to influencing behaviour and improving operational performance in warehouses. By mapping game design elements to each stage of the warehousing process, the framework provides a foundation for analysing empirical applications in the literature and identifying gaps for future research.

METHODOLOGY

Systematic literature reviews (SLRs) have frequently been used across operations and supply chain management research. As highlighted by Tranfield et al. (2003), the strength of an SLR lies in its systematic, transparent, and replicable procedures, enabling researchers to synthesise existing knowledge while minimising bias. In the emerging field of gamification in warehousing, the body of research remains fragmented and dispersed across multiple disciplines, including operations management, human-computer interaction, behavioural sciences, and logistics. Given this fragmentation, an SLR is particularly valuable for consolidating existing studies, identifying methodological patterns, and revealing conceptual and empirical gaps. As seen in other emerging logistics topics, such as sustainable warehousing and Industry 4.0 technologies, SLRs are essential for building cumulative knowledge (Perotti et al., 2025) and enabling reproducibility in subsequent research. To ensure methodological rigour and replicability, this study adopts the five-step SLR procedure proposed by Denyer and Tranfield (2009). This structured approach provides a robust foundation for conducting reviews in management and is well aligned with the objective of mapping gamification research across the warehousing domain. The adapted research process is outlined hereafter.

Phase #1 involved establishing clear research questions that reflect both the topic's emerging nature and the need for conceptual consolidation. The paper aims to explore how gamification has been applied within warehouse operations, examining the warehouse processes, gamification elements, and performance outcomes reported in the existing literature. These goals parallel the formulation process used in other warehouse reviews, e.g., those on digitalisation or sustainable warehousing, where research questions are grounded in both conceptual gaps and emerging industrial trends (as in the approach described by Perotti et al., 2025). In our context, the growing interest in gamified workforce engagement, performance management, and training systems in warehousing provided the initial impetus to define the review scope.

Phase #2 involved designing a search strategy using keyword combinations that capture the conceptual scope of gamification and its connection to warehousing. Similar to the deductive procedure used in other warehousing reviews, the authors collaboratively selected keywords that capture relevant terminology across both gamification and warehouse operations. The search strategy, therefore drew on two keyword categories, one related to the warehouse context and the other related to gamification applications:

- **Category 1: Warehousing Terms**
  (warehous* OR "distribution cent*" OR "fulfilment cent*" "logistics building" OR "logistics facility" OR "cross-dock" OR "material handling" OR "internal logistics" OR intralogistics OR picking)
- **Category 2: Gamification Terms**
  (gamif* OR "serious game*" OR "game-based" OR "gameful design" OR "game design"OR "game mechanic*" OR "game element*" OR "points badges leaderboards" OR motivational)

Categories were combined using the Boolean operator "AND" to ensure that results concerned gamification explicitly within intralogistics or warehouse environments. As in the original methodology, Scopus was selected as the primary database due to its breadth of peer-reviewed journal coverage, multidisciplinary scope, and extensive use in existing SLRs on logistics, operations, and production management (Crossan & Apaydin, 2010; Jaghbeer et al., 2020). The initial search yielded 537 articles.

Phase 3 applied a multi-stage filtering procedure to ensure quality and relevance. Only English-language publications appearing in peer-reviewed journals or international conference proceedings were retained, following established practices in logistics SLRs (Oloruntobi et al., 2023; Aravindaraj & Chinna, 2022). Grey literature, technical reports, and non-scholarly sources were excluded. Screening proceeded through title, abstract, and keyword analysis. Studies that examined warehousing without linking it to gamification were removed. Articles on gamification in general management, education, marketing, or customer engagement were also excluded unless they explicitly applied transferable concepts to warehouse operations. This process reduced the dataset, and after relevance checks, an initial sample of 30 papers remained. To reduce subjective bias, all papers were independently reviewed by all authors, consistent with practices recommended by Hohenstein et al. (2015). This detailed assessment led to the exclusion of some papers that did not substantively address the review's research questions.

In **Phase 4**, the selected papers underwent structured analysis along four dimensions including bibliometric characteristics (i.e., year of publication, journal or conference source, and domain), research methodology (i.e., conceptual papers, surveys, case studies, illustrative cases, data analyses, decision support models, analytical models, and simulations), supported warehouse processes (i.e., receiving, storage, picking, packing, shipping, cross-docking, production logistics), gamification elements (i.e., points, badges, leaderboards, progression, status, levels, rewards, roles). This structured coding enabled cross-comparison of gamification applications across processes and research streams.

FINDINGS

The coding of the retrieved literature on warehousing and gamification indicates an emerging yet increasingly prevalent research domain, with the evidence base primarily concentrated over

the past ten years and disseminated through logistics, operations, and applied technology outlets. Collectively, the coded studies depict two predominant modalities of gamification in warehousing: (i) as a motivational design integrated within operational systems to enhance engagement and task performance, and (ii) as a serious-game and simulation-based training tool for developing warehouse-related competencies. Empirical evidence indicates that gamified interface design can significantly enhance workforce engagement in warehousing tasks under controlled experimental conditions (Passalacqua et al., 2020). Concurrently, organisational data suggest that adoption depends on governance structures and implementation conditions; managers acknowledge the potential advantages, such as reinforcing productivity and accuracy objectives and fostering engagement, while also expressing concerns about fairness, monitoring intensity, and alignment with existing performance management practices (Bahr et al., 2022). Table 1 summarises the bibliometric characteristics (such as publication year and outlet) and the research methodologies employed in the final set of warehousing–gamification studies included in this research.

Author(s)	Year	Domain Focus	Research Methodology
Passalacqua et al.	2020	WMS interface gamification; workforce engagement	Controlled experiment
Bright & Ponis	2021	AR-enhanced order picking	Conceptual framework accompanied by illustrative scenario
Bahr et al.	2022	Warehousing management perspectives	Qualitative exploratory study
Franke et al.	2024	Picking techniques learning	Serious/educational game and user evaluation
Romero Marras et al.	2025	Multi-task warehouse training	Prototype development and comparative evaluation

Table 1: Sample of bibliometric characteristics and research methodologies

A clear process-level finding is that the extant literature is primarily focused on picking. Most contributions directly address order picking, either by examining the effects of gamification on picking-related activities (Passalacqua et al., 2020), proposing the integration of gamification into AR-enhanced order picking systems (Bright & Ponis, 2021), or developing games that teach picking techniques through repeated, performance-based gameplay (Franke et al., 2024). This dominance indicates that gamification is predominantly employed in environments where warehouse work is: (i) highly repetitive, (ii) measurable through real-time metrics such as time, errors, and throughput, and (iii) closely linked to operational key performance indicators (KPIs), conditions most prevalent in picking activities. Evidence pertaining to other warehouse processes remains comparatively limited. Although the management literature discusses the potential of gamification across a wider range of warehousing activities, such as receiving, storage, or packing and shipping, it offers few process-specific intervention designs and evaluations beyond picking (Bahr et al., 2022). The most evident movement beyond interventions targeting individual processes is observed in immersive training systems that simulate multiple warehouse tasks, including receiving, material placement, picking, and forklift operations. This trend suggests an emerging training pathway focused on multi-process readiness rather than isolated process optimisation (Romero Marras et al., 2025). Table 2 outlines a sample of the identified studies with regard to warehouse processes addressed, the gamification elements applied and the enabling technologies used.

Article	Supported Warehouse Processes	Gamification Elements	Enabling Technologies
Passalacqua et al. (2020)	Picking	• Goal setting • Real-time feedback	• Wearable/handheld WMS interface • Engagement measurement

Article	Supported Warehouse Processes	Gamification Elements	Enabling Technologies
Bright & Ponis (2021)	Picking (AR-enhanced)	• Reward/points logic • Motivational design • Feedback	• AR/pick-by-vision layer integrated with monitoring/WMS
Bahr et al. (2022)	Receiving; put-away; storage; picking; dispatch	• Competition • Rewards/recognition • Performance feedback	• Not technology-specific (implementation/governance emphasis)
Franke et al. (2024)	Picking	• Score • Competition • Time/error-based performance	• Serious game platform (WareMover)
Romero Marras et al. (2025)	Receiving; material placement/put-away; picking; forklift operations (training)	• Points • Levels • Time constraints • Progress/results displays	• Simulation platform with WMS-like interface • Adaptive/interactive assistance

Table 2: Sample of the process, element and technology covered

Gamification mechanisms are predominantly characterised by KPI-aligned feedback, goal-setting, and reward systems rather than by generic "badges and leaderboards." Two prominent design rationales are evident. First, feedback- and goal-oriented gamification is implemented through operational interfaces, where goal configuration and real-time feedback serve as pivotal tools for enhancing engagement during task performance (Passalacqua et al., 2020). Second, points, levels, and scoring-based gamification are primarily observed in training-related activities, often supplemented with time and error constraints and competitive performance displays, thereby motivating repeated practice and procedural mastery (Franke et al., 2024; Romero Marras et al., 2025). Furthermore, technology remains a consistent supporting layer. Wearable and handheld WMS interfaces facilitate ongoing feedback loops and micro-interventions "in the flow of work" (Passalacqua et al., 2020). AR pick-by-vision systems offer a channel for integrating motivational elements directly into picking workflows (Bright & Ponis, 2021). Additionally, simulation and serious-game environments provide secure, repeatable training contexts, recently augmented through adaptive assistance enabled by large language model components (Romero Marras et al., 2025).

Finally, reported outcomes are categorised into three main groups: engagement and motivation, task-level performance indicators (such as time taken and errors made in controlled or training environments), and capability development (including learning and skill acquisition). Controlled experimental evidence substantiates the influence of engagement effects attributable to the design of gamified interfaces (Passalacqua et al., 2020). Studies of serious games emphasise learning and competence-building in picking activities (Franke et al., 2024), while immersive training platforms extend the capability development framework across various warehouse activities (Romero Marras et al., 2025). Importantly, from a managerial perspective, these benefits are unlikely to scale without explicit governance measures to ensure perceived fairness and clarity about the role of gamification in performance monitoring and incentives (Bahr et al., 2022). Overall, the findings suggest that warehousing gamification currently follows two credible application pathways: (i) operationally integrated feedback and goal-setting interventions (primarily in picking tasks), and (ii) structured training interventions utilising serious games and simulations (which are increasingly encompassing multiple warehouse tasks). However, coverage of processes beyond picking and longitudinal evaluations in real-world settings remains underdeveloped within the current body of research.

CONCLUSION

This review highlights that gamification has become an increasingly relevant approach for addressing the human and operational challenges of modern warehousing. Rooted in established

definitions emphasising the use of game design elements in non-game contexts, gamification leverages feedback, progression, and goal-oriented mechanisms to enhance engagement and performance. Its adoption is driven by persistent labour shortages, high turnover, and the growing technological integration of warehouse environments. The literature demonstrates clear benefits, particularly in labour-intensive and metrics-driven processes such as order picking, where gamification supports accuracy, motivation, and real-time performance improvement. Evidence beyond picking remains limited, although emerging immersive training systems indicate a shift toward multi-process capability development. Another key finding is the strong alignment between gamification mechanisms and warehouse KPIs, which explains why interventions are most effective in tasks with measurable, high-frequency performance data. Overall, gamification presents a promising, human-centred approach, yet broader process coverage and longitudinal real-world evaluations are needed to substantiate its long-term impact.

REFERENCES

Baker, P. & Canessa, M. (2009). Warehouse design: a structured approach. *European Journal of Operational Research*, 193(2), 425-436.

Bahr, W., Mavrogenis, V., & Sweeney, E. (2022). Gamification of warehousing: Exploring perspectives of warehouse managers in the UK. *International Journal of Logistics Research and Applications*, 25(3), 247-259.

Boysen, N., De Koster, R., & Weidinger, F. (2019). Warehousing in the e-commerce era: A survey. *European Journal of Operational Research*, 277(2), 396-411.

Bright, A.G., & Ponis, S.T. (2021). Introducing gamification in the AR-enhanced order picking process: A proposed approach. *Logistics*, 5(1), 14.

Crossan, M. M., & Apaydin, M. (2010). A multi-dimensional framework of organizational innovation: A systematic review of the literature, *Journal of Management Studies*, 47(6), 1154-1191.

De Koster, R., Le-Duc, T., & Roodbergen, K. J. (2007). Design and control of warehouse order picking: A literature review. *European Journal of Operational Research*, 182(2), 481- 501

Denyer, D. & Tranfield, D. (2009). Producing a systematic review, in Buchanan, D. and Bryman, A. (Eds), *The Sage Handbook of Organizational Research Methods*, Sage Publications Ltd, London, 671-689.

Deterding, S., Dixon, D., Khaled, R., & Nacke, L., (2011). From game design elements to gamefulness: defining "gamification". In: *Proceedings of the 15th International Academic MindTrek Conference: Envisioning Future Media Environments*. ACM, Tampere, Finland, 9–15.

Franke, S., Hermes, S., & Roidl, M. (2024). An educational game to learn picking techniques in warehousing – WareMover. *Simulation & Gaming*, 55(5), 964-975.

Gartner (2026). Gartner Predicts 40% of Large Warehouse Operations Will Adopt Gamification Tools by 2028. Retrieved (08/02/2026) from: https://www.gartner.com/en/newsroom/press-releases/2026-02-04-gartner-predicts-40-percent-of-large-warehouse-operations-will-adopt-gamification-tools-by-2028

Grosse, E. H., Glock, C. H., Jaber, M. Y., & Neumann, W. P. (2015). Incorporating human factors in order picking planning models: framework and research opportunities. *International Journal of Production Research*, 53(3), 695-717.

Gu, J., Goetschalckx, M. & McGinnis, L.F. (2007). Research on warehouse operation: A comprehensive review. *European Journal of Operational Research*, 177, 1-21.

Gunasekaran, A., Marri, H.B. & Menci, F. (1999). Improving the effectiveness of warehousing operations: a case study, *Industrial Management & Data Systems*, 99(8), 328-339

Hellström, D. & Saghir, M. (2007). Packaging and logistics interactions in retail supply chains. *Packaging Technology and Science*, 20(3), 197-216.

Hohenstein, N., Feisel, E. Hartmann, E. and Giunipero, L. (2015). Research on the phenomenon of supply chain resilience: A systematic review and paths for further investigation, *International Journal of Physical Distribution and Logistics Management*, 45(1-2), 90- 117.

Jaghbeer, Y., Hanson, R., & Johansson, M. I. (2020). Automated order picking systems and the links between design and performance: a systematic literature review. *International Journal of Production Research*, 58(15), 4489-4505.

Klumpp M., Hesenius M., Meyer O., Ruiner C., & Gruhn V. (2019). Production logistics and human-computer interaction—state-of-the-art, challenges and requirements for the future. *International Journal of Advanced Manufacturing Technology*, 10.1007/s00170-019- 03785-0.

Koivisto, M., Costa, M., Werner, J., Heiska, K., Talvitie, J., Leppänen, K., ... & Valkama, M. (2017). Joint device positioning and clock synchronization in 5G ultra-dense networks. *IEEE Transactions on Wireless Communications*, 16(5), 2866-2881.

Passalacqua, M., Léger, P.M., Nacke, L.E., Fredette, M., Labonté-Lemoyne, É., Lin, X., Caprioli, T., & Sénécal, S. (2020). Playing in the backstore: interface gamification increases warehousing workforce engagement. *Industrial Management & Data Systems*, 120(7), 1309-1330.

Perotti, S., Cannava, L., Ries, J-M. & Grosse, E. H. (2025). Reviewing and conceptualising the role of 4.0 technologies for sustainable warehousing. *International Journal of Production Research*, 63(6), 2305-2337.

Richards G. (2018). Warehouse management: A complete guide to improving efficiency and minimizing costs in the modern warehouse (3rd ed.). Kogan Page Publishers.

Romero Marras, J.J., De la Torre, L., & Chaos García, D. (2025). WarehouseGame Training: A gamified logistics training platform integrating ChatGPT, DeepSeek, and Grok for adaptive learning. *Applied Sciences*, 15(12), 6392.

Rouwenhorst, B., Reuter, B., Stockrahm, V., van Houtum, G. J., Mantel, R. J., & Zijm, W. H. (2000). Warehouse design and control: Framework and literature review. *European Journal of Operational Research*, 122(3), 515-533.

Seaborn, K. & Fels, D.I. (2015). Gamification in theory and action: A survey. *International Journal of Human-Computer Studies*, 74, 14-31.

Tranfield, D., Denyer, D., Smart, P., (2003). Towards a methodology for developing evidenceinformed management knowledge by means of systematic review, *British Journal of Management*, 14(3), 207–222.