



Proceedings of the 29th International Symposium on Logistics (2025)

Embedding Circularity in Supply Chains

06-09 July 2025



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INTRODUCTION

We are delighted to welcome our friends and colleagues, both old and new, to the 29th International Symposium on Logistics and Supply Chains. This year's event provides an opportunity for the ISL community to debate 'circularity' and its knock-on effect on the management of supply chains. The underpinning argument is that as more and more organisations seek to transition towards sustainable and circular practices, the integration of energy management, digitalisation, last-mile logistics, transport and mobility systems, and other elements plays a vital role in reducing carbon emissions and promoting resource efficiency. By leveraging these domains, businesses can create resilient, circular supply chains that not only meet current demands but also contribute to a sustainable future within the context of an ever-changing political landscape and constantly evolving weather patterns across the globe. All these challenges, as well as ongoing major global conflicts, mean that there are delays in shipments due to re-routing, disruptions in sourcing, reduced flexibility, skill shortages, and increased complexity, etc., are a major concern for many logistics and supply chain planners and managers.

The organising committee, based on learning from previous hybrid ISL conferences, decided to continue with the hybrid mode again this year, which worked quite well during the ISL 2022, 2023 and 2024. This year's conference although primarily face-to-face, also offers all online participants access to the online presentation sessions, as well as the keynote presentations. Whilst the hybrid mode is not an ideal context to network, it is an acceptable compromise considering the concerns around sustainability issues, as well as increased levels of travel restrictions imposed by many universities around the globe.

Bearing this in mind, two categories of paper submissions were invited. The first category was so called 'Full Papers' - that is up to 8 pages in length along with a one-page structured abstract. These types of papers were subject to a peer review process. These papers, if accepted, are included in part 2 of the Proceedings of the Conference with an ISBN number. The second category were structured abstracts of 1000 words. These may be considered as developmental papers, representing early-stage research ideas or initial findings. Only the abstract was required for the initial submission, which underwent the review process. Both types of paper submissions – full papers and structured abstracts – were considered for an invitation to submit to the special issue of the International Journal of Logistics Management or Computers and Industrial Engineering. The duration of the in-person presentations was 30 minutes (including Q&A), whilst the online presentations were for 15 minutes during the two-day event.

Considering the increased trend towards efficient and effective resource utilisation as well as increased digitalisation of supply chains operations and the greater need to promote excellence in this field. The chosen theme for ISL 2025 was '**Embedding Circularity in Supply Chains**'. This 29th ISL aims to provide a forum for both academics and practitioners to discuss the current and future research in the area of logistics and supply chain management. The papers in this book of proceedings represent the latest in academic thinking, as well as case examples of successful implementations. The 29th ISL also presents an opportunity to engage in various discussions and debates during the course of the event, exploring how our models, concepts and findings are pushing the frontiers of knowledge in the area of logistics and supply chain. Equally, it is important to explore how our cumulative know-how in our discipline can be successfully applied to develop the next generation of experts through our teaching and curriculum development as well as helping the practitioner community to enhance the competitiveness of industry.

For us as event organisers, we have been able transfer learnings associated with using online platforms from last year and combine it with expertise generated over the years in hosting physical events to deliver an excellent experience for our ISL delegates. We are delighted with the success in terms of number of submissions, resulting in 73 paper presentations representing authors from 33 countries. In addition to this, we were fortunate to have two excellent and thought provoking keynote speakers namely Professor Alan McKinnon, Kuehne Logistics University, Hamburg, Germany and Emeritus Professor at Heriot-Watt University, Edinburgh, UK and Timothy Glaz, Head of Corporate Affairs at Werner & Mertz, Germany. We were equally pleased to host a workshop on 'Designing cascades for systemic circularity in material/product circular supply chains' ably led by Prof. Dr. Matthias Kalverkamp, Wiesbaden Business School, RheinMain University of Applied Sciences, Germany, Prof. Dr. Helen Rogers, Technische Hochschule Nürnberg Georg Simon Ohm, Germany, Katrin Auer, Deggendorf Institute of Technology, Germany and Tim Ahlheim, Wiesbaden Business School, RheinMain University of Applied Sciences, Germany.

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

- Circular Supply Chain
- Smart/digital connectivity in logistics and supply chains
- Supply Chain Analytics
- Sustainability in Logistics and Supply Chains
- Building resilience for supply chains
- Logistics Connectivity
- Humanitarian Logistics
- Supply Chain Skills, Training and Education

Part II: Full Papers

- Circular Supply Chain
- Smart/digital connectivity in logistics and supply chains
- Supply Chain Analytics
- Sustainability in Logistics and Supply Chains
- Building resilience for supply chains
- Logistics Connectivity
- Humanitarian Logistics

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 Prof. Dr. Matthias Kalverkamp, Wiesbaden Business School, RheinMain University of Applied Sciences, Germany for hosting the event, to his president Professor Eva Waller for her continuous and valuable support and to his excellent colleagues at the university for the organisational support for the entire event. We are equally indebted for organising the very popular industrial visit to Mewa, a family-owned closed-loop textile service provider, Germany.

Prof. Andrew Potter, Prof. Kulwant S Pawar, Prof. Dr. Matthias Kalverkamp and Prof. Helen Rogers – July 2025.

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SECTION ONE: ABSTRACTS

CIRCULAR SUPPLY CHAIN

Sustainable Supply Chain Management in the Circular Beauty Industry: An Analysis of Status, Challenges, and Opportunities in Europe

Kathrin Auer¹, Helen Rogers², Björn Sven Ivens³

1: TH Nürnberg & University of Bamberg, Germany; 2: TH Nürnberg, Germany; 3:
University of Bamberg, Germany

Purpose of this paper:

Food loss and food waste are major problems because many resources, such as land, labour and water, are wasted, and an excess of greenhouse gases is produced during food production (Ma & Liu, 2019). However, many companies have recognised the problems related to waste and are trying to use waste material or byproducts as a new resource for products in line with the bioeconomy and circular economy. In this paper, we look at companies in the circular material-based cosmetics sector, as more and more (young) companies are discovering the topic of circular cosmetics for themselves. (Morea, Fortunati, & Martiniello, 2021).

In this current paper, we use a large survey and in-depth interviews to find out more about companies that already exist in this relatively new sector in the European market, particularly in Germany, Austria, and Switzerland. We investigate how they differ, particularly in terms of their supply chains, their procurement logistics and production processes. What factors lead to successful circular cosmetics operations, and what factors lead to failure? In the work we deal with sourcing and logistics processes, required raw material qualities and quantities, legal conditions, market conditions, bioeconomy and circular economy-specific knowledge of the companies, and possible business partners, as well as technical aids.

In their exploratory work, the authors gain an overview of the spread of circular cosmetics in Europe, process patterns of cosmetics companies, and factors for success and obstacles that they perceive in the field of circular cosmetics.

After gaining insight into the current situation of the companies, theoretical frameworks are created, and practical suggestions for improvement are made.

Research Questions:

1. What is the current state of circular cosmetics in Europe regarding knowledge and supply chain design?
2. What are (supply chain) challenges circular cosmetics companies in Europe face?
3. How can those companies overcome stated challenges?

Design/methodology/approach:

The study is explorative and both qualitative and quantitative in nature. It is considered mostly primary data (surveys and semi-structured in-depth interviews with key cosmetics companies in Europe).

Findings:

The circular beauty market is still an underdeveloped market in Europe. Several factors, like lack of knowledge, missing trade connections, decentralised supply chains and lower leverage, lead to higher prices and thus business disadvantages for circular (cosmetics) businesses. Those need to be overcome using the suggested business strategies.

Value/Originality:

Our study is the first of its kind since circular cosmetics supply chains are still an under-researched area. The study proposes a conceptual framework on how to create new circular and bioeconomic value chains and innovative business models deriving from food waste,

especially in the field of cosmetics. It depicts and clusters business model types and supply chain and procurement strategies in the context of new value streams, and also gives practical value for start-ups and companies.

Research limitations/ implications:

Naturally, the survey is limited by the limited number of participating companies and should therefore be reviewed in an even larger and more international context. It should also be checked whether the findings also apply to other related industries, such as the consumer goods market, as the same laws should apply here.

Practical implications:

The study aims to identify best practice opportunities for companies that want to engage with circular business models. The companies can also recognise potential pitfalls and use the knowledge from the study for their own development of successful circular companies or business areas. The study aims to contribute to the creation of new, sustainable and circular cosmetics-related supply chains and business models, to foster bioeconomy, to create more resilience and independence within local supply chains and to diminish raw material dependencies, not only, but especially in politically turbulent times.

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Logistics Challenges and Resource Demands in Adopting Re-Commerce for Secondhand Fashion Retail

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Purpose of the paper:

Secondhand fashion retail, traditionally associated with thrift stores, flea markets, and garage sales, has undergone a significant transformation with the advent of online resale, which is known as re-commerce (Liu and Wang, 2024). This shift to online platforms has refined the secondhand fashion market, offering consumers broader access to affordable and unique fashion items by eliminating geographical barriers (Sun and Choo, 2023). The convenience of searching for and purchasing online has contributed to the rapid growth of re-commerce, positioning it as a critical component of secondhand fashion retail. In 2024, the global secondhand fashion market was valued at \$177 billion, with re-commerce generating \$99 billion in revenue (Statista, 2024). By 2029, the re-commerce market is projected to grow to \$448bn USD (ibid).

Despite its potential, the integration of e-commerce presents unique logistical and operational challenges for secondhand fashion retailers. Re-commerce platforms are still in the early stages of development compared to traditional e-commerce (Aycock et al., 2023). Unlike traditional e-commerce, re-commerce deals with diverse product conditions, variations in quality, and unpredictable supply chains. Reverse logistics, including product collection, sorting, and distribution, often require firms to establish entirely new systems. Additionally, meeting consumer expectations for seamless experiences-from product descriptions to shipping and returns-demands innovative strategies and resource configurations. This study aims to explore the logistical challenges in operating re-commerce for secondhand fashion retail and examine the critical resources required to achieve profitable operations while maintaining an efficient reverse logistics system.

Design/methodology/approach:

This study adopted the Resource-Based View (RBV) as the theoretical framework to investigate the secondhand retail firms' logistics challenges and resource requirements in transitioning to re-commerce. In RBV, a firm's resources encompass a wide range of tangible and intangible assets, including processes, capabilities, and knowledge that support executing strategies aimed at gaining a competitive advantage (Varadarajan, 2020). This theoretical framework provides a foundation to explore key challenges and the importance of aligning various resources and capabilities to operate an efficient and effective re-commerce platform for secondhand fashion retail.

A qualitative research design was employed, utilising semi-structured, in-depth interviews with ten secondhand fashion reselling companies. The rationale behind the selections was the secondhand resellers operating business-to-consumer (B2C) re-commerce platforms within the Nordic region. A deductive framework was employed to capture the firms' perspectives regarding logistical challenges and resource requirements to overcome such challenges in shifting to/operating re-commerce. Interview participants included managers, logistics coordinators, and IT specialists who are knowledgeable about re-commerce logistics and operations. On-site observations complemented the interviews, providing insights into operational procedures such as inventory management practices, reverse logistics workflows, and customer service mechanisms. All interviews were recorded, transcribed, and subjected to thematic analysis. Data triangulation was applied to ensure the alignment between observations and interview responses. Themes were identified related to logistical challenges, resource allocation, technological adoption, and capability development. This dual approach provided a rich, multi-faceted understanding of how firms develop their re-commerce capabilities. This methodology enabled a robust

exploration of the logistical and operational frameworks shaping re-commerce in the secondhand fashion sector.

Findings:

Findings reveal that secondhand fashion retailers face substantial challenges in optimising and streamlining re-commerce operations, stemming from product, process, and supply chain complexities. Product-level challenges stem from the uniqueness of each garment, along with variations in quality, condition, and size. Meeting high price and quality criteria is essential for online sales; otherwise, operational costs of re-commerce platforms cannot be recovered. Irregular supply and a shortage of high-quality garments further disrupt re-commerce platforms. Process-level challenges include sorting, photographing, cataloguing, and warehousing unique secondhand items. These tasks are time-consuming, labour-intensive, and often inefficient. Each garment requires individual photography and detailed data entry, demanding skilled labour for accuracy and consistency. Supply chain challenges include unpredictable supply flows, complex reverse logistics, and high delivery costs for individual orders, making distribution less economical. Coordinating collection, transportation, and inventory management remains difficult, while integrating re-commerce with traditional retail adds further complexity.

To tackle these challenges, secondhand resellers have invested in crucial resources while identifying further resource needs. Respondents emphasised the necessity of trained staff for evaluating secondhand products, implementing dynamic pricing, and leveraging data analytics to drive success. Partnerships with reverse logistics providers were also mentioned as advantageous for ensuring timely product availability. A strong focus has been placed on developing technological solutions to automate tasks such as photography, writing product descriptions, listing items, and processing commission payments, with Artificial Intelligence (AI) increasingly taking a central role. Collaboration with technology vendors and third-party platforms is vital for closing resource gaps, particularly for charities and independent resellers with limited financial capital to invest in technology. Meanwhile, fashion brands have integrated re-commerce with existing e-commerce platforms; however, some brands have struggled to make the re-commerce business model profitable due to inefficiencies in reverse logistics processes and the additional resources required to enhance efficiency and profitability. The success of re-commerce depends on effectively balancing logistical efficiency with sustainability goals. Firms expressed concerns about the financial burden of implementing technological solutions, highlighting a paradox between profitability and sustainability in re-commerce operations.

Value:

This study presents a novel exploration of the logistical and operational challenges unique to re-commerce within the secondhand fashion industry. It offers original insights into how secondhand retailers can leverage resources and capabilities to successfully transition into re-commerce, a growing yet complex segment of the retail market. By utilising RBV, the study emphasises the critical role of resource alignment, innovative logistics practices, and technological integration in overcoming challenges such as reverse logistics and inventory management. Ultimately, this paper enriches the broader discourse on sustainable retailing and the evolving role of logistics in supporting re-commerce platforms. It also serves as a resource for academics and practitioners seeking actionable strategies to support profitable, sustainable re-commerce operations within a circular supply chain framework.

Research limitations:

This study focused on a selected group of secondhand fashion retailers, which may limit the applicability of findings to a broader context. Further research could explore variations in re-commerce adoption across different platforms and geographical regions. Another limitation is the evolving nature of re-commerce logistics. As technology and consumer behavior continue to shift, some of the identified challenges and solutions may change over

time. Longitudinal studies tracking the development of re-commerce capabilities would provide a more dynamic understanding of industry trends.

Practical implications:

The paper's findings are particularly valuable to secondhand fashion retailers and re-commerce platforms focused on fostering sustainable retail practices. By identifying best practices and outlining resource needs, the research seeks to empower secondhand fashion retailers to navigate the complexities of re-commerce.

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Driving Systemic Change in the Circular Economy: Exploring the Role of Social Enterprises

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Purpose of this Paper:

Social enterprises (SEs) are emerging as **Green skills** pivotal actors in advancing the Circular Economy (CE), leveraging their hybrid social and commercial objectives to address systemic challenges in traditional supply chains (Boehme et al., 2023; Dacin et al., 2011; Bacq & Janssen, 2011). Acting as intermediaries, SEs foster grassroots initiatives, advocate for policy change, and drive innovation to promote resource regeneration, waste reduction, and sustainable development (Kirchherr et al., 2017; Ellen MacArthur Foundation, 2013).

This paper investigates SEs' transformative role in embedding CE principles into supply chains, with a specific focus on their ability to disrupt linear systems and create scalable, innovative pathways that align with global sustainability goals, including Goal 12: Responsible Consumption and Production (United Nations, 2015). By highlighting how SEs address systemic barriers, the study presents a practical roadmap for accelerating the adoption of CE practices within and across supply chains.

Design/Methodology/Approach:

The study employed a qualitative research approach, conducting semi-structured interviews with leaders from seven SEs and complementing this with archival data for triangulation (Saunders et al., 2016; Yin, 2018). These interviews, carried out over nine months, revealed recurring themes and patterns synthesised to develop the SE Circular Transition Model. This model highlights five core strategies SEs employ to embed CE principles and drive systemic change. Table I presents a deidentified summary of the interview participants, all approved by the University of Wollongong's Human Research Ethics Committee (Application 2023/194).

Table I: Overview of Deidentified Interview Partners

Interview ID	Sector	Focus Area	Geographic Focus
SE-01	Recycling Enterprise	Recycling materials overlooked	Regional Australia
SE-02	Educational Social Enterprise	Waste diversion and education	Urban Australia
SE-03	Community Enterprise	Composting and waste reduction	Urban and Rural Australia
SE-04	Circular Resource Organisation	Transparency in recycling processes	National focus
SE-05	Sustainability Enterprise	Repurposing discarded materials	Urban Australia
SE-06	Local Waste Management	Localised recycling initiatives	Regional and Urban Australia

SE-07	Environmental Advocacy Group	Policy advocacy for CE principles	National and International focus

The methodological rigour of this approach ensures that the insights derived are credible and applicable across diverse supply chain contexts. The analysis identified five innovative strategies through which SEs transform supply chains.

Findings:

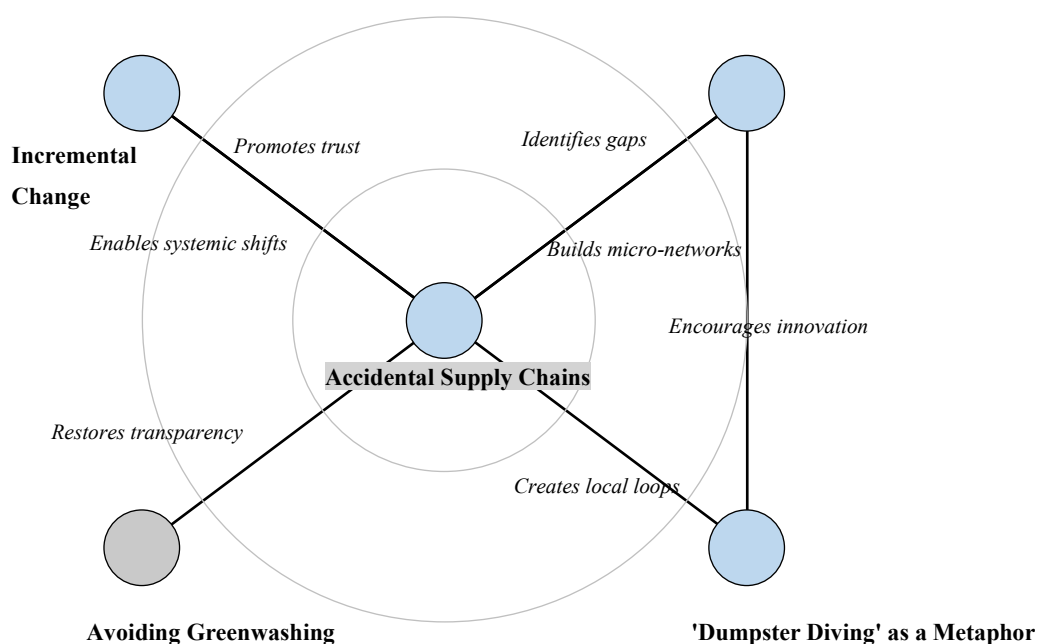
The SE Circular Transition Model illustrates how SEs address systemic barriers and embed CE principles into traditional supply chains. The strategies identified through the interviews include:

1. **Operating in Overlooked Areas:** SEs fill gaps in traditional supply chains by focusing on often neglected materials and processes. *"We step in where others don't. Our focus is on creating access to recycling for materials that most people don't know what to do with."* (Operations Manager, Recycling Enterprise)
2. **Creating Accidental Supply Chains:** SEs establish informal networks by converting waste into resources, promoting localised recycling and upcycling solutions. For example, a workshop on waste management evolved into a network for reusing soft plastics. *"What started as a simple workshop on waste management has grown into a network of people collecting and reusing materials we never expected to see reused."* (Founder, Educational Social Enterprise)
3. **Driving Incremental Social and Political Change:** SEs enable cultural shifts toward sustainable practices through education and advocacy. Campaigns for standardising recycling behaviours and workshops on composting exemplify these impacts. *"We teach people how to compost, how to reduce waste—one small step at a time."* (Workshop Coordinator, Community Enterprise)
4. **Ensuring Authenticity and Avoiding Greenwashing:** Transparency and accountability are central to SE operations, ensuring measurable outcomes and stakeholder trust. For instance, one SE collaborates with local councils to verify recycling processes. *"Everything we do is measurable. We track outcomes, so there's no question about our impact."* (Impact Analyst, Circular Resource Organisation)
5. **Reclaiming Resources Through 'Dumpster Diving':** SEs reclaim value from discarded materials, transforming societal waste culture. This concept is demonstrated in an interviewee's efforts to repurpose coffee grounds and soft plastics into valuable inputs for circular systems. *"We don't see waste—we see potential. Everything can have a second life."* (Founder, Sustainability Enterprise)

Figure 1: SE Circular Transition Model

Figure 1 illustrates the interconnected strategies SEs use to transform supply chains. It highlights how these strategies create localised loops, foster trust and transparency, and enable systemic shifts. The model demonstrates the scalability and replicability of SE-driven innovations across industries.

Figure 1: SE Circular Transition Model



Source Author (This model was crafted from analysis of interviews conducted for Eunice Quintana-Smark's PhD research.)

Value and Practical Implications:

This study underscores SEs' transformative potential in embedding CE principles into supply chains. By addressing systemic barriers and leveraging their unique hybrid mission, SEs bridge critical gaps in traditional systems. Policymakers and businesses can use the SE Circular Transition Model as a roadmap for scaling circular practices, fostering partnerships, and accelerating progress toward global sustainability goals. The findings offer actionable insights for stakeholders aiming to integrate CE principles into supply chain operations at both local and international levels.

Originality/Value:

This paper highlights early investigations into SEs' innovative role in advancing CE practices within supply chains. The findings emphasise SEs' potential to challenge linear systems, create localised solutions, and drive systemic change. The SE Circular Transition Model offers an innovative framework for understanding and applying transformative strategies and contributes to the broader discourse on embedding sustainable supply chain innovation.

Conclusion:

Social enterprises are critical in redefining traditional supply chains by embedding CE principles through innovative strategies. Their hybrid focus on social and commercial objectives positions them as key catalysts for systemic change. By leveraging their grassroots connections and disruptive approaches, SEs demonstrate how local actions can inspire global sustainability impacts, bridging gaps in CE adoption and accelerating the transition to a sustainable future.

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Green Skills and Competencies in Achieving Net-Zero Supply Chains

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Purpose:

In an urge to reduce CO₂ emissions, policymakers have committed to climate pledges and sustainability strategies (e.g. Paris Agreement, European Green Deal). Research has shown, supply chain (SC) activities are a main contributor to CO₂ emissions (World Economic Forum, 2021). In an effort to realise these competitive commitments (e.g. net zero by 2050), organisational skills & capabilities for green jobs, green living, and green transformation (Cabral and Lochan Dhar, 2019; Kwauk and Casey, 2022) play a critical role (Balci and Ali, 2024).

Whilst *green skills* encompass the abilities required to develop green jobs that facilitate the shift to a more carbon-neutral economy (Cabral and Lochan Dhar, 2019; Kwauk and Casey, 2022), *green capabilities* facilitate the adoption of environmental initiatives on an organisational level, ultimately enabling organisations to effectively address environmental challenges (Shaharudin et al., 2019). However, the literature lacks a clear definition of the terminology as well as research on equipping organisations with essential green skillsets and competencies (e.g. Cabral and Lochan Dhar, 2019; McCoy et al., 2024).

To this aim, this research seeks to explore the required green skillset and competences at different organisational levels (i.e., micro, meso and macro), and investigates the role of SC partners in the development of green skillset and the successful transition to net-zero SCs.

Design/Methodology/Approach:

Guided by a deductive approach, this study integrates the theoretical perspectives of the dynamic capability view (Teece et al., 1997) and the institutional theory (DiMaggio and Powell, 2000) to address the following research questions (RQs):

- *RQ1: What green skills and competencies are required to achieve net-zero SCs?*
- *RQ2: How can SC actors contribute to developing green skills and competencies for net-zero?*

The case study research method is particularly suitable for this study, as it enables an in-depth exploration of complex phenomena within real-world contexts (Eisenhardt, 1989). Given the intricate nature of organisational processes and behaviours related to sustainability transitions, case studies provide a robust empirical foundation for analysing the development of green skills and competencies. Moreover, case study research facilitates context-specific knowledge generation, while allowing us to uncover how theoretical concepts manifest in practice, while capturing the contextual factors influencing skill development. It offers valuable insights into industry-specific challenges and opportunities in net-zero transition.

To achieve this, primary data are collected through semi-structured interviews with organisations in the Waste Management, Logistics, and Construction sectors across the United Kingdom and Italy. This cross-sectoral and cross-country analysis enhances the generalizability of this study and provides a comparative perspective on the development of green skills and competencies necessary for net-zero SCs.

Findings:

Findings from the literature demonstrate that shifting towards net-zero requires a green systems change. In doing that, the research developed a new framework which maps the

green skills & competencies based on the three different levels of micro, meso and macro level. The micro-level refers to the employees and their green skillset required; meso-level investigates Firstly, the micro-level, which refers to organisational competencies and macro-level, highlights the supply chain competencies from a systems perspective. Literature identified examples of individual-level green skills, amongst others, as the expertise in critical renewable generation (McCoy et al., 2024) and environmental strategy and leadership (Paterson et al., 2022). Organisational capabilities encompass remanufacturing capability (Okumus et al., 2024), environmental capabilities and entrepreneurial learning (Paterson et al., 2022). At the macro level, SC competencies include supply chain visibility (Balci and Ali, 2024) and the ability to decarbonise the supply chain (Mishra et al., 2023).

These findings have been tested with interviews of organisations in three different industry sectors. Preliminary findings demonstrate alignment with existing literature, while placing particular emphasis on elements such as behavioural capabilities at the individual level. Currently, organisations focus on capability development primarily through scaling up training programs and fostering collaborations with universities.

Value:

This study develops a novel conceptual framework that maps green skills and competencies across micro-, meso-, and macro-levels, providing a structured understanding of net-zero-related capabilities within organisations, industry networks, and institutional environments. By examining the interplay between these levels, the research highlights how green skills are cultivated, transferred, and institutionalised within supply chains.

Additionally, the study explores the role of SC actors in fostering and enhancing these competencies through collaboration, knowledge-sharing, and institutional pressures. By integrating cross-sectoral and cross-country insights, it offers both theoretical contributions and practical recommendations for organisations and policymakers.

Moreover, this research bridges gaps in existing literature while supporting the development of a workforce aligned with the general net-zero objectives.

Research limitations/implications:

This study examines green skills and competencies across three industry sectors and two countries, offering insights into sustainability-related workforce capabilities. The conceptual framework developed provides a foundation for further validation through larger-scale studies, such as survey-based research. Future research can assess the generalisability across additional industries and countries to strengthen its applicability. This would enhance understanding of how green skills are developed and transferred across different contexts, supporting policymakers, industry leaders, and educators in aligning workforce competencies with sustainability and net-zero objectives.

Practical implications:

This study provides valuable insights for managers and practitioners navigating the transition to net-zero by identifying the green skills and competencies required at various levels. It offers practical recommendations and decision-making support for skill development and introduces a competency framework to guide organisations in implementing net-zero practices, and sheds light on the next generation of education for net-zero-related job titles.

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Sentiment-Driven Market Prioritisation: Assessing Country-Level Readiness for Circular Logistics Practices

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Purpose of this paper:

The transition to circular supply chains is a strategic imperative for logistics companies aiming to align with major sustainability initiatives such as the European Circular Economy Action Plan (European Commission, 2025). However, market potential for circular practices (e.g., reverse logistics, reusable packaging, waste-to-resource systems) can vary significantly across geographies due to differences in public opinion, policy support, industrial orientation and corporate engagement (Nowak-Marchewka et al., 2025; OECD, n.d.). This paper addresses a critical gap in circular economy research by analysing country-specific sentiment toward sustainability and circularity to guide logistics firms in identifying high-potential markets for early investment in circular initiatives.

Methodology:

This study adopts an exploratory approach to evaluate the viability of using the Global Database of Events, Language, and Tone, short GDELT (The GDELT Project, n.d.), as a tool for sentiment analysis in the context of circular logistics. Developed within a Google Jigsaw-supported research project, GDELT's vast database of global news and event media, spanning over 100 languages and capturing real-time updates, provides a unique opportunity to analyse social sentiment at scale (The GDELT Project, n.d.).

In this work, based on the initial data collection, sentiment analysis is conducted to quantify sentiment—positive, neutral, or negative—for different geographic regions. This involves the systematic aggregation of tone scores and identification of trends in media coverage to assess overall sentiment intensity. To provide a deeper context, it is tested whether thematic coding can be applied to categorise media mentions into key themes, such as policy support, corporate initiatives, and public opinion. This step helps to identify the drivers of positive or negative sentiment and highlights areas of focus within the circular logistics discourse. Finally, countries are to be classified into tiers based on sentiment intensity and media coverage volume. High-priority markets are characterised by strong positive sentiment and high coverage, emerging markets show moderate sentiment and growing coverage, and resistant markets exhibit neutral or negative sentiment with low coverage.

Findings:

The analysis of the GDELT data indicates potential as an evidence base for gaining insights into country-specific sentiment on circular logistics market readiness. However, operational challenges such as accurately linking press articles to the correct geographic context exist. For example, German media reporting on developments in other countries can skew results if not properly filtered. Additionally, the tone analysis may miss nuanced contexts like sarcasm or indirect criticism. Despite these limitations, the proposed approach is a valuable supplementary tool for decision-making, offering scalable and cost-effective insights into global trends. However, it should not be used exclusively. Instead, it should complement traditional market research, stakeholder consultations, and on-the-ground assessments to ensure a comprehensive understanding of market readiness.

Value:

This research provides significant value to both practitioners and academics by introducing a scalable, data-driven approach to assess market readiness for circular logistics. For logistics companies, the study offers a cost-effective method to identify high-potential

markets, such as those with strong positive sentiment and high media coverage, enabling targeted investments in circular initiatives like reverse logistics or reusable packaging. It also highlights emerging markets with growing discourse, signalling opportunities for early engagement, and resistant markets where additional efforts may be needed to address barriers. By complementing traditional market research with sentiment analysis, firms can enhance their strategic decision-making and reduce risks associated with circularity adoption.

Research implications:

Theoretically, this research highlights the role of public discourse in shaping circular supply chain potential, offering a new metric to complement traditional indicators like policy frameworks. Limitations, such as challenges in linking media coverage to geographic contexts and capturing nuanced tones, provide opportunities for future research. Future studies could integrate GDELT with other data sources, such as social media, patent databases, startup registers, or corporate reports, and conduct longitudinal analyses to track sentiment shifts over time, further refining the use of sentiment analysis in circular logistics.

Practical implications:

Practically, logistics firms can use sentiment analysis as a supplementary tool to prioritise markets and allocate resources effectively. However, sentiment analysis should complement, not replace, traditional market research and on-the-ground assessments to ensure a comprehensive understanding of market readiness. Broadening the information basis enables companies to optimise their resource allocation in general and better integrate market sustainability readiness into decision-making processes.

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Incentivising Circular Supply Chain Participation

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Purpose of this paper:

In this study, we seek to understand the drivers and incentives for agribusinesses to reconfigure into more circular supply chains, in order to intensify participation in circular supply chains and enhance circularity. Adopting and implementing a CE requires diversifying business models, including redesigning supply chains to embrace and integrate circular thinking (Hazen et al., 2021). However, little is known about the principles, processes, and outcomes that characterise circular supply chains (Howard et al., 2019). Knowledge about the characteristics of the circular supply chain is critical to the development of CE in the agri-food sector.

As an emerging concept, circular supply chain management (CSCM) aims to integrate circular thinking into the management of the supply chain and its surrounding industrial and natural ecosystems (Farooque et al., 2019). CSCM extends the boundaries of earlier sustainable supply chain concepts such as closed-loop supply chains and green supply chains, and enables a higher level of supply chain circularity by recovering value across different supply chains that partner with firms in the same or different industry sectors (Zhang et al., 2021).

Gonzalez-Sanchez et al. (2020) have clarified that circular supply chains involve both closed-loop supply chains that deal with the practice of returning products to the original manufacturer for reuse and open-loop supply chains that involve recovery of products and reuse by parties other than the original producer. A commonly quoted example of an open-loop circular supply chain is Nike using pineapple leaves for sneaker production (Mitchell, 2021).

While there is a growing body of literature on circular supply chains, most are conceptual and qualitative, with a lack of comprehensive quantitative and analytical studies. The limited prior modelling mostly utilises a reuse-recycle-remanufacture approach (e.g., Xu et al., 2023), which is not applicable to most agricultural business contexts. Quantitative studies on CE in agriculture mostly adopt the life cycle assessment approach rather than analytical modelling (e.g., Velasco-Muñoz, 2022). This study proposes to fill the gap by providing a quantitative analysis of open-loop circular chains in the agri-food sector.

Design/methodology/approach:

This study combines empirical investigation and game theory modelling in analysing agribusinesses' incentives for participating in circular supply chains. Farmers and agribusinesses that process by-products are interviewed to understand their key trade-offs, which are modelled via a comparison of three scenarios under a non-cooperative game-theoretic framework. Each scenario corresponds to a different supply chain configuration and involves varying trade-offs for farmers and processors. (1) A supply chain with no circularity, that is, the traditional linear business model. In this case, agricultural by-products generated in the processing stages (e.g., grape seeds, skins, and pomace for a winery) are considered solely as wastes and of no value to the processor. The production decision and payoff are characterised for the processor and farmers, considering consumers' purchasing behaviours and the resource costs. This serves as a benchmark case.

(2) A closed-loop circular chain, where by-products are recycled and used in the original chain. For example, agricultural by-products are collected and converted into fertiliser for the farmers. The processor needs to decide whether to undertake recycling activities and

initiate a circular supply chain, which requires additional investments and incurs an increased cost.

(3) An open-loop circular chain, in which by-products are recycled, converted, and used in a secondary chain. For example, winery by-products such as grape seeds and pomace can be extracted and used for antioxidants, colourants and dietary fibre (Lavelli, 2021). This involves a separate processor that converts by-products into value-added products as inputs into a secondary chain. Interactions between the two supply chains are modelled regarding the incentives for the primary and by-product processors' participation.

Findings:

We analyse the mechanisms that the processor can use to incentivise farmers to supply waste and participate in CE. From this, we discuss how different factors, such as the waste trading price, product discount, and a certification program for farmers to access a premium market, influence farmers' decisions of joining a closed-loop versus an open-loop circular chain.

Value:

This work compares the three scenarios, analyses the interaction between farmers and the processors, and discusses their incentives to join or build circular supply chains. This provides practical guidance on motivating businesses to construct and enhance circularity. While most existing studies describe the circular supply chain archetypes as closed-loop versus open-loop and prescribe some solutions qualitatively, this work proposes to utilise an analytical modelling approach combined with empirical investigations to conduct a quantitative investigation and provide a framework to enhance participation in alternative circular supply chain archetypes.

Research limitations/implications:

The research implications will be forthcoming after the comparison of the results with prior works.

The nature of the modelling undertaken necessitates assumptions in order to simplify to the point of feasibility. Further research is therefore required to verify the outcomes in a broader, more realistic setting. Alternative methods would provide triangulation of the results and address many of our approaches' shortcomings. Likewise, further work could explore additional constructs and the potential interactions.

Practical implications:

CE requires targeted incentivisation in order to enhance uptake. Open-loop supply chains provide the most common scenario when CE is applied across complex dynamic networks. Drivers and environmental strategic agendas provide a means to connect supply chain actors via circular economy principles.

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Capabilities and Challenges to Circular Manufacturing Supply Chain Reorganisation Within Geographical Textile Recycling Cluster

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Purpose of this paper:

With the prioritisation of the textile circular economy (CE), textile recycling as a circular manufacturing option has gained prominence. As per recent market studies, the global textile recycling market size is projected to grow from USD 6.08 billion to USD 8.49 billion between 2024 and 2032, exhibiting a CAGR of 4.3%, with a growing dominance of the Asia-Pacific region with a market share of 44.97% (Fortune Business Insight, 2025).

While this provides strong support for the growth of many textile recyclers globally, the industry still remains highly fragmented, unorganised and informal with an increasing number of small-scale actors. Current valorisation potential is hindered by challenges to designing and managing a well-functioning circular manufacturing supply chain (CMSC) that can handle the growing volume of textile waste flows (Hinkka et al., 2023), and its logistics, improve feedstock and process quality through standardization and optimization, and align demand and supply in conjunction with end market needs (Sandberg and Pal, 2024).

At an overall level, CMSCs in the textile recycling industry are global and highly transnational, typically stretching from the global north to the global south, and then, after some type of valorisation (e.g. collection, sorting, recycling, and/or manufacturing), back again to the global north. However, zooming in on the recycling of textile waste and subsequent manufacturing operations, this part of the global supply chain tends to be highly localised or regionalised. In fact, these operations are often conducted in geographically consolidated locations, where related and complementary companies along a value chain of a specific industry sector operate. Such geographical clusters, also referred to as industrial districts or regional agglomerations, are especially beneficial when operations are intrinsically intertwined and surrounded by complex relationships and boundaries, as is the case for textile recycling and the subsequent manufacturing practices. In fact, the existence of geographical clusters is widespread, and the many benefits of clustering are often considered as key aspect for the success of an industry (Schiele, 2008).

A premise of this research is that geographic consolidation plays an important role to design and configure the complex and fragmented textile recycling value chain optimally. In contrast to many other “non-clustered” textile recyclers that are now emerging in for instance a European context, cluster-specific CMSCs are relatively stable and integrated, and involve capabilities that are more established. For instance, in Europe, we see the formation of ReHubs – a partnership-based collaboration hub working to industrially scale textile recycling. However, research attention to geographical clusters in the textile industry in the context of CE is sparse, except, e.g. Bressanelli et al. (2022) exploring the functioning of the industrial district of Prato in Italy, well-known for wool recycling, and how the role of supply chain structure and relationships evolved within.

In light of these shortcomings, the purpose of this paper is to explore the capabilities and underlying challenges of firms embedded in multi-tier supply chains of geographical textile recycling clusters and how these circular manufacturing supply chains reorganise in evolving clusters.

Design/methodology/approach:

A case study approach is employed to explore how a textile recycling cluster in the Panipat region of India has reorganised, what the underlying capabilities of the CMSC actors are to support this reorganisation, and what challenges they face. Panipat is one of world's largest geographical cluster in textile recycling (Arisa & Sympany, 2022) and is also known as the "cast-off capital" due to being the global centre for recycling textiles. Through a complex network of companies, acting along the CMSC, textile waste is valorised into new textile products. Customers of these products exist in India, but also internationally in the US and European markets.

Data was collected from October 2021 onwards, starting with nine semi-structured interviews to understand the competitive positioning of the different actors (sorters, traders, recyclers and recycled textile producers), their operations, and underlying challenges and capabilities. In conjunction, field visits (to 8 companies) were organised in March/April 2022 and February 2023. Field notes were taken to document the processes, conditions, and work practices. During each visit, we discussed with the CEO or any other top management personnel the general situation in the cluster, in terms of competitiveness, relationships and strategies, retrospectively as well as the current situation and future directions. A workshop was also conducted in February 2023 that was participated by 6 textile recyclers from Panipat cluster, represented by the top management (mainly owners/CEOs), to jointly discuss not only their own firm's competitiveness, i.e. firm-level challenges and strategies, but rather cluster-level development in terms of status quo of challenges and strategies and *quo vadis*. To further clarify and confirm our understanding revealed through the interviews, two additional interviews and discussions were conducted in 2024. Secondary documents, such as Arisa & Sympany (2022) were sources of additional information.

Data was analysed in two steps: first, inductively to identify the supply chain capabilities of the CMSC actors, along with the key challenges they face. In second step, with an objective to understand the supply chain capabilities underpinning the cluster reorganization enforcing its evolutionary fitness, we analyzed the data from the perspective of structural and relational characteristics of supply chains in geographical clusters, such as aspects of integration, control and power issues, flexibility, and knowledge assimilation, cooperation and coordination mechanisms etc. (in line with Bressanelli et al., 2022). Within the cluster, while our level of analysis was each tier of the CMSC, the unit of analysis was each firm in the tier. Our study can be considered as a partial replication study; following an approach drawing similarities to that of in Bressanelli et al. (2022).

Findings:

The first level of findings was in terms of the supply chain capabilities of the value chain actors, and what challenges are faced by them. In total 12 supply chain challenges were revealed in the 3-tier CMSC, of which 5 were observed in more than one tier. These challenges were related to lack of market orientation, lack of supply chain visibility and inherent fraudulent practices, and lack of finances. In addition, external factors like legislation posed an impending threat as well. Other, lesser prioritised challenges were mainly related to waste quality and lack of formalised supply chain practices. In total 11 supply chain capabilities were revealed in the 3-tier CMSC, of which 3 were observed in all tiers while 6 in more than two tiers. These capabilities were related to supply chain orchestration to meet large order demands, adopting flexible payment terms, financial risk taking, and knowledge integration. In addition, the capability to understand market demand by adopting formal approaches aided some sorters and recyclers in setting the right price points and finding a market for all waste fractions.

We also reveal that some of these emerging supply chain capabilities have led to the transformation of the Panipat cluster's structural and relational characteristics overall. While previously, the cluster functioned in a decentralised way with a fragmented structure dominated by smaller recyclers (as it currently exists in the "non-clustered" textile

recycling industry), it has, in recent years, verticalized, where larger actors have integrated their operations across tiers, e.g. recyclers also becoming sorters and yarn producers. With higher degree of consolidation, we also notice higher degrees of orchestration roles, such as trading agents acting as waste aggregators to offer flexible supply chain linkages. Knowledge assimilation mechanisms have also become more formalised. In terms of relational characteristics, cooperative norms have transformed from being predominantly based on opportunism-led to that of mutual trust, commitment and long-term (contractual) agreements. High degrees of information and knowledge-based integration have also enabled improved collaborations and coordination among the CMSC actors in the cluster.

Value:

The emergence of CMSC capabilities seems to foster and strengthen the CE-driven reorganisation of the geographical clusters as identified in this study. It is clear that proximity matters, and cluster approach is one way to valorise from proximity advantages. Together with the CE-driven intent to find new valorisation opportunities, proximity enables geographical clusters act as a promising environment for CE transition (Bressanelli et al., 2022). Our study also highlights emergence of orchestrating role of certain “hub firms” in order to coordinate the transition to CE practices (Sandberg, 2023). This intensifies contacts and knowledge-based integration, coordination, and adoption of relational assets etc., as were observed in the evolving Panipat textile recycling cluster, that may foster and facilitate the transition towards a CE. In light of this, we argue that geographic clusters offer a better context to embed CMSCs and support their emergence.

Practical implications:

The global textile recycling industry is still relatively small and in a developmental phase; it is fragmented, with an increasing number of small-scale actors. By drawing upon the inferences on how proximity and geographic consolidation can offer structural and relational characteristics for reorganisation of CMSCs to develop optimally, this study can aid textile recycling in increasing revenue generation and market share, thus achieving industrial resilience in the circular textile economy.

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A Network Analysis of Circular Bioeconomy Business Models

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Purpose of this paper:

The circular bioeconomy is seen as a key driver for sustainable development due to its focus on environmental, social and economic challenges (Salvador et al., 2020). As the circular bioeconomy grows conceptually and in practice, it is crucial to explore and understand the business models that underpin its success, as well as the relationship between these business models and the wider circular bioeconomy ecosystem. The term business model is used to describe value creation, value proposition, and value delivery to value capture, including roles and relationships of actors within a firm and beyond (Donner and De Vries, 2023). Relationships amongst supply chain and ecosystem actors is a key mediator of value for sustainable circular business model transformation (Parida et al., 2019). There is currently limited understanding of sustainable circular business models types or the relationships of actors involved (Snihur and Bocken, 2022), particularly in the bioeconomy. This study therefore aims to review circular bioeconomy business models and network theory, and on this basis critique emerging business model typologies in the circular bioeconomy focusing on the Irish food system. By mapping out these business model types, examining their underlying drivers and constraints and the roles and relationships of actors involved, we aim to provide a deeper understanding of how these models contribute to the operationalisation of circular bioeconomy principles.

Design:

This study employs a qualitative, integrative literature review methodology to explore the intersection of circular bioeconomy (CBE) business models and network theory, with a specific focus on the Irish food system. A search of peer-reviewed academic literature and policy reports was undertaken using databases such as Scopus, Web of Science, and Google Scholar. This review identified key studies such as Snihur and Bocken (2022) who provide a useful organising framework addressing unit of analysis (firm focused or ecosystem focused, i.e. business model innovation or ecosystem innovation) and value emphasis (economic only or economic plus social and environmental, i.e. sustainable business model innovation or sustainable ecosystem innovation). Recent work on food systems has also highlighted the evolution from a linear business model focus to a broader appreciation of the role of business ecosystems (Halberg and Westhoek, 2019). Donner and de Vries (2023) develop a food business model (BM) typology based on key characteristics, main sustainability dimensions and role in the food system. They develop an analytical tool, a game approach, based on seven building blocks (players, playing field, pieces, moves, rules, time and outcomes). Application of this tool provides particular insight into food ecosystems including, actors and roles, boundary spanning activity/scope, resource efficiency, dynamics and governance. This and other tools are required to support research approaches that enhance understanding of how diverse internal and external interactions and strategies between actors impact on the evolution of circular bioeconomy business models and systems. Drawing on this research, this paper is theoretically grounded in strategic management and network theory, and employs an industrial ecology approach with a particular focus on food systems.

Findings:

The initial phase review of literature has focused on the conceptualisation of sustainable business model development in the context of the broader ecosystem. Initial findings underscore the significance of network analysis in identifying and examining the connections between business model innovation and business ecosystems. While the business model links to customers, suppliers and other 'complementors' (Zott et al. 2011), the business ecosystem is constituted by many additional interdependencies. Consequently, applying network analysis in sustainable business module innovation research could provide valuable insights into how various ecosystem actors collaboratively contribute to the co-development of a value proposition (Laasch, 2019). This approach conceptualises a business model as a boundary-spanning activity system (Zott and Amit, 2010) which spurs firms to broaden their networks and develop new network ties (Oskam, et al., 2018). Tapping into new technologies, knowledge and markets in other industries/sectors is often fundamental to the development of more sustainable products and services (Williamsson and Schaad, 2018). This reflects the recognition that it is not only (sustainable) business models that evolve but by extension (sustainable) business ecosystems evolve. These findings suggest that incorporating network analysis in sustainable business model research offers a useful approach to investigate the conditions that support circular business model development in the bioeconomy.

Value:

This paper provides a novel focus on the bioeconomy, a crucial yet underexplored aspect in the circular business model literature. A focus on the bioeconomy also has a particular practical value for crucial sectors such as food which will rely on bio-based innovations to protect and ensure food safety but also food security. A literature review establishes the usefulness of a network theory lens when investigating key business innovation ecosystem elements and characteristics such as actors and roles, boundary spanning activity/scope, resource efficiency, dynamics and governance. This approach provides analytical frameworks (such as Actor Bonds, Activity Link, Resource Ties) to critique emerging typologies which aim to identify scalability strategies and adapt business models to foster sustainable growth. This provides the basis for the development of a novel bioeconomy typology as a key tool in theoretical advancement, as typologies form the organising framework for understanding previous research while setting the foundation for addressing new research questions in the field. Therefore, this paper will be of value to those carrying out future research on sustainable business models and in the circular bioeconomy. This typology will enable businesses to better understand their position within an ecosystem, optimise their network interactions, and develop strategies for sustainable value creation, capture, and delivery. By leveraging these tools, companies can enhance their innovation capabilities, ultimately contributing to the growth and sustainability of the bioeconomy.

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Transforming Plant Protein Value Chains: Socio-Technical Innovations in Transition Pathways

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Purpose of this paper:

The transition towards a sustainable food system requires innovation, however innovative niche development faces challenges, including resistance from established regimes and market structures (Schot and Kanger, 2018; Geels, 2024). While policy can encourage niche emergence and development (Schot and Geels, 2008; Manning, 2022), its practical impact, particularly regarding supply-side strategies focusing on R&D investment (Manning, 2022), remains underexplored (Haddad and Bergek, 2023; Gaitán-Cremaschi, Valbuena and Klerkx, 2024). This knowledge gap is particularly evident within complex food systems (Engels et al., 2024), where understanding the interplay between niches and the broader socio-technical context is essential. This study analyses the sequence of patterns within transition pathways, particularly focusing on the supply-side policy interventions that shape the development of plant-based protein niches within the wider food system. Understanding the dynamics of plant-based protein value chain development within this specific context is necessary to informing policy and strategic interventions aimed at developing a more sustainable and resilient food system. The study aims to contribute to understanding how transition pathways to more sustainable food systems are constructed and provide insights into unfolding pathways and informs the design of future support measures.

Design/methodology/approach:

This study adopts a multi-stakeholder perspective to identify pathways for the transition to plant-based of plant protein value chains in Ireland, examining how innovation systems can be effectively integrated to facilitate their development. Given the nature of the problem, the Multi-level Perspective (MLP) (Geels, 2024) was adopted. This framework positions actors at the centre of the food systems, recognising that the roles and interactions of stakeholder's key in shaping the system's outcomes. Grounded in socio-technical theory, the (MLP) lens allows for a comprehensive analysis of how innovation systems influence plant protein value chain development.

A study design based on three phases was adopted: (i) Value Chain Analysis, (ii) Interdisciplinary workshops, (iii) depth interviews. Value Chain analysis adopted a co-design methodology. A detailed value chain map, based on comprehensive desk research, was used in a codesign workshop involving 28 actors from different stages of the value chain within the cereal industry in Ireland. Workshop sessions sense-checked the value chain map and identified key development challenges and opportunities. Two interdisciplinary workshops were held with researchers active in plant-based protein development projects across a range of disciplines. The first workshop identified a range of crops and technological approaches being explored to develop sustainable plant-based proteins. The second workshop addressed guiding policies and impact pathways. These workshops identified key innovations pursued. These were mapped against the opportunities and challenges identified in the value chain co-design workshop. Phase three adopts the MLP framework and utilises semi-structured interviews with key innovation actors to examine the roles and interactions of niche and regime actors (as defined by MLP).

Findings:

Insights from the stakeholder workshop indicate that public R&D investments are a key driver of innovation within these niches. However, challenges persist in the dynamics of niche development. Specifically, limited processing infrastructure and difficulties in meeting processing specifications due to crop quality and quantity issues have been identified as key barriers. Despite growing consumer demand for plant-based foods, Irish producers struggle to build value chains that substitute imports. Ongoing data collection, through semi-structured interviews with key niche innovation actors, aims to elucidate how innovative actors interact to address these challenges and contribute to the promotion of sustainable plant protein value chains in Ireland. While phase three data collection is ongoing, preliminary findings suggest that supply-side policy interventions influence plant protein niche development in Ireland. Specific mechanisms (i.e. network formation, learning, and power) are identified that supporting or constrain the development of sustainable plant protein value chains.

Value:

The study contributes to existing literature by enhancing our understanding that transition pathways are constructed from a sequence of patterns. The codesign methodology adopts an inclusive approach that leverages divergent views and experiences, which supports the emergence of pathways. The study highlights how the identified pathways are unfolding and informs policy and strategic measures to support sustainable food system transformations. Focusing on scalable, equitable, and actionable transition pathways, this research aims to inform policy and guide industry practices to adopt food systems that are resilient, equitable, and capable of supplying a growing global population while minimising ecological footprints. Ultimately, the research contributes to building a food system that supports long-term planetary health and the well-being of future generations.

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Coordinating Closed-Loop Supply Chains Considering Dynamic-Related Costs with Game Theoretic Analysis and Contract Design

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Purpose of this paper:

The operations of closed-loop supply chains (CLSC) are well-established as being important for the sustainable development of businesses, however the different stakeholders involved in the CLSC operations have diverse targets. Overall, this can decrease the overall effectiveness of CLSC, and may hinder business in achieving sustainability. The independent objectives of various stakeholders may lead overall to an irrationality in strategic activities, leading to a reduction in recycling volumes, alongside a lessening of the total supply chain profits as well. To solving this problem, multiple studies have proposed strategies for CLSC coordination. For example, different contracts are designed to deal with various conditions: two-part tariff contracts are designed to coordinate CLSC when parallel supply chain structures are considered (Choi et al., 2013), while revenue sharing contracts are designed to coordinate CLSC when both profits and social responsibility are regarded as important factors of supply chain performance (Panda, 2014). However, there are few studies considering the influence of CLSC dynamics when coordinating stakeholders. Such an ignorance can make the coordination strategies suboptimal, failing to inform managers appropriate practices in CLSC operations. To address this important issue, this paper aims to solve the following research question: when the supply chain costs influenced by CLSC dynamics are considered, how can the stakeholders in CLSC be coordinated to maximise the overall supply chain profits?

Design/methodology/approach:

We adopt a game theoretic approach to study strategic CLSC behaviours by including the cost of CLSC dynamics in operational processes. Specifically, we consider a CLSC with a manufacturer, a third-party remanufacturer, and a customer market which can be fulfilled by the new and remanufactured products indifferently. From a coordination perspective, we study the system from decentralised and centralised modes. The former means the manufacturer and the remanufacturer have different market power and move as two individual Stackelberg game players. The latter represents the supply chain that makes decisions as a whole. After solving the models from decentralised and centralised perspectives, the optimal decisions under the two modes are compared to check the difference between return rates and between profits. Finally, a cost-sharing contract is designed to coordinate the supply chain by considering the dynamic related cost of CLSC to improve the total profits.

Findings:

We obtain the following findings. First, under the decentralised mode, the optimal return rate is positively associated with the mean demand of customers and manufacturing cost, but negatively associated with the demand variance, unit cost of inventory variance, return variance, and order variance, as well as the absolute value of the difference between manufacturing and remanufacturing lead time. The optimal remanufacturing price is positively associated with manufacturing cost, but can have complex connections with other parameters. Second, under the centralised mode, the directions of parameter influence on the optimal return rate are the same as those under the decentralised mode, but we found that the value of the return rate and supply chain total profit under the centralised mode are both higher than those under the decentralised mode. This may mean that the decentralised mode is less sustainable and economical than the centralised mode.

Therefore, to achieve the centralised mode, we developed a cost-sharing contract to coordinate the CLSC. Different from previous literature, the cost we shared here is the dynamic-related cost.

Research implications:

To the best of our knowledge, this is the first paper linking CLSC dynamics and operational parameters to return rate optimisation and CLSC coordination. The theoretical contributions of this paper are to enrich the CLSC coordination literature by adding the considerations of supply chain dynamics and the design of a new contract type.

Practical implications:

Our paper demonstrates the importance of carefully considering CLSC dynamics and coordination, emphasising the enhancement of both inventory and production management practices from a supply chain coordination perspective. The findings highlight the benefits of partnerships and strategic alliances within supply chains to enhance the overall sustainability of CLSCs.

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Turning the Tide: Strategic and Institutional Enablers for Circular Supply Chains in the Blue Economy of Bangladesh

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Purpose of this paper:

We aim to understand the challenges of developing a circular supply chain ecosystem where waste fishing gears have been transformed into new business opportunities (new marketable products). About 12 million tonnes of plastic end up in the oceans every year, with abandoned, lost or discarded fishing gear [also known as "ghost gear"] inadvertently killing a significant variety of marine wildlife. It can be envisaged that most of the blue economy sectors (out of 26) in Bangladesh will be impacted due to this. So, first, we aim to understand the motivations, challenges, and success factors for designing a circular supply chain for these discarded fishing gears (plastic/metals) and thus showing the path towards creating a circular blue economy for Bangladesh. Afterwards, drawing on the combination of Resource-based view (RBV) and Institutional theory, we further go in-depth analysis to identify the internal capabilities, institutional enablers, and strategic resources necessary to transform discarded fishing gear into circular business opportunities in the coastal economy of Bangladesh. Doing so, we ask an overarching research question- What are the critical factors for developing circular business model (s) for blue economy sectors of Bangladesh? We also ask two sub research questions: i) What are the motivations, challenges, and success factors for designing circular supply chain network in fishing gear supply chain ii) How the combination of internal resources and institutional pressure drives the circular supply chain practices in fishing gear supply chain?

Design/methodology/approach:

This research uses a qualitative method for research design. Primary data was collected by focus group discussion followed by interviews with variety of Stakeholder groups in Bangladesh maritime sector. Snowballing sampling technique has been applied. Data analysis was done by using NVivo. Secondary data was also collected from government reports, company reports, UN reports, etc and was analysed using the content analysis technique.

Findings:

Preliminary result shows that circular strategies could generate sustainable business opportunities focused on marine plastic waste solutions through informed, innovative and collaborative efforts, for the benefit of enterprises, local economies, and the environment.

We found some critical factors for implementing circular business models in blue economy as below-

I. Policy & Regulation

- Legislative framework & enforcement
- Standards & certification for recycled/refurbished/remanufactured products

II. Economic & Financial

- Economic incentives (subsidies, EPR fees)

- Market demand & price stability for recycled gear including refurbished/remanufactured
- Financial viability & return on investment

III. Infrastructure & Logistics

- Collection systems & logistics efficiency
- Processing facilities & capacity (refurbishing, remanufacturing, recycling)
- Gear design for recyclability (modular, cleanable)

IV. Technical & Innovation

- Innovation in recycling technology & materials
- Traceability & data systems (e.g., FAIR data)

V. Stakeholder Collaboration & Culture

- Multi-stakeholder coordination (public private)
- Awareness & cultural acceptance among fishers/public

VI. Skills & Knowledge

- Training & technical competency
- Research & development capacity

We propose the theoretical framework based on the findings which demonstrates the interactions among variables that drive circular supply chain activities in circular fishing gear supply chain:

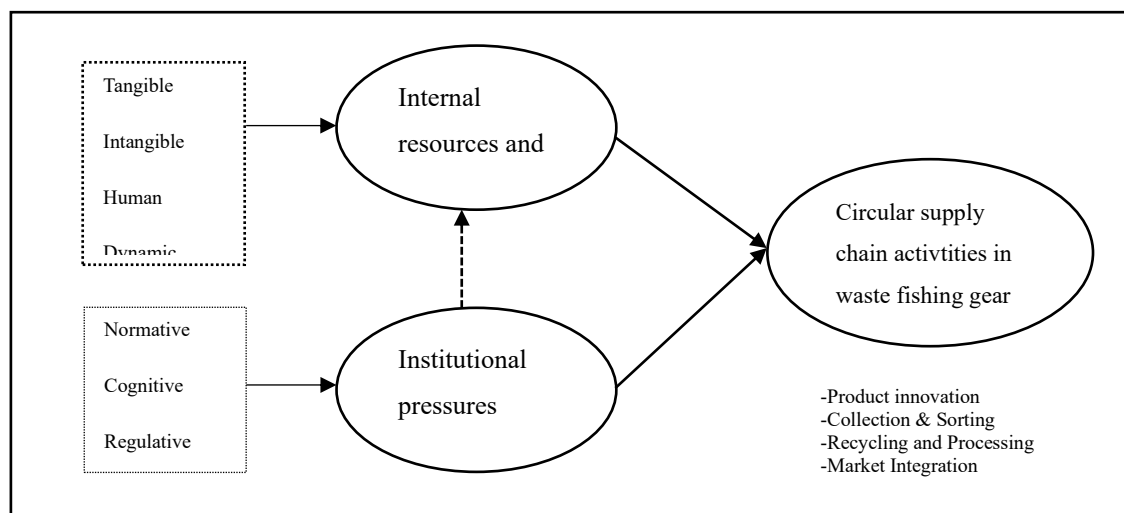


Figure 1: Conceptual model for circular fishing gear supply chain using combined RBV and institutional theory lens

Value:

Most studies on the circular economy (CE) in fisheries focus on Europe or high-income countries. There's little empirical work rooted in Global South contexts, particularly on how CE applies to marine plastic from ghost gear. There is no endeavour of finding circular supply chain solutions for waste fishing gears in the context of Bangladesh as well. Development of a conceptual framework or model for a circular supply chain ecosystem that addresses low-resource settings—integrating informal collectors, digital traceability, and localised manufacturing/reuse systems. Policy makers may benefit from this research while crafting environmental regulations, developing relevant industrial infrastructure and modifying economic policy.

Research limitations/implications:

This research is a preliminary work for finding challenges and circular strategies, which are limited to fishing gear only. Including all types of wastes and designing a holistic supply chain network would be beneficial.

Practical implications:

Government, NGO's, and local government authorities may benefit from the outcome of this research while crafting policy for circular initiatives. Plastic industry stakeholders such as recyclers may grab newly created business opportunities. Further, reduced plastic pollution will increase the health outcomes of the local inhabitants of the coastal areas in Bangladesh.

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Comparative Analysis of Returnable Asset Management Practices in the UK Dairy Industry

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Purpose of this Paper:

There is increasing pressure amongst supply chain actors to deliver items which are faster, better and cheaper and at the same time reduce emissions and waste. Although this can be achieved by adopting a range of strategies, using Returnable Transport Items (RTI) is becoming a popular way of reducing waste and is an alternative to traditional single use packaging. Typical RTI include items such as roll cages, barrels, pallets, reusable trays, refillable containers, engine stillages to name a few. Supply Chains that use RTIs are also called closed loop supply chain as they consider the return flow of used materials in addition to the downstream flow of products (e.g. Mishra et al., 2023). Typically, the supplier loads the RTI with goods to the customer and once consumed the customer returns the empty asset back to the supplier. Once received, these may be cleaned, tested, and repaired by the customer or by the supplier. Various configurations exist in the return flow of RTIs—for example, an intermediary may collect used items on behalf of the supplier and return them after cleaning and inspection, or a milk-run approach may be employed, whereby the supplier collects empties from multiple customer sites. Regardless of these variations, effective RTI management remains critical for controlling logistics costs and ensuring operational efficiency. As one expert claims “*Without adequate container management your container assets may just be the most expensive one-trip packaging you can buy*”(Maleki and Reimchi 2011). Hellström & Johansson (2010) highlight three main types of control strategies for RTI systems – switch-pool system, transfer system and depot system. Glock (2017) undertook a systematic literature review on Returnable Asset Items and identified only 33 papers, with the majority published by mainstream publications, which clearly indicates the need for further research. They found the research on the management of RTI closed-loop supply chains can be differentiated into four content categories.

1. Studies that compare alternative packaging systems
2. RTI forecasting with respect to time and quantity
3. Studies that determine the purchasing of new RTIs
4. Management of RTI systems.

Although prior research on RTI systems has predominantly centred on analytical and simulation-based decision support models (Glock, 2017), there remains a notable lack of empirical studies examining how control strategies are applied in practice. Specifically, little is understood about how different organisational approaches to forecasting, asset tracking, and accountability influence RTI loss rates and operational efficiency in industries where RTIs are integral to the supply chain.

In the UK, fresh milk is delivered directly to stores (supermarkets & smaller retail shops) in small metal roll cages (tets, tetrainers, dollies, roll cages). For this paper they will be referred to as tets. The tets are owned individually by the dairy companies, delivered full of milk & collected when empty by delivery drivers. Hence following the ‘transfer system’ as identified by Hellström & Johansson (2010). Broadly this follows the closed loop supply chain (CLSC) as described in Bottan and Castella (2018).

Research Aims:

This paper aims to examine the way RTI flows are managed in the UK dairy industry with a focus towards forecasting tet returns, equipment tracking and management of equipment

loss. While exploring methods used across the industry, the paper primarily focuses on two larger dairy processors (referred to as 'Dairy A' and 'Dairy B') and one smaller processor ('Dairy C'). Together, these dairies hold the majority market share in the UK, making them representative of the industry. Recommendations will also be made for

Design, Methodology and Approach:

Case study methodology has been adopted due to the exploratory nature of research and the need for gaining in-depth understanding about the tets management practices (Yin, 2018). Interviews with returnable asset managers was conducted and quantitative data (where possible) such as volume of tets, cycle time etc were gathered from company's internal systems.

Findings:

The volume of tets handled is very high across all the dairies. Dairy A packs circa 24,000 tets per day across 4 production plants. Distribution is made either direct from the dairy to supermarket, or via 3 RDCs.(Regional Distribution Centres – operated by Dairy A or its distribution partners). Dairy B is also large milk processor with 5 fresh milk processing sites & 4 distribution centres. They deliver to main brand supermarkets but also a high number of middle ground stores. Although the exact volume is not known, it is expected that the volume will be very similar to Dairy A. Dairy 'C' is a small milk processor with two major retailers as its sole customers and deliver directly to retailers. It packs around 500 tets of milk per day. It has a small fleet of 3000 roll cages.

Management of Returnable Assets

Although the three companies adopts the 'transfer system' as RTI control strategy, they adopt a distinct approach to managing empty tet forecasting, equipment purchases although they face similar challenges.

Dairy 'A' spends a considerable time with spreadsheets & calculations to identify equipment flows uses live and historical data for accurate forecasting, leading to lower tet losses. They also purchase high quality steel cages with a life span of 15 years.

In contrast, Dairy B relies on daily averages (E.g. using last week day's tet return data) for forecasting. They use cheaper tets and also spend less time and resource on the entire RTI asset management. This results in higher loss rates when compared to Dairy A.

Dairy C lacks forecasting tools and depends on chance for tet availability and serve only two retail customers. Their operations are less complex when compared to Dairy A and B. From an asset management they are efficient with minimal loss. It is mainly due to less complexity. All the three dairies reported loss in roll cages mainly due to misplacement, theft, and industry crossover, with Dairy A reporting the least loss. Additionally, fluctuations in demand caused by weather, production breakdowns, and transport delays create challenges in maintaining the right roll cage availability.

Value:

This research uncovered some contrasting practices amongst three Dairy companies in the UK. It is evident that adopting a scientific approach (Data driven decision making) towards the management of returnable assets will reduce overall loss of steel cages resulting in better profit margin. Adopting a low-cost approach still works but the environmental costs may outweigh the savings made by investing fewer resources. The findings of this research will be beneficial for improving the returnable asset management practices and it can serve as a foundation for other industries which operate closed loop supply chains.

Research Limitations:

Data gathering was primarily through conversations with key stakeholders. Although some numerical data were obtained, many insights reflect managerial perspectives, which may not fully capture ground-level realities or the views of retailers.

Practical Implications:

The findings of this paper will be useful for all closed-loop supply chain professionals, as the insights provided can be adopted in other industries.

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Circular Supply Chain Design for Electronic Livestock Ear Tags

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Purpose of this paper:

The increasing amounts of waste of electronic equipment is a major challenge globally. Circular approaches for electronics are needed to increase reuse, recycling and remanufacturing of components and materials. There are several major barriers for creating circular supply chains for electronics. For instance, large amounts of products containing electronics are imported from Asia to Europe. The circular loops from the end of life phase back to product design and sourcing of raw materials are missing due to that traditional linear supply chains still dominate the global electronics industry.

Within livestock farming the new EU animal health law sets new requirements for tracking of animals such as sheep and lambs. This implies an expected significant market potential for tracking technologies, such as smart ear tags. A European start-up company, RTID, has invented a new type of tag for this purpose, with the aim to provide a competitive solution for livestock management in countries across the world. Ear tags marked with unique identification numbers have been required by law in many European countries and are applied also outside Europe. However, electronic tags are still more expensive for farmers compared to traditional plastic tags that are widely implemented in livestock management practices. In order to reduce the cost and environmental footprint, RTID seeks to reuse the ear tag electronics by establishing a circular supply chain.

There is still a general lack of empirical research dealing with circular supply chain design considering real-world scenarios (Islam and Huda, 2018; MahmoudGonbadi et al., 2021). In addition, there is a need for more research on the application of simulation modelling techniques to predict system behaviour in these often complex supply chains (Lahane et al., 2020). The purpose of this research is to contribute with new knowledge regarding how a new circular supply chain can be designed, supported by simulation, and provide empirical insights to a real-life case of a closed-loop supply chain and its environment.

Design/methodology/approach:

Research is carried out to design and develop a new circular supply chain for the new electronic ear tag, as part of a three-year research and innovation project with the objective to develop a new production line, as well as a circular supply chain. In this paper, the design of the circular supply chain constitutes the main focus.

A combination of research methods are used to develop the new circular supply chain. The single case study focusing on RTID contributes with detailed insights to empirical conditions and the specific company setting. Data are collected from actors in the supply chain including the case company, slaughterhouses, and farmers. Data include tagging routines, expected volumes, the frequency of lost tags throughout the tag's life cycle, processes for collecting animals, registration procedures and preferred systems for returning used tags. Interviews and field visits are carried out. Graphical illustrations of the supply chain are made to establish a common understanding of various concepts among the project team members, including researchers and practitioners. A simulation model of the circular supply chain, including relevant actors, expected volumes, failure rates and lost tag frequencies, is developed to analyse design scenarios in more detail. Design changes to main components as well as the casing of the main product are investigated with respect to improved reuse capabilities.

Findings:

The investigated case supply chain is considered to be especially suitable for adopting circular strategies, mainly due to the “closed-loop” approach, where large volumes of RTID tags are collected at slaughterhouses and can be easily separated from other ear tags on the market and returned to RTID for disassembly and re-manufacturing. Farmers may also collect and return used and unused tags gathered at the farm. Slaughterhouses and farmers play a key role for ensuring high volume take back.

Results show major opportunities for reuse, especially of the electronics (PCB), that may reduce costs, and open for cheaper tags. Moreover, the product has a simple structure with few components and materials, and slaughterhouses can easily collect tags. Plastics may also be recycled. A large part of the total sales volumes of tags is expected to be returned after use for disassembly and electronics reuse. Entire ear tags may further be reused for other purposes in industrial settings, military or in livestock farming. A new regional logistics concept further enables marking and distribution of tags to farmers in various regional markets, as well as take-back and disassembly of tags. The research also reveals major challenges related to product design and design for disassembly, unique identification numbers of tags that hinders reuse of tags as identification tags, practical issues related to handling and sorting of used tags and quality assurance challenges.

In addition to case specific opportunities and challenges, results show how a circular supply chain can be developed based on evaluation of various conceptual design alternatives, and a simulation model for more detailed analysis of scenarios.

Value:

The paper illustrates the design of a real-life case of a circular supply chain that is being developed for electronic ear tags. This adds to the limited previous empirical research on circular supply chain design based on data from real-life environments. The case provides in-depth insights to how a circular supply chain can be designed in the specific context of a manufacturer of electronic ear tags.

Many circular initiatives struggle to be sustainable, both economically and environmentally, and are often left with the challenge to make actors in the return-value-chain prioritise investments in modern technologies optimal for the task at hand. For the case company, there are several feasible circular supply chain scenarios depending on the scope selected i.e. a global scope with a worldwide network, a national scope and a regional/local scope. The case supports the EU policy of bringing more manufacturing back to Europe, and to reduce dependencies on Asian manufacturers. The case may serve as an example for other manufacturing companies in different industries.

Research limitations/implications:

This research is based on a single case, which limits the direct applicability of results across contexts. However, results may still be relevant for other companies, especially in electronics industries and start-up settings.

Since the case is a start-up company establishing an entirely new supply chain, findings are based on data mainly representing planned and forecasted scenarios. This implies that the concepts and models developed need to be further tested for validation. Also, the newly designed product might be improved over the next years to be even more suited for circularity.

Practical implications:

The design activities are primarily expected to be directly useful for the case company, providing valuable input to the decision process of selecting a proper circular supply chain design. Other manufacturing companies may find this research useful as an illustrative example of how to develop circular supply chains in their own environment. The case

explores how circular strategies can be integrated as part of the development of the linear supply chain, and may help managers in their efforts with supply chain design.

Future research directions include:

- The products can be re-designed several times to improve recycling capabilities through 'design for X' initiatives going forward.
- The most optimal partners for a new reverse value chain should be identified.
- Rechargeable small batteries can be a future technology for these types of situations, eliminating need for replacement.
- Alternatives to today's laser-engraving of ID numbers might ease direct reuse.

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Sustainable Procurement of Returnable Transport Items in Temperature-Controlled Logistics: Enablers and Challenges

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Purpose of this paper:

Using Returnable Transport Items (RTIs), e.g., reusable pallets, barrels or containers, in logistics promotes a closed-loop system in the Circular Economy and minimises single-use packaging and waste. Robust reverse logistics processes incorporating innovative technologies, effective processes and enhanced collaboration between various stakeholders are key to a successful RTI application (Schneikart et al. 2024). Furthermore, designing reusable packaging, such as containers, for reliability and durability, ease of maintenance and repair, standardisation and compatibility (Bocken et al. 2016) can at the same time enhance sustainability and reduce logistics costs. A sustainable and effective RTI design helps businesses to achieve sustainable procurement, a proactive and responsible commitment shared with suppliers on social, environmental and economic sustainability. In this study, we aim to determine the system factors related to sustainable procurement that influence the design and operations of secondary/tertiary returnable packaging that safeguards products during deliveries and returns them for replenishment and transportation. The focus is on temperature-controlled logistics in the pharmaceutical sector that has strict regulatory compliance, specialised active/passive systems and innovative packaging.

Design/methodology/approach:

The analysis follows the framework presented by Bradley and Corsini (2023). It focuses on complex interactions between environmental, economic, social and technical aspects that impact the sustainability of reusable packaging systems. A combined deductive-inductive method was adopted, including a review of academic literature, interrogation of companies' websites and a single case study 'deep dive' to explore the interconnections between sustainable procurement, reusable packaging, and the Circular Economy for temperature-controlled pharmaceutical logistics. Two managers from the global supply chain and global operations departments of an international company renting out RTIs participated in semi-structured interviews to explore further the key principles of sustainable procurement practices.

Findings:

The exploratory research identifies key features influencing sustainable procurement based on environmental, social and economic aspects. The inclusion of sustainability criteria in the supplier selection process aligns the responsible procurement and business strategies to create a sustainable supply chain. Every strategic sourcing activity, e.g., development, prototyping, manufacturing and end-of-life, incorporates sustainability considerations.

The compliance, current environmental legislation and accreditation form the basis of all procurement activities. Suppliers must share the commitment to respecting and promoting human rights, including but not limited to the UN principles. Other strategic sourcing steps include a sustainability questionnaire, ensuring supplier expertise while prioritising local suppliers to support the community and maintain supply chain control, ISO/viability

compliance, location of the source, technical acceptance and commercial proposition, such as price, terms and lead time.

Furthermore, by connecting the reusable packaging design with sustainable supply chain operations, a design is based on using lightweight materials, maximising container utilisation and evaluating the product lifecycle and recyclability to extend its lifespan. Ongoing R&D activities also focus on using recycled ocean plastic and re-grinding waste plastics for manufacturing. The challenges of customers adopting the returnable temperature-sensitive containers were also explored, and they included initial cost and complexity, logistics and return network and balancing cost and efficiency, where network optimisation is crucial for efficiency.

Value:

This study extends the limited research related to the concept of sustainable procurement for the design of returnable transport items in the pharmaceutical sector in multi-modal transportation settings for national/international deliveries. The research supports the design of sustainable supply chains and business strategies.

Research limitations/implications:

The focus is on temperature-controlled logistics in the pharmaceutical sector with strict safety and quality standards. While the study is on sustainable procurement for product design, raw materials, manufacturing, repair and maintenance, recycling/repurposing & end of life stages, other aspects of the Circular Economy can be investigated further. Also, research into different sectors with unique challenges and regulations can help identify sector-specific factors for future studies.

Practical implications:

The practical implications of this research further encourage innovation in reusable packaging design to support the Circular Economy. Furthermore, an analysis of economic, environmental, and social consequences informs the sector about building a long-term strategy for controlling variables that affect the sustainability of reusable packaging.

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Logistics Implications of a Circular Economy – Incorporating Circular Business Models into Linear Retail Supply Chain Practices

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Purpose of this paper:

For many retailers with an existing linear business model a crucial step towards a circular economy (CE) is to introduce and scale up complementary circular business models (CBMs) that can engage with end consumers and recover consumer-used products. Retailers, positioned in the supply chain next to the consumers, are in a pole position for capturing the value of these products and, ultimately, contribute to the transition from a linear economy to a circular one (e.g. Butt et al., 2024).

A prerequisite for the scaling of CBMs is however appropriate reverse logistics (RL) activities in conjunction with various CBMs, which have shown to be difficult, complex and costly (Mallick et al., 2023; Mishra et al., 2023). For retailers with existing linear business models, there is a need to design and perform RL activities that are harmonised with the current linear practices. Within the logistics system, a diverse set of RL activities must be combined with linear operations that are typically more efficient, standardised and predictable in their nature.

Too often existing research has been isolated to examine RL activities in isolation, without taking into account the existing linear practices. Little is known about how a linear business model is to be complemented with a circular one, and what logistics implications this brings. Hence, this research is guided by the overall question: *What are the logistics implications when linear retail business models are complemented with circular ones?*

Design/methodology/approach:

To complement existing, often conceptually based research on RL, and contextualise findings into the retail sector, this research is based on empirical data (mainly in the form of interviews) at five Swedish retailers and their CBMs. All five retailers have in common strong, profitable linear business models that have, in the recent decade, been complemented with CBMs. Although not their main business (the CBMs represent minor shares of the total turnover in the companies), the companies have gained a rich experience when it comes to the design and management of logistics and supply chain operations in conjunction with the various CBMs.

Investigated CBMs cover various forms of second-hand sales (e.g. online as well as sales via physical store) as well as rental services. Products covered in the empirical data range from fashion clothes, ski equipment, kitchen and home styling products, shoes, bags, watches and children's clothes.

To structure the findings, the paper provides a literature review on the nascent literature stream on CE and RL in the retail industry context. In particular, the main RL activities of collection, sorting, recovery and redistribution are further elaborated in a retail context.

Findings:

The findings elaborate several logistics implications when linear retail business models are complemented with circular ones. Findings are structured around the four main RL activities of collection, sorting, recovery and redistribution.

In conjunction with *collection*, (1) leveraging the existing linear infrastructure, (2) designing the collection processes that should be provided, (3) understanding the "true costs" (i.e. complete costs) that are associated with the collection, and (4) coordinating

linear and circular transports (especially last mile and first mile deliveries) are examples of logistics implications identified.

For *sorting*, (1) developing and embracing adequate sorting capabilities provided existing resources in the form of staff competence are crucial, as well as (2) deciding the location of the sorting. Furthermore, (3) aligning with product and quality standards when sorting, and (4) keeping track of the sorted products for instance through adequate IT system, are also crucial logistics implications.

For *recovery*, (1) new activities and processes must be identified and designed by the retailer, and (2) there is a need to combine linear product-specific knowledge with logistics know-how for making correct recovery decisions. Furthermore, (3) in conjunction with rental services there is a need to ensure availability of spare parts that were previously not required.

For *redistribution*, (1) as for collection, there is a need to utilise existing linear infrastructure such as physical stores as well as processes such as returns management also for redistribution purposes of recovered products. Also, (2) a new sales structure such as pop-up stores, may be utilised for redistribution, which may cause new logistics flows. Finally, (3) an adequate planning and forecasting of sales volumes and related capacities when linear and circular sales are combined needs to be accomplished.

Value:

This research contributes to the emergent stream of literature on logistics and supply chain practices in conjunction with retail CBMs. Based on empirical data at five case companies we provide further insights regarding the actual logistics implications that retailers face when they complement their linear business models with circular ones. This research goes beyond generic, often conceptual existing research on barriers to circular logistics operations, providing more detailed knowledge on logistics implications along the four RL activities of collection, sorting, recovery and redistribution.

Research limitations/implications:

This research is based on five retailers operating mainly in a Swedish and Nordic setting. Future studies should cover other geographical areas.

Practical implications:

The findings demonstrate that the introduction and growth of CBMs require retailers to leverage the existing linear infrastructure. The success of CBMs hinges upon various challenges, such as the recognition of costs, optimisation of transportation, and the management of variability of supply and demand of circular products.

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SMART/DIGITAL CONNECTIVITY IN LOGISTICS AND SUPPLY CHAINS

Blockchain Use Cases for Procurement Under Supply Disruptions

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Purpose of this paper:

One area within supply chain management where blockchain technology (BCT) shows significant potential is the procurement management of limited shelf-life products, such as perishables, healthcare products (e.g., vaccines and pharmaceuticals), and high fashion goods. These products pose challenges as they are susceptible to deterioration over time, rendering them unfit for use beyond a specified period. Therefore, close monitoring of the overall procurement processes, including transportation and intermediate storage, is crucial to avoid any disruptions that can undermine the integrity of the product (Grida and Mostafa, 2023).

The speed and complexity of global supply chain transactions demand novel approaches to handle the inherent dynamics and mitigate the impact of disruptive risks. With the improved transparency, speed, and data security made possible with the permission-based blockchain platform for the supply chain, BCT-driven practices offer a compelling approach to effectively manage interactive procurement processes for limited shelf-life products (Chang *et al.*, 2021).

This research explores the permission-based blockchain system's effectiveness in addressing the challenges associated with procuring limited shelf-life products under supply-side disruptions. According to the US National Institutes of Health, blood platelets can only be stored up to seven days before transfusion (Aubron *et al.*, 2018). Also, the Pfizer-BioNTech COVID-19 vaccine stored in a refrigerator must be used within 10 weeks (Centres for Disease Control and Prevention, 2024). This paper examines how businesses can leverage BCT to improve traceability and mitigate disruptive risks. Further, the paper aims to identify business settings suited for BCT-enabled solutions in achieving transparency and accountability in managing these products.

Design/methodology/approach:

This paper studies a two-tiered supply chain, in which the retailer receives the shipment of a product from an offshore vendor. In the base case, the paper considers single sourcing in which the vendor supplies the retailer with a limited shelf-life product. The product is exposed to supply-side disruptions, which may occur for reasons such as port congestion, raw material shortages, or global health crises. Considering the profound impact of potential delays of the time-sensitive product, the retailer strives to secure sufficient inventory for the selling season.

This research uses the newsvendor approach as the normative model. With no supply disruptions, the retailer expects to receive a regular order shipment before the selling season, which depicts a standard newsvendor setting. With supply disruptions in place, however, the order shipment will be delayed by the length of the disruption duration (exponentially distributed), causing the selling season to be shortened due to the disruption, which occurs as per the Poisson distribution.

This paper proposes the implementation of a blockchain-based process in which the information regarding the transfer of goods is shared between parties in a permission-based blockchain platform, enhancing responsiveness and agility for the businesses impacted by the disruption in the procurement process. In the proposed case, the retailer sets up separate contracts with two independent suppliers (offshore and local suppliers). BCT-based practice will allow information at each transfer point within the procurement

process to be recorded and made transparent to every participant on the permission based blockchain platform, enabling the retailer to properly combine different type of suppliers.

Findings:

Without a proactive measure, disruptions in the procurement process will lead to a stockout situation at the beginning of the selling season, reducing the effective demand for the product. The resulting delay due to the disruption is contingent on the speed of the restoration process to the normal state. The ideal order quantity, in this case, will naturally be proportional to the effective demand and the actual length of the season. Any overstocked quantity due to the disruption will need to be properly accounted for.

In the proposed case, a permission-based blockchain system allows the utilisation of information visibility to manage supply disruptions in procurement. It should be noted that the offshore supplier offers a lower wholesale price but is subject to a long lead time and significant exposure to potential disruptions; the local supplier, on the other hand, offers a higher wholesale price but a shorter lead time with a lower likelihood of disruptions.

The analytical model and the initial results of the numerical experiments show that using a local supplier with blockchain-based practices provides an effective risk-hedging mechanism and protection against stockout situations. Results show that the value of BCT adoption is way more pronounced when supply-side disruptions prevail in the procurement of limited shelf-life products.

Value:

Stakeholders in the supply chain for limited shelf-life products may have different incentives and risk preferences. BCT-enabled procurement practice in the proposed case in this research offers an innovative approach by which businesses can manage risk hedging and improve supply chain performance via information sharing in the permission-based blockchain system.

Most existing research on the procurement of limited shelf-life products presumes demand-side uncertainty. This paper fills the research gap by investigating the effectiveness of blockchain-based procurement practices capable of elevating supply chain performance *under supply disruptions* in addition to the demand-side uncertainty.

Practical implications:

The study of the procurement management of a limited shelf-life product subject to supply disruptions can be readily applied to numerous business situations where supply delays could lead to devastating impacts, as seen in the untimely supplies of COVID-19 vaccines. The use of BCT and smart contracts facilitates the self-execution of procurement processes while enabling information visibility along the shipment process, providing enhanced responsiveness in combining different types of suppliers.

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A Prescriptive Digital Transformation Maturity Model for Food Supply Chains

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Purpose of the paper:

Compared to other types of supply chains, food supply chains (FSCs) are different because of the perishability of the products (Shukla & Jharkharia, 2013), short shelf life, the wide variety of products, and the high frequency of orders (Viet et al., 2020). Understanding this need, food companies have started leveraging Industry 4.0 digital technologies/capabilities to target their business problems with the shift from traditional to digital FSCs by implementing emerging technologies defining the digital transformation process of the FSC (Wang et al., 2024). However, most food companies are still in the early stages of this journey, and the complexity of various Industry 4.0 technologies makes it difficult for businesses to assess their capabilities and determine the extent of their utilisation (Tortorella et al., 2023; Caiado et al., 2021).

The maturity model is a useful means for decision-makers to evaluate the current situation and determine possible guidelines as key components of the future supply chain roadmap at strategic and tactical levels (Reefke & Sundaram, 2018). However, regardless of the topic, most maturity models still lack a prescriptive purpose to utilise the maturity model for improving their maturity levels. This study is built upon the previously established evidence-based digital transformation maturity model, which comprehensively outlines key dimensions and five distinct maturity levels to support the evaluation of digital transformation maturity. To advance this foundation, this study aims to provide a process-based prescriptive framework to guide the development of tailored processes for improving digital transformation maturity in FSCs.

Design/methodology/approach:

This research employs a qualitative methodology, with focal organisations serving as the primary unit of analysis. It is structured into three stages. The first stage draws on insights from previously established evidence-based digital transformation maturity models, summarising key actions to enhance digital transformation maturity within FSC. Building upon these insights, a conceptual flow diagram is developed to provide a structured, step-by-step guide for improving digital transformation maturity in FSCs.

In the second stage, two real-world FSC cases were conducted to utilise the flow diagram based on the evaluation results of the established maturity model. These two food companies were chosen for their distinct characteristics in terms of size and portfolio complexity. Semi-structured interviews were conducted with participants from each case company, who were selected for their expertise in the technological, organisational, and environmental dimensions based on the Technology-Organisation-Environment (TOE) framework. All participants assessed the current digital transformation maturity level, identified areas for improvement, and established target maturity levels. Furthermore, customised improvement guidelines were developed for each case company. Finally, a cross-case analysis was conducted to compare the outcomes, resulting in a unified mechanism that serves as a prescriptive framework to benefit a wider range of users, enabling improvements in digital transformation maturity within their supply chains.

In the validation phase (three), further evidence for the recommendations and actionable guidance was provided on how to improve digital transformation and sustain higher maturity levels. A workshop was conducted with 32 experienced practitioners from the food industry or those who have closely worked with it. Participants were divided into six groups

to discuss improvement strategies and recommendations for sustaining maturity. Key discussion points were documented and transcribed into a PDF file. Finally, the recommendations from both Stage 2 and Stage 3 were summarised, shedding light on the prescriptive maturity model that demonstrates detailed strategies for improving digital transformation in FSCs.

Findings:

Through in-depth case studies and a workshop, a five-step improvement process is developed. The first step starts with understanding value through implementing emerging digital technologies. At this stage, it is crucial to identify where technology-driven value demonstrates its value proposition. Subsequently, a clear vision is essential to justify the need for digital transformation and to define the specific business challenges that must be addressed. A gap analysis is beneficial for effectively aligning innovative solutions with the identified problems. Several prerequisites must be considered. Leadership support is significant, along with a cost-benefit analysis to demonstrate the advantages of digital transformation. Once the necessary preparations are in place, the following key step is to establish relevant key performance indicators (KPIs) to measure the effectiveness of digital transformation initiatives. Furthermore, fostering a digital culture is essential, as it requires active employee engagement and regular training programs to educate internal stakeholders. In the last step, sustaining a higher maturity level requires a thorough understanding of technologies and recognition of their dynamic nature, requiring continuous updates on digital innovations. Beyond understanding, it is essential to ensure that internal stakeholders understand both the present and future implications of these technologies, supported by continuous training to facilitate upskilling. Furthermore, digital transformation must remain a strategic priority, aligning with the organisation's vision to foster commitment to its implementation.

Value:

Building on the established maturity model, this research advances the understanding of digital transformation by developing a prescriptive maturity model. The proposed process-based framework enhances existing maturity models by providing actionable recommendations to guide each step of the improvement process. The research provides a foundation for food companies to systematically upgrade their digital transformation maturity level to reach their objective.

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Digital Twin for Environmental Sustainability

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Purpose of this paper:

Organisations are under growing pressure to reduce environmental impact while maintaining profitability (Sánchez-Flores et al., 2020). In response, manufacturing and logistics firms adopt Industry 4.0 technologies such as IoT, sensors, blockchain, and cloud computing to support green practices (MacCarthy and Ivanov, 2022). Within this context, Digital Twins (DTs), a virtual system that digitally represents elements like firms, processes, or products, have emerged as a key tool offering real-time monitoring, simulation, and analytical capabilities of supply chain operations (Guo and Mantravadi, 2024).

However, despite promising contributions, significant research gaps remain regarding integrating DTs in Operations Management (OM). These gaps include the understanding of DT integration and interoperability across departments and systems, decision-support capabilities, sustainability applications, complexity management, and practical adoption strategies for enhancing future supply chain operations (Dolgui and Ivanov, 2023; Padovano *et al.*, 2024; Werner *et al.*, 2024). Therefore, the study aims to explore how organisations adopt and implement DTs for environmental sustainability by developing a conceptual framework grounded in the Technology-Organisation-Environment (TOE) and Natural Resource-Based View (NRBV) theories and formulating a practical implementation roadmap. The following research question guides the study:

- How do organisations overcome the challenges of adopting and implementing DTs to enhance environmental sustainability through strategic implementation and improved decision-making?

Methodology:

The study adopts the TOE framework Tornatzky and Fleischer (1990) and the NRBV Hart (1995) to examine how manufacturing firms adopt and implement DTs for environmental sustainability in OM. The TOE framework is used to systematically identify and analyse the technological, organisational, and environmental factors influencing DT adoption and implementation, while NRBV informs the assessment of how firms integrated sustainability-driven capabilities, such as pollution prevention and product stewardship, into their strategic use of DTs. These frameworks provide the analytical structure for coding and the conceptual grounding for developing a practical roadmap that links DT adoption and implementation to environmental performance outcomes.

Given the exploratory nature of the research question, a multiple-case study design is employed to investigate DT applications in real-world OM settings (Yin, 2014; Eisenhardt, 1989). Manufacturing organisations are selected to ensure depth and analytical feasibility. The organisation level is the unit of analysis, focusing on DT initiatives in the aerospace, automotive, and energy industries. This selection enables a balanced analytical depth and breadth, focusing on industries with high environmental impact and advanced digital transformation adoption, which aligns with the study's sustainability-driven objectives.

Expert interviews are being conducted to complement the case studies and strengthen data triangulation (Bogner *et al.*, 2009). Participants are purposively sampled from organisations with active DT initiatives to ensure relevance and depth of insights. Primary data are being collected through semi-structured interviews, complemented by secondary sources, including company documents and industry reports. The interview protocol was developed based on the research objectives derived from the literature review, guided by

the TOE and the NRBV. It was designed around core themes, including DT opportunities, challenges, adoption strategies, decision-making processes, and a guidelines road map for environmental sustainability. The protocol went through the typical stages of pilot testing and follow-up refinement.

The Thematic Analysis followed the six-phase model by Braun and Clarke (2006), guided by abductive reasoning (Timmermans and Tavory, 2012; Dubois and Gadde, 2014), following ethical protocols and validation strategies to ensure rigour and credibility.

Findings:

The preliminary analysis revealed five core themes that form the basis of the conceptual framework developed to explain how organisations adopt and implement DTs for environmental sustainability in OM. These themes are (T1) Opportunities and Enablers, (T2) Challenges, (T3) Strategies, (T4) Adoption Guidelines, and (T5) DT Capabilities and Outcomes. Grounded in the TOE framework and the NRBV, the developed framework offers a dual lens for examining contextual readiness and strategic outcomes.

T1 highlights the drivers of DT adoption and implementation, including access to advanced technologies, leadership support, and regulatory pressures, factors aligned with NRBV strategies such as pollution prevention and sustainable development (Hart and Dowell, 2011). T2 outlines challenges across the TOE dimensions, such as data quality, cybersecurity risks (Preut, Kopka and Clausen, 2021) skills shortages, and ROI uncertainty (Zhang et al., 2023), and policy misalignment (Padovano et al., 2024). T3 and T4 present strategies and best practices for the roadmap guiding phased implementation. T5 captures DT-enabled capabilities, including monitoring, analytics, and decision-support systems, which promote emissions reduction and circularity.

Value:

This study contributes to the OM and environmental sustainability domains by developing a conceptual framework grounded in the TOE framework and the NRBV. This combined lens provides a comprehensive explanation of the technological, organisational, and environmental factors influencing the adoption and implementation of DT. The research uncovers context-specific enablers, challenges, and strategic responses to DT implementation across sectors through a qualitative multiple-case study design. A key output is a roadmap that transforms theoretical insights into a practical, sequential guide, ranging from readiness assessment to full-scale deployment, offering valuable decision support for sustainability practitioners and operations managers.

The findings highlight DTs' role in enabling low-carbon, circular, and transparent operations, contributing to digital sustainability strategies aligned with global policy frameworks such as the European Green Deal and circular economy initiatives (European Commission, 2020). This study informs future research, policy, and practice by positioning DT as a technological tool and a strategic enabler. It opens avenues for further investigation into human-DT interaction and its role in supporting sustainability-oriented decision-making.

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An Investigation into the Integrated Optimisation of Additive Manufacturing and Transportation

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Purpose of this paper:

This paper aims to optimise manufacturing systems by leveraging 3D printing (additive manufacturing) not merely as a production tool but as a key element in a system-wide strategy. Recent research has demonstrated that focusing solely on individual 3D printers or isolated production stages overlooks broader opportunities for efficiency gains; the true competitive advantage is achieved by managing additive manufacturing from a holistic systems perspective. Evers and Potter (2017) proposed a comprehensive theoretical framework for industrial additive manufacturing systems that highlights the importance of integrating multiple components and processes to enhance overall manufacturing efficiency.

Building on this theoretical foundation, the primary objective of this research is to integrate manufacturing system optimisation with logistics planning, particularly in the context of time-window-constrained delivery. Production decisions and distribution scheduling are inherently interdependent – a product must be manufactured before delivery, and adherence to customer time windows necessitates seamless coordination between production and logistics. Kesen and Bektaş (2019) have empirically demonstrated that integrating production scheduling with distribution planning can significantly improve system performance. Yet, few studies have addressed the joint optimisation of additive manufacturing operations and delivery routing under stringent time constraints.

In addition, Rinaldi et al. (2022) have shown that an integrated approach to manufacturing and supply chain configuration can reconfigure a system's operational structure, thereby realising substantial improvements in responsiveness and overall efficiency. Inspired by these findings, this paper develops an integrated optimisation model that synchronises 3D printing production schedules with vehicle routing plans. The model is designed to achieve the fastest possible order delivery by incorporating both production and logistics considerations into a single framework.

Design/methodology/approach:

This study employs an optimisation modelling framework for last-mile delivery that builds on prior work by Demir *et al.* (2019) and incorporates the additive manufacturing (AM) systems perspective proposed by Evers and Potter (2017). For model validation, machine and material parameters drawn from the literature are used to simulate manufacturing times and influence machine allocation decisions. Customer orders are synthetically generated from a uniform random distribution as a proof of concept. The current experimental scope is limited to the UK region; however, due to computational constraints, the model is presently restricted to processing orders from only one or two manufacturing centres (MPCs). Future work will integrate more fine-grained simulations based on actual UK geography and increase the number of MPCs, scaling up to a realistic national map with orders primarily distributed in urban residential areas.

A three-stage optimisation procedure is implemented using Python and the Gurobi solver to coordinate production scheduling and delivery routing. Preliminary results show that an instance of 50 customer orders can be solved in approximately 5 minutes with a relative optimality gap of 0.1. The robustness of the approach for larger instances (e.g., 50–100

orders) has not yet been examined. It remains to be determined whether computational performance will become a bottleneck as the problem scale increases.

Findings:

The study identified limitations in the system's computational capability and scalability. The current model was validated with 50 orders but has not yet been stress-tested on significantly larger instances (e.g., 100 orders). Thus, the approach's scalability remains unconfirmed. In particular, the **transportation model** in the third stage requires further refinement to handle more significant volumes effectively. Future experiments will involve adjusting model parameters and evaluating performance on larger order pools to examine scalability and uncover any latent performance bottlenecks.

Analysing the system's performance, a potential bottleneck was found in the **machine allocation and selection** process during production. The present scheduling strategy prioritises high-speed machines first for production tasks. While this approach minimises processing time per task, it can inadvertently lead to under-utilisation of slower machines and potential resource wastage. These findings suggest that using machines with more balanced speeds could improve overall throughput and efficiency. In some scenarios, distributing tasks among fast and slow machines—rather than exclusively relying on the fastest resources—may reduce idle times and increase parallelism, thereby enhancing overall performance.

Looking ahead, several improvements are planned. One recommendation is to develop or apply heuristic algorithms to optimise machine scheduling decisions, which could mitigate the identified resource utilisation issues. The system can avoid over-reliance on a few high-speed machines by refining how tasks are assigned to machines of varying speeds. Additionally, further tuning of model parameters and expanded scenario testing will be carried out to ensure that the system maintains performance as the order pool size grows. These enhancements improve resource utilisation and scalability, enabling the system to handle larger workloads while minimising order delivery times efficiently.

Value:

This research contributes significantly by integrating 3D printing production optimisation with logistics scheduling into a unified framework. The core innovation is a holistic approach that considers manufacturing and delivery simultaneously, whereas traditionally, these processes have been planned separately. The study achieves better alignment between production output and delivery routes and time by coordinating additive manufacturing processes with distribution schedules. This integration is highly valuable to industry and operations management because it improves overall supply chain efficiency. In practical terms, the approach can boost production throughput and delivery efficiency – for example, reducing idle wait times between printing a product and shipping it. As a result, organisations can expect faster order fulfilment and more efficient resource utilisation, demonstrating the substantial value of the proposed integrated optimisation strategy.

Research limitations/implications:

While the results are promising, this study has certain limitations. One major limitation is computational complexity – the integrated optimisation model requires substantial computing power for large-scale problems, which can impede its practical use. Additionally, the solution approach risks getting trapped in local optima rather than finding the absolute best solution, given the problem's complexity. These limitations suggest several implications for further research. First, future work could develop more efficient heuristic or metaheuristic algorithms to obtain high-quality solutions with lower computational costs, helping to overcome scalability issues. Second, the model can be extended to consider more complex production constraints (such as multiple machines, maintenance schedules,

or stochastic demand) to reflect real-world conditions better. Third, testing and validating the approach using real-world data or case studies would be valuable, ensuring that the findings generalise to practical settings. Acknowledging and addressing these limitations in future studies will strengthen the robustness and applicability of the integrated optimisation approach.

Practical implications:

This research offers clear, practical implications for manufacturing and logistics operations. By linking production scheduling directly with delivery planning, the proposed approach can be applied to actual production systems to reduce lead times and improve coordination. For real-world implementation, companies would need to adjust the parameters and settings of the model to fit their specific context, such as tuning cost coefficients or time constraints to match a particular industry's requirements. The flexibility of the integrated method means it can be adapted to various sectors. For example, the printing schedule with immediate distribution is crucial in the customised medical devices industry, where patient-specific products are 3D-printed. The proposed optimisation framework could be extended to such scenarios, optimising the production and delivery of personalised medical devices to ensure timely availability for patients. In summary, with appropriate calibration to context, this method can significantly streamline production and distribution processes across different manufacturing domains, enhancing overall operational efficiency.

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SUPPLY CHAIN ANALYTICS

Exploring the Potential of Chatbots in Demand Forecasting: A Comparative Study

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Purpose of this paper:

This study investigates the potential of chatbots to forecast demand by systematically comparing their performance with traditional forecasting techniques (Boylan and Syntetos 2021; Jackson et al. 2024). The research explores the application of prompt engineering to improve chatbot-generated forecasts and assesses their alignment with results obtained through established methods. With a focus on practical implications, this research aims to evaluate the feasibility and conditions under which chatbots can contribute effectively to demand planning.

Design/methodology/approach:

This study employs a three-stage methodology. First, a series of datasets are created to reflect various demand patterns, ranging from simple to highly dynamic fluctuations. These datasets are then split into training and test sets, where the test sets serve as a benchmark. Traditional forecasting models such as ARIMA and exponential smoothing are trained on the training sets and used to predict the test set (Romero-Gelvez et al. 2019). These predictions serve as the baseline for comparison. Next, chatbots are provided with the same training data and tasked with forecasting the test sets using initial, unrefined prompts (Wamba et al. 2024). In the second stage, targeted prompt engineering techniques, such as zero-shot prompting and refinement patterns, are applied iteratively to improve forecast accuracy (Sahoo et al. 2025). Finally, the chatbot-generated forecasts are compared against the baseline results from the traditional forecasting models. The evaluation considers qualitative (e.g., in terms of the prompt engineering effort required) and quantitative (e.g., in terms of forecast error) aspects of forecasting performance.

Findings:

Preliminary findings suggest that chatbot-generated forecasts can approximate the accuracy of traditional methods under specific conditions, particularly when enhanced by prompt engineering. Techniques such as zero-shot prompting and iterative refinement notably improve performance, bringing forecasts closer to benchmarks set by established statistical models. However, certain limitations in chatbot reasoning and understanding of complex patterns highlight areas requiring further development.

Value:

This study is among the first to explore the use of chatbots for demand forecasting and to systematically compare their performance with traditional techniques. It demonstrates the potential of integrating conversational AI tools into supply chain processes, offering novel insights into their capabilities and limitations. The findings provide actionable guidance for practitioners considering chatbot-based forecasting solutions, emphasising the importance of effective prompt engineering.

Practical implications:

The research identifies key considerations for deploying chatbots in forecasting tasks, including the importance of carefully structured prompts and scenarios where chatbots can outperform or complement traditional methods. These insights offer practical value for supply chain professionals seeking to enhance efficiency through AI-driven tools.

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SUSTAINABILITY IN LOGISTICS AND SUPPLY CHAINS

Practices of Implementing Green Initiatives and ESG Reporting - The Perspective of Polish Logistics Service Providers (LSPS)

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Purpose of this paper:

The implementation of environmental initiatives is linked to the achievement of sustainable development goals, hence it also seems to be a natural challenge for logistics service providers (LSPs, 3PL operators and logistics integrators 4PL) implementing logistics services in supply chains to implement solutions aimed at reducing negative environmental impacts as a consequence of adapting the services provided and offered to customers' requirements and achieving sustainable development goals. Although publications addressing environmental issues in various industries can be found in the literature, there is still much to be identified on the issue of managing environmental issues in logistics and among logistics service providers (Lin and Ho, 2008, Fürst and Oberhofer, 2012). Some researchers signal that there is still a lot of uncertainty about how 3PLs implement environmental strategies and how they put environmental efforts into practice (Evangelista et al. (2017). Furthermore, it is important to note the context of research on CSR reporting by logistics service providers. Piecyk and Björklund (2015) reviewed the CSR reports of logistics service providers and analysed the factors influencing the level and extent of CSR reporting, indicating the need to continue further research in this area. As the literature review shows, the issue of ESG reporting by logistics service providers is still an unexplored research area. This article aims to present selected results from a quantitative survey indicating the identified implemented green sustainability initiatives and solutions and practices related to ESG reporting by LSPs.

Design/methodology/approach:

The research methodology adopted a multi-stage approach. In the first stage, a systematic literature review was conducted, following the procedure proposed by Tranfield, Denyer and Smart (2003) and using the PRISMA approach (Page et al., 2020). Based on the systematic literature review conducted, a survey questionnaire was developed in the next stage. Stage three involved the implementation of a pilot survey. The pilot survey was carried out on a sample of companies operating in sections of Section H in the PKD, i.e. Transport and Warehousing. Purposive sampling was used; sample size: 10 enterprises (n=10) providing logistics services to supply chains - TSL (transport-freight forwarding-logistics) enterprises in Poland. Respondents in the pilot study did not make any comments on the survey instrument. The fourth stage was to conduct a quantitative survey, also a purposive sampling was applied, which were operators (3PL) and logistics integrators (4PL) of logistics service providers in supply chains - leaders of the TSL sector in Poland, the number of respondents n=68. The last stage included the analysis of the results of the conducted survey.

Findings:

According to the research findings, industry leaders (LSP's - operators (3PL's) and logistics integrators (4PL's)) have implemented a wide range of sustainability initiatives and CSR practices in the logistics services provided. In addition, with the Corporate Sustainability Reporting Directive - CSRD - coming into force in January 2023, the ESG reporting obligation with thresholds for reporting per group extends to companies operating in the EU, hence LSPs operating in the EU must also prepare ESG reports. In this respect, the survey results showed that LSPs also adopt other reporting guidelines, including but not limited to the SASB (Sustainability Accounting Standards Board) standards, TCFD (Task

Force on Climate-Related Financial Disclosures) recommendations, GRI (Global Reporting Initiative) guidelines, ESRS (European Sustainability Reporting Standards) guidelines.

Research limitations/implications:

The main limitation is that the research sample covered logistics service providers operating in only one country, Poland. Therefore, it is recommended that the survey be repeated or even extended in new contexts.

Practical implications:

The research findings can provide in this area a set of different practices - environmental initiatives that can be considered by both large logistics service providers and smaller companies in the logistics sector as a checklist, for identifying and proposing the implementation of sustainable logistics service solutions. The findings made correspond with the literature review, which confirms that although sustainability aspects and CSR reporting issues, are considered a strategic priority, there is still some diversity in the implementation of environmental strategies in logistics service providers (Evangelista, Colicchio and Creazza (2017)).

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Assessing Carbon Management and Sustainability Strategies in Chemical Supply Chains

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Purpose of this paper:

The chemical industry is one of the most energy- and emissions-intensive sectors in Germany and faces the urgent task of reducing greenhouse gas emissions and defossilising its products (see Bähr et al. 2023 and Ausfelder et al. 2019 for an overview on the transition of the chemical industry). This requires a transition to renewable raw materials and energy sources, as well as profound changes in production processes and value chains. Thus, this transition poses substantial economic risks caused by massive investment requirements, a highly competitive market environment, and an unclear regulatory framework. On the other side, the chemical industry is one of the few industrial sectors which controls carbon flows in the technosphere and has the capabilities to manage energy transformation processes at scale. Thus, the chemical industry can contribute to the defossilisation of the economy by managing carbon in its processes and products as well as using these energy-intensive processes for buffering fluctuations in the energy grid. This role offers new business opportunities under a suitable regulatory regime. Depending on regulatory and market conditions (like positive and negative emission prices, biomass availability, green chemical imports, etc.) various pathways for the transition of chemical industry in Germany are possible and economically reasonable. Yet it is unclear this transition process will take place and which structure sustainable future chemical supply chains in Germany will have. From a political and economic perspective, it is important to understand which factors affect competitiveness of green chemical production in a global market environment and which supply chain structures result from such environmental scenarios.

Design/methodology/approach:

This study presents a technology selection model for the chemical industry transition, which allows for the analysis of the impacts of regulatory and market parameters on technology selection and, thus, the structure of the German chemical supply chains. The model is formulated as a linear program (see Schneider et al. 2025 for a similar model). It uses a techno-economic database deduced from life-cycle assessment databases to describe established and sustainable chemical production technologies (ranging from steam cracking to biomass gasification, direct air capture, and mechanical recycling, to carbon-capture-and-storage). Additionally, operational and investment costs for chemical production assets are used to describe production and investment decisions. Another set of input parameters considered in the model are the amount of available sustainable and fossil resources (such as biomass, oil, or waste) and imported green feedstocks and basic chemicals. The selection of raw materials, imports, and technologies is optimised by minimising total operating costs in 2045 to produce a predefined set and quantity of final chemical products. The model is used in an experimental study to investigate the effects of environmental parameters on technology selection, which defines the chemical supply chain structure. Environmental parameters varied include prices of emissions, energy, green imports, and domestic feedstock as well as availability of resources like biomass or CCS storage capacity.

Findings:

Overall, the findings indicate that chemical supply chain structures heavily depend on the price ratios between (sustainable) imports, emissions, electricity, and domestic sustainable resources. One scenario leads to supply chains with reduced vertical integration (compared to the status quo) by substituting upstream processes to produce basic chemicals with

green imports. In this case, substantial parts of current production processes in basic chemical industry for example based on steam cracking and Haber-Bosch production of ammonia are no longer competitive and will have shut down. Green basic chemicals like ethylene or even basic plastics like PET are produced abroad and imported to supply domestic downstream demand in other industries (see also Verpoort et al. 2024 for a similar study). This comes along with a substantial decline in economic activity in the German chemical industry. This scenario results when prices for electricity and core sustainable feedstocks like hydrogen, biomass and waste are high or the availability of sustainable feedstocks is limited (e.g. due to a lack of infrastructure). In case of favourable environmental conditions, a fully integrated closed-loop supply chain structure regarding carbon results. This structure uses biomasses and waste as renewable feedstocks at scale. This scenario results when domestic feedstock and energy costs are low and regulatory environment grants financial rewards for negative emission balances. I.e. it requires carbon-capture and storage capacities at scale. The interrelationships between regulatory and market parameters that lead to these different supply chains are complex. The results imply that there are multiple regulatory alternatives to incentivise certain strategic pathways of development in the chemical industry. Even more decisive are market parameters like energy cost and raw material availability.

Value:

The study is the first to systematically analyse the effects of environmental conditions on the structure of the chemical supply chain in Germany. It uses an up-to-date and comprehensive database of technological processes and assessments of future chemical production costs. It highlights the interrelation between market and regulatory conditions affecting the structure of industrial chemical production in Germany. Thus, it provides valuable insights for politicians and managers in the chemical industry on shaping and adapting to environmental conditions.

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Sustainability in the Thai Automotive Supply Chain

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Purpose:

Increasing pressure on firms to incorporate the triple bottom line of sustainability, namely environmental, social and economic dimensions into their Supply Chain (SC), has increased attention on the concept of Sustainable Supply Chain Management (SSCM) (Corriea et al., 2024; Shekarian et al., 2024). Besides the economic impact, automobiles affect the environment and the well-being of people in terms of air pollution, contributing to global warming and ineffective handling of end-of-life products (Shekarian et al., 2024). Prior research on SSCM in the automotive industry has focused on a variety of theoretical and practical issues: for instance, developing conceptual frameworks (e.g., Corriea et al., 2024), exploring the impact of resilience strategy on SSCM (e.g., Singh et al., 2023), SSCM barriers (e.g., Shekarian et al., 2024), and the relationship between SSCM practices and organisational performance (e.g., Youngswaing et al., 2024; Harikannan et al., 2025). However, past research has mostly focused on large OEMs, neglecting smaller key players in the industry (Corriea et al., 2024). Consequently, limited research has investigated prominent automotive Small and Medium Enterprises (SMEs) practices.

Thailand is the premier automotive producer in Southeast Asia, ranking 10th globally (Youngswaing et al., 2024). Focusing on SMEs, particularly automotive parts manufacturers in Thailand, this study adds to the body of knowledge by capturing and reviewing the effectiveness of current environmental sustainability practices in the SC. The research question that guided our research was: "What is the nature and implications of environmental sustainable practices in the Supply Chain?"

Design/methodology/approach:

Our research aim is twofold: to identify the focal areas of the sustainability practices, i.e. processes and decisions, that contribute to increasing sustainability in the SC, and to capture the scope they target. Due to the exploratory nature of our research and our research question, a qualitative research approach was decided. The unit of analysis was the automotive SMEs and their sustainability activities in the SC. Our study represents an embedded case study (Yin, 2018). Five automotive parts manufacturers were selected to participate in in-depth interviews. The interviews elicited SSCM practices in procurement, logistics, design, manufacturing, reverse logistics, and the benefits achieved from SSCM practices. An interview protocol was developed to ensure interview focus and consistency, which went through a standard pilot process. The protocol was developed in English, and then translated and employed in Thai. The interviews were then transcribed, translated in English, and analysed using thematic analysis. In all translation stages, an independent to this research academic with knowledge of both languages validated them. Given the focus of the study on environmental responsibility, the overarching categories of themes identified were: reduction of carbon emissions and waste, resource conservation, use of renewable energy, and sustainable sourcing.

Findings:

Our findings capture practices that enhance sustainability across the SC, their source and the associated benefits and challenges. Based on the analysis of our data, we identify key dimensions of sustainability practices (both intra- and inter-organisational) and the relative duration of implementation/reaction (both short-term planning and long-term planning).

These are discussed along those axes, allowing the identification of clusters of practices with similar focus and degree of challenges faced.

Subsequently, different scenarios of SSCM practices in procurement, logistics, design, manufacturing, and reverse logistics can be incorporated. The benefits companies achieved from SSCM practices concerning the environmental impact of sustainability are identified. Reviewing the identified SSCM practices in the automotive industry, specifically in the SMEs of Thailand, provides key practical and theoretical insights, allowing for clear lessons to be learned from the case studies. Hence, apart from the theoretical contributions, the results provide a deeper, more up-to-date understanding of the actions and perceptions of practitioners in their specific contextual situations and their experiences with SSCM practices.

Value:

Thailand's automotive sector is one of the government-focused S-curve industries requiring continuous innovation and has been one of the main contributors to the economic prosperity of the country (Chollacoop, 2020; Youngswaing et al., 2024). With the SME sector having been typically overlooked in past academic research, the outcomes of this study capture the range of practices and their associated domain within the SC, illuminating and developing understanding from the in-depth review of current SSCM practices in SMEs in this industry. The outcomes of this research will enhance practitioners' ability to identify, prioritise, and adopt appropriate SSCM practices.

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Bottlenecks in Non-Timber Forest Product Supply Chains

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Purpose of this paper:

This paper aims to identify and analyse the key bottlenecks hindering value creation in upstream natural product supply chains, with a particular focus on the Finnish non-timber forest product (NTFP) sector. As environmental awareness and consumer demand for sustainably produced goods grow, natural products have emerged as a critical domain for value-driven development. Despite increasing interest, the natural product sector struggles with inefficiencies and fragmented structures that impair its competitiveness and scalability. By examining the upstream end of the supply chain—from harvesting and initial processing to storage and transportation—this study explores how underdeveloped value networks and limited cooperation among actors constrain sectoral growth. Understanding these challenges is crucial for enabling more resilient and value-generating ecosystems. The research contributes to both supply chain and sustainability literature by shedding light on the multidimensional obstacles that restrict NTFP value creation and offering practical insights into how upstream improvements could elevate the sector's potential.

Design/methodology/approach:

The research employs a theme-centric literature review, complemented by a case-based exploration of 168 development projects sourced from the Finnish Aitoluonto.fi project registry. The dual approach facilitates a deeper understanding of both the theoretical underpinnings and real-world constraints of value creation in the natural product supply chain. Following established literature review protocols (Linnenluecke et al., 2020), relevant academic and grey literature was systematically gathered using databases such as ResearchGate and governmental reports. Emphasis was placed on peer-reviewed articles, industry documentation, and recent data to reflect the sector's evolving nature. The project data were thematically analysed to identify repeated patterns, categorise bottlenecks, and explore linkages between theoretical concepts such as customer value, core competencies, and networked collaboration. The research framework integrates value creation theory (Allee, 2000; Bowman & Ambrosini, 2000), network logic (Kothandaraman & Wilson, 2001), and upstream supply chain efficiency (Chopra, 2018), thereby enabling a holistic interpretation of how practical obstacles relate to theoretical constructs.

Findings:

The study identifies six major bottlenecks hindering value creation: (1) lack of training and information for forest owners and collectors, (2) insufficient entrepreneurial and marketing capabilities among SMEs, (3) limited networking and cooperation across supply chain actors, (4) inadequate harvesting volumes and poor raw material availability, (5) weak technological infrastructure and logistics arrangements, and (6) inconsistencies in quality management. The results indicate that value in upstream supply chains is constrained not by product demand, but by systemic weaknesses in stakeholder collaboration and knowledge transfer. The findings also reveal regional disparities, with most development initiatives concentrated in Northern Finland. Despite dozens of projects aimed at remedying the issues, few have addressed the underlying causes holistically. By aligning theoretical models of value networks with empirical project-level data, the research shows how fragmented actor relationships and poorly developed core competencies diminish value co-creation. The study maps these problems onto a visualised value chain to highlight their systemic nature and interdependencies. Ultimately, the analysis suggests that boosting training, enhancing cooperation structures, and investing in logistics capabilities are key leverage points for enabling scalable value production in the sector.

Value:

This paper offers a novel contribution by combining thematic literature review with empirical analysis of sectoral development projects—an approach rarely applied to the upstream end of natural product supply chains. The integration of value creation theory with real-world bottleneck analysis provides a more nuanced understanding of how sectoral transformation could be achieved. The findings are relevant for academics studying sustainable supply chains, policymakers crafting rural development strategies, and entrepreneurs seeking to expand natural product markets. By exposing concrete hindrances to value creation, the paper provides actionable insights for shaping a more resilient and value-generative NTFP sector.

Research limitations/implications:

The study is limited to Finnish development projects and literature primarily focused on the Nordic context, which may affect generalisability. Future research should examine upstream NTFP supply chains in diverse geopolitical and ecological settings, as well as conduct actor-specific studies to reveal tailored development strategies. Quantitative assessments of project impact and comparative studies across regions would further enrich the findings.

Practical implications:

Practitioners, especially in forestry and rural entrepreneurship, can use these insights to better structure training programs, develop cooperative models, and invest in logistics infrastructure. Policymakers may design targeted support mechanisms to strengthen value networks and improve stakeholder connectivity. The research also informs funding bodies on where project support is most needed.

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Robust Multi-Period Expansion Planning for Inclusion of Green Energy: A Case Study of Sultanate of Oman

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Purpose of this paper:

Renewable energy inclusion and expansion is a cornerstone of development policy worldwide and is also part of the Global Sustainable Development Goals. With conventional energy generation, the power plant location is heavily influenced by the presence of the available transmission grids infrastructure, and transmission expansion planning is not needed; this is not the case for renewable energy. The best available renewable energy resources are sometimes not in proximity to the existing transmission network, and to incorporate green energy in the national energy mix, countries must expand their transmission network by hundreds of kilometres to incorporate these renewable energy resources. (transmission expansion planning).

NetZero emissions targets are another important policy initiative supporting the use of renewable energy resources in the national grid. There is no single planning methodology which identifies and assesses the impact of incorporating renewable energy resources into the national grid and its impact on the grid; this gap is being filled by our research. To demonstrate this approach, we apply it to the Sultanate of Oman, a member country of the GCC nations, and a country with a strong commitment to incorporating renewable energy resources in its national energy mix and with future ambitions of using green energy to generate green hydrogen.

Another key area of application of this research is sustainable zero emissions national cold chain network design. One of the biggest challenges of incorporating in the international food supply chains the agricultural output of developing nations, is the lack of cold supply chains in the developing nations. The proposed methodology can also be applicable towards designing sustainable zero emissions cold chains using renewable energy resources (Solar and Wind) for energy resource location and its energy availability assessment.

Design/methodology/approach:

To implement the proposed methodology, multiple phases of analysis are required. The first phase identifies and estimates the available renewable energy resources using Spatial Multi-Criteria Analysis (SMCA) and DBC. The second stage of analysis encompasses forecasting energy consumption based on spatial settlement data. The third stage is the development of a multi-period renewable energy expansion plan based on multiple social and cost objectives. The final stage of analysis is the transmission network impact assessment due to renewable energy integration.

The identification and estimation of the national renewable energy potential follows the methodology proposed in the [1], [2], [3]. The main advantage of using this methodology is its ability to pinpoint the available exploitable renewable resource, all other Spatial GIS MCDM approaches identify suitable regions but are unable to pinpoint the exploitable energy clusters. The methodology identifies suitable solar and wind regions using clustering and multiple criteria analysis, discussed in detail in [2].

The energy consumption is modelled using four main user categories, i.e. Residential and commercial usage, agri-based energy usage, industrial usage and the transportation sector usage [10]. The distribution of the energy through the transmission network will be simulated using the population distribution densities and the corresponding total historical energy usage. Different stochastic and deterministic scenarios are simulated with their corresponding supply and demand requirements and their corresponding impact on the network, along with the shortfall and excess energy. Long-term generation expansion

scenarios will be tested, starting with the baseline of already available brownfield projects and stepwise incorporating the greenfield green energy clusters identified by this research. The main life cycle and cost assumption will be taken from [11].

To model and assess the impact of the energy cluster on the grid we will use PyPSA [6] an open-source power system analysis framework compatible with open source and proprietary MIP solvers. The current national energy transmission network comprising transmission lines, underground cables, transformer links, energy generators and storage capacities, and the load centres. The national transmission lines information is extracted from open infrastructure map [7]. Currently, the Sultanate of Oman has 400 kV, 220 kV, and 132kV AC networks providing energy to different load points with an estimated peak load demand estimates of 10500-12000 MW in 2040 [8]. The generation capacities of the system are assessed from the global power plant data set [9], containing the generation capacities, their locations, and the energy carrier i.e. gas, solar, hydro etc. To reduce the complexity of the model we spatially simplify and aggregate the national transmission network as well as grid reduction techniques [2].

A multi-period renewable energy expansion plan is devised based on the demand forecast using a multi-objective optimisation approach. Using four main objectives of energy availability, social impact, distance from the existing transmission network and corresponding technical difficulty of transmission network connectivity i.e. roughness of the terrain [4]. Each identified cluster is assessed based on its exploitable energy content and its environmental variables i.e. the characteristics of the terrain between the available cluster and the possible nearest grid connection point, this variable is useful proxy for the developmental effort required. The distance between the cluster and the nearest grid connecting point, which is a proxy of the cost of transmission network development, and the potential social impact, as the transmission network expansion planning entails the social development priorities. The social impact is quantified using population proximity within the 10 km distance from the line route. This impact will be based on spatial population distribution data as well as future population growth projections using [5]; these values will further be standardised and converted from a fuzzy representation to a crisp one.

The transmission network impact assessment is carried out using different developmental scenarios. To keep the model tractable, the monthly simulation cycle is considered with extending to 2040 developmental projection scenarios. One of the possible interesting scenarios will be net zero emissions, this could be useful to assess first if the identified renewable energy does have the potential for net-zero and secondly what proportion will be useful. [10]. To simulate the demand, the current demand of energy and the future developmental scenario are proposed using current energy and population and future growth and population numbers available at EIA [12]. Future developmental needs and scenarios are devised and different zero emission scenarios are tested incorporating the LCOE (levelised cost of energy) and developmental cost [11]. The optimisation scenario will be considered in multiple dimensions, time, space and stochastic occurrences. The discrete time series events and their corresponding location, as well as the probabilistic scenarios [13].

Findings:

The study identifies suitable national solar and wind energy clusters and their generation capacities using global wind and solar data. The spatial multi-criteria analysis identifies approximately 22 large clusters (13 solar and 9 wind sites) capable of producing renewable energy. These identified sites are the most energy-dense sites available nationally.

The developed multi-period expansion planning model, for inclusion of green energy into the current transmission network, prioritises solar energy in the short to medium term expansion and later on wind energy. The main objectives to consider are the social impact maximisation and transmission network expansion cost minimisation.

Another main finding of this study is the importance of the national level energy consumption models which can model the temporal energy use by different sectors of the economy. Any decision related to the green energy inclusion requires these models because of the inherent temporal availability of the renewable energy. Currently we are using the synthetic data combining the energy forecast and the energy usage consumption model developed for Germany. The spatial distribution of this energy consumption is based on population data. Combining the energy forecasts with the temporal consumption model and the spatial distribution is also a novelty and key finding of this research. This finding helps us to assess the impact of different NetZero emissions objectives i.e. 20-30-40-50 percent reduction in CO2 emissions.

Value:

The novelty of the study is in methodologically integrating DBC technique with transmission network planning. The second novelty of the study is its methodological innovation for green energy integration planning using open-source frameworks and internationally accredited spatial data sources. The proposed methodology will be useful for both developing and underdeveloped nations. The approach is applied on a national level case study, but it is equally applicable in cases where the spatial extent is local. This methodology can also be applied to designing sustainable zero emissions national cold supply chains network design, because the methodology identifies, assess the energy available, and then optimises the inclusion of green energy in the national transmission network. Similar approach can be applied using national transportation network data and the agricultural sources to assess the storage requirements and then identifying the renewable clusters which can be used power these cold storage sites.

Practical implications:

The research has direct implications in policy decisions of renewable energy system design, their impact on the national grid, and life cycle cost assessment of integrating renewable energy in the national energy supply chains.

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The Mineral Supply Chain and Sustainable Emobility: Current Landscape and Future Directions for the EU

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Purpose of this paper:

The European Automotive industry (EAI) represents a significant economic contribution of approximately 8% to the EU's GDP. It employs nearly 13.8 million individuals, thereby highlighting its critical role not only in financial performance but also in workforce development (European Commission, 2025). This sector is the home of some of the largest global automotive manufacturers, accompanied by a comprehensive supply chain (SC) featuring prominent automotive suppliers such as Bosch, Continental and Schaeffler.

The expansion of the automotive industry in the European Union (EU) is intricately associated with the proliferation of zero-emission vehicles, guided by both regulatory frameworks and market trends. The EU has enacted substantial policies and incentives aimed at fostering the manufacture and utilisation of environmentally friendly vehicles, including electric and hybrid models, as an integral part of its low-emission mobility strategy. This initiative aspires to establish Europe as a frontrunner in renewable energy and to enhance innovation within the automotive field. Several EU member states and municipalities are progressively instituting limitations on internal combustion engine (ICE) vehicles to systematically attain the zero-emission objective.

In this study, we perform an exploratory analysis in pursuit of demand vs supply, the dependency of the EU for CMs on the rest of the world (RoW) by 2030 and 2035, and key supply chain risks (SCRs) to be ready to counter them, as preparation for a sustainable SC for the future growth engine of EV implementation in the EU. Given these findings, we explore the following four research questions:

1. What is the current and projected state of demand versus supply in the EU MSC?
2. What is the current status of end-of-life recycling for critical minerals (CMs) in the EU?
3. To what extent is the EU MSC dependent on the RoW?
4. What are the key risks and barriers to establishing a sustainable MSC in the EU?

The corresponding aims of this paper are to investigate these research questions by;

- Searching for examples of demand and supply situations.
- Analysing the relevant data to discuss the current status of end-of-life recycling.
- Analysing and discussing the EU dependency of CMs on RoW.
- Carrying out a literature review to identify the potential MSC risks.
- Mapping of key CMs on the dependency and risk matrix.

Design/methodology/approach:

This study integrates peer-reviewed research with secondary data from reputable sources such as the International Organisation of Motor Vehicle Manufacturers (OICA), World Mining data (World Mining Data, 2024), International Energy Agency (IEA, 2024), German Association of the Automotive Industry (VDA, 2025), World Resources Institute (Jaeger, 2023), European Commission (European Commission, 2024) and Social Progressive Imperative (Porter & Stern, 2025), Environmental Performance Index (Block et al., 2024), and the World Bank Governance Indicators (World Bank Group, 2024) to get meaningful insights to understand the MSC better and holistically in the European context.

To carry out our study, we explored the two policy scenarios stated policy scenario (STEPS) and the net-zero emission (NZE) scenario (Schiffer, 2023). STEPS takes into account the measures that have either been implemented or put into effect (the Fit for 55 package by the EU in July 2021) to achieve the announced energy and climate policy goals, while NZE puts energy systems on a viable path for the global energy system to achieve the net zero emissions by 2050 (United nation's climate goals).

A mixed-methods approach combines qualitative literature review and quantitative data analysis to evaluate the EU's MSC and develop a conceptual "House of Sustainability" framework.

Findings:

There is no strategy that is durable enough to last forever, owing to the ever-changing business environment, especially in the automobile industry (Gautam et al., 2025a, 2025b). Srivastava and Rogers (2022) discussed that in each industry sector, the global SCRs and their mitigation strategies differ. Therefore, the automotive industry functions under unique constraints such as scarcity of sustainable raw materials for production, fierce competition, traditional, constant technological innovations, and changing government policies that require a different approach to deal with such unique constraints (Gautam et al., 2023; Rogers et al., 2016).

Currently, the automotive industry is undergoing a massive transformation toward electric mobility (eMobility) to reduce carbon emissions. Critical minerals (CMs) such as lithium, graphite, cobalt, nickel, and rare earth elements (REEs) are essential for electric vehicle (EV) batteries, electronics, and drivetrains (Schmid, 2020). Therefore, the automotive industry has heavily relied on several CMs for decades to continue its growth voyage. The transformation of the global automotive industry towards eMobility has further up-scaled its dependency on CMs and REEs to a great extent.

Currently, the EU is the second largest manufacturer of overall and EV category after China. According to the data from IEA (2024), around 2.45 million cars were sold in 2023 (As shown in Figure 1). According to the STEP and NZE policies scenarios announced by several states of EU27 towards zero emission, it is expected to grow to 10.10 million by 2030 and 21.51 million by 2035. We observed that currently, the EU seriously lacks in fulfilling the current and futuristic demands of several CMs required for EVs. The overall domestic production of CMs mining is less than 2% of the total CM production of the RoW. In most cases, the EU is reliant on RoW by approximately 34% to 100% for various CMs. Therefore, a balance between the supply and demand of CMs is of paramount importance for the sustainable growth of eMobility in the EU.

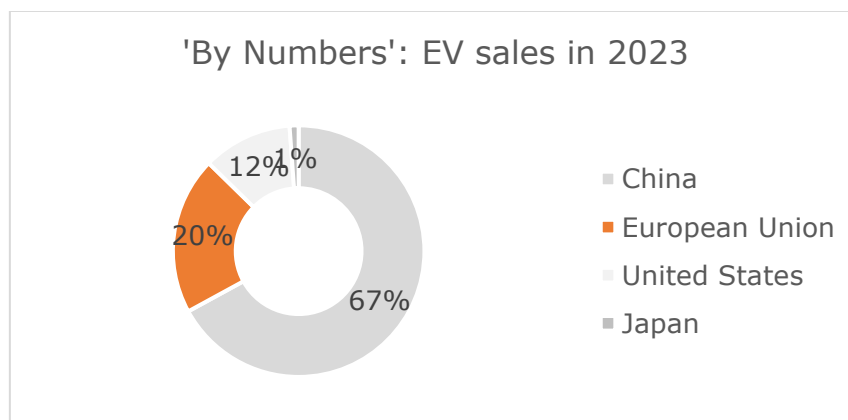


Figure 1: EV Sales in 2023 (Ref: IEA, 2024)

On the other hand, the MSC is significantly exposed to several unique challenges hindering the widespread adoption of eMobility. These bottlenecks are mainly related to the regional

disparity in terms of the uneven distribution of minerals, mostly in high-risk South African countries, security challenges due to a lack of legislation in these countries, socioeconomic and socio-political challenges, and security threats in these countries. Therefore, the availability of sustainable CMs and REEs is one of the biggest challenges for all major automobile manufacturing countries (Soto Crisanto et al., 2024). The EAI, for instance, has faced significant challenges due to its dependency on CMs, primarily sourced from China, which holds a dominant position in the global market for these materials (Nagy et al., 2024). The dependency was further magnified by geopolitical tensions and the strategic use of CMs as leverage in international disputes and conflicts between China and the US (Saadaoui et al., 2025; Schmid, 2020). Therefore, managing these challenges effectively is the bottom line for the Sustainable Development Goals (SDGs) framework.

To tackle these challenges towards sustainable MSC, we proposed the “House of Sustainability” framework (Figure 2), showing environmental (Balaram, 2019; Dushyantha et al., 2020; Jia et al., 2025; Richert & Dudek, 2023), societal (Baars et al., 2021; Gong et al., 2025), and governance issues (Barragan-Contreras et al., 2025; Burton et al., 2024b, 2024a; Dou et al., 2023; Iguma Wakenge et al., 2021) in the mining and refining of CMs (upstream side of MSC) at the bottom. Addressing these issues in MSC is the bottom line for achieving the SDGs in the region. By addressing these issues by bringing environmental sustainability (Chen et al., 2025), institutional sustainability (Sauer, 2021), economic sustainability (Bleichwitz, 2020; Blengini et al., 2017; Chen et al., 2025; Olivetti et al., 2015), social sustainability (Aslam et al., 2025; Renneboog et al., 2022), along with technological innovations through circular economy practices (Asif et al., 2025; Gurzawska, 2020; Husmann et al., 2024; Ullah et al., 2024).

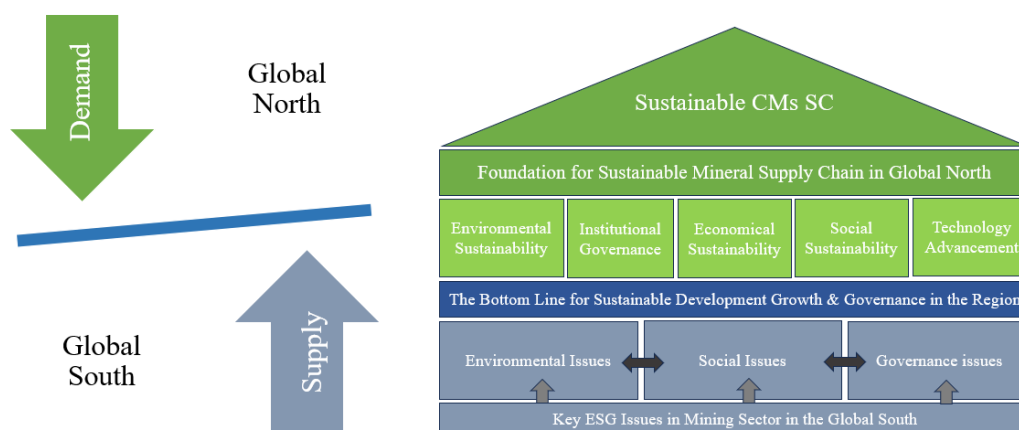


Figure 2: House of Sustainability framework

Value:

This study will develop a holistic understanding of the gaps between the demand and supply of CMs, managing the risks threatening the EU’s sustainable future, which are of utmost importance for net NZE goals within the SDG framework. Subsequently, we will develop strategies and a resilience framework to manage these challenges effectively.

Research Limitations/implications:

As the research in MSC is a less-researched topic in academia, especially in the EU automotive context, we didn’t come across any study integrating credible resources and knowledge from peer-reviewed articles to map the gaps in supply and demand of CMs.

The clear insights from the supply and demand gaps will serve as a guiding tool in navigating the strategies to bridge the supply/demand gaps for the EU’s sustainable future.

Integrating the existing knowledge in the sustainability and resilience domain from peer-reviewed published research, mainly from the traditional automotive SC, will help in crafting the potential strategies in managing the risks threatening the EU's sustainable future.

Practical Implications:

This research contributes a comprehensive overview of the demand-supply imbalance, governance challenges, and supply chain vulnerabilities in the EU's pursuit of eMobility. It offers a strategic foundation for policymakers and industry stakeholders aiming to enhance resilience within the MSC, aligning with the EU's carbon neutrality goals. This paper will also serve as the foundation to perform empirical research, adding to the literature in the context of MSC for successful eMobility adoption in the EU.

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Leveraging Technology for Uyghur Forced Labour Prevention Act (UFLPA) Compliance in Global Supply Chains

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Introduction

For years, labour exploitation has been an ongoing issue in global supply chains, mainly in places where labour laws are ignored or poorly implemented. Of great concern these days is the forced labour of Uyghurs in Xinjiang, China, with both human rights bodies and government officials confirming their extensive exploitation [1]. Among other things, the allegations involve workers being forced to change jobs, sent to internment camps, and made to do labour in textiles, electronics, and farming worldwide.

Because of increased pressure from other nations, the United States officially approved and drew into force the UFLPA in December 2021, which took effect on June 21st, 2022 [2]. Any products produced in Xinjiang, both partly and wholly, are considered to have been made with forced labour under the UFLPA and so are shut out from being admitted to the United States [3]. Because of this legislation, businesses have to show that their supply chains are free from forced labour and must do so using reliable proof, a process that is sometimes complicated and time-consuming.

What is the UFLPA?	The UFLPA establishes a presumption that all goods coming out of the Xinjiang Uyghur Autonomous province of the People's Republic of China (XUAR), or produced by certain entities, are not entitled to entry into the United States
When?	President Biden signed the act into law on December 23, 2021 The Act took effect June 21, 2022
Who?	The UFLPA will be enforced by the Forced Labor Enforcement Task Force, a cross-agency task force established by the USMCA Implementation Act
1 June 13, 2022	CBP published their operational guidance for the UFLPA. The guidance provided: — Insight to release, detention, exclusion, exceptions, protests and seizures of merchandise subject to the UFLPA — Key resources for importers to consult as they prepare for the UFLPA — Information and documentation that CBP might request in the case of merchandise flagged under the UFLPA
2 June 17, 2022	— FLETF published the UFLPA Strategy — The Act's rebuttable presumption against the importation of goods originating in the XUAR or entities identified by FLETF took effect.
3 Post June 21st, 2022	Continual monitoring of CBP action regarding the UFLPA and monitoring of the FLETF entity list will be key to guiding one's own anti-forced labor program

Because of these issues, businesses are considering using artificial intelligence (AI), machine learning (ML), and blockchain to make their supply chains clearer, trackable, and compliant [4]. These technologies can automate checking for risks, conduct thorough checks on suppliers, pick out unusual details, and confirm evidence in suppliers' records using warrants in a digital ledger. Though promising, the use of such technologies leads to important concerns about both data quality and how far these systems can be expanded, along with ethical and financial considerations, mainly in obscure or sensitive locations.

The main reason for this study is the urgency to know how using technology can help comply with the UFLPA, manage related challenges and deal with ethical problems. Due to mounting demands for responsible sourcing, many global firms now need to incorporate AI- and ML-powered compliance tools in their ERPs (Oracle, SAP, etc.) to scan the parties with which they are dealing in the real business environment.

In section two, I give an overview of the literature surrounding forced labour in supply chains, the UFLPA, and the part technology plays in monitoring compliance. Section 3 discusses the methodology used in this research. Section 4 explains how AI and ML

technologies are being used for UFLPA compliance, mentioning both the good and bad outcomes. Section 5 looks at the topics industry stakeholders and policymakers need to consider. Finally, Section 6 concludes with key insights and recommendations for future research and technological development.

Research Question

- How are artificial intelligence and machine learning technologies being applied to improve compliance with the UFLPA in global supply chains, and what challenges and opportunities do they present?

Literature Review

Efforts to eliminate forced labour from global supply chains have gained renewed urgency in recent years, especially in light of well-documented abuses in the Xinjiang Uyghur Autonomous Region of China [5]. Several investigations show that Uyghur minorities are forced to work in global industries such as textiles, electronics, and agriculture. This research has encouraged a review of ethics, operations, and legal issues when handling products for international trade [6].

The UFLPA sweeps in a major change, making it so that goods wholly or partly made in Xinjiang or through companies on the official list are deemed made with forced labour and are unable to be brought into the United States [7]. It has been made clear by U.S. Customs and Border Protection (CBP) that "The UFLPA sets a presumption that any goods, wares, articles or merchandise produced in the Xinjiang Uyghur Autonomous Region of the People's Republic of China are prohibited by Section 307 of the Tariff Act of 1930." The presumption is removed only when there is "clear and convincing evidence" that the goods were free of forced labor.

Enterprise platforms such as Oracle Global Trade Management (GTM) and SAP Global Trade Services (GTS) are increasingly being used to automate regulatory compliance processes, including trade screening, classification, and documentation, though they often lack detailed labour-specific due diligence functionality. In response to these demands, technology has emerged as a potential enabler of greater visibility and accountability. Blockchain technologies are being applied to trace raw materials from origin to finished product, creating transparent and tamper-proof records of transactions and sourcing events. Artificial intelligence and machine learning are increasingly used to detect risk patterns in supplier behaviour, analyse customs and trade data, and flag high-risk shipments for further review [8]. Some systems are being developed to cross-reference large datasets, including trade flows, satellite imagery, and supplier declarations, to assess forced labour risk more proactively.

Despite growing interest in technological solutions, the integration of these tools into regulatory and operational compliance practices remains inconsistent and underexplored. There are limited empirical studies assessing the effectiveness, scalability, and ethical implications of these technologies when applied to UFLPA enforcement [9]. This gap in current knowledge underscores the need for targeted research that evaluates how artificial intelligence and machine learning are currently being deployed for UFLPA compliance, and what challenges and opportunities they bring [10]. Understanding these dynamics is critical for building robust, ethical, and enforceable supply chain frameworks capable of addressing the complexities of modern forced labour regulation. The UFLPA operates alongside other national laws which target forced labour through supply chain responsibility. The UK Modern Slavery Act (2015) requires businesses to disclose yearly statements about their supply chain risks for slavery and human trafficking. The German Supply Chain Due Diligence Act (Lieferkettengesetz) requires businesses to perform periodic human rights risk evaluations and establish preventive measures. The European Commission has introduced a new regulation that prohibits all products made through forced labour from entering EU markets. The worldwide regulatory framework demonstrates an emerging trend toward legally binding ethical sourcing standards that require adaptable cross-border compliance solutions.

Methodology

This study adopts a descriptive research design grounded in qualitative secondary data. The focus is on analysing real-world documents and tools addressing forced labour risks in global supply chains, particularly in the context of U.S. regulatory and technological responses.

- **Research Design:** The study uses qualitative, interpretive methods to analyse and describe the content and structure of known case studies and what they mean in practice. It fits well for tracking both the social, legal, and operational details in preventing people from being exploited.
- **Justification for Case Study Use:** Using real-world cases and official documents, researchers gain detailed information about how organisations and governments face forced labour problems. Along with a policy strategy from DHS, the report demonstrates how the CUMULUS platform from Verité works, offering a good mix of policies and practices.
- **Inclusion Criteria for Data Sources:** Sources were required to be publicly available, credible, relevant to forced labour or supply chain compliance, and published in English with practical applicability to due diligence. Due to scope limitations, the study draws entirely on publicly available documentation rather than primary interviews.

Case Study Analysis

This section presents an in-depth descriptive analysis of two selected real-world case studies that demonstrate practical strategies and technological innovations to identify and mitigate forced labour in global supply chains.

Case Study 1: U.S. Department of Homeland Security (DHS) UFLPA Strategy Document [11]

- Enacted in 2021, the UFLPA strengthens enforcement of existing U.S. laws banning the import of goods produced with forced labour, especially from Xinjiang, China.
- The strategy was developed by the Forced Labour Enforcement Task Force (FLETF), chaired by DHS, in consultation with public and private stakeholders.
- It includes:
 - Risk assessment of goods linked to forced labour in China.
 - Evaluation of forced labour schemes and priority sectors.
 - Creation of the UFLPA Entity List and enforcement tools.
 - Guidelines for U.S. Customs and Border Protection (CBP) to enhance inspection and entry denial of non-compliant goods.
 - Recommendations on interagency collaboration, importer guidance, and resource planning.
- The strategy serves as a comprehensive enforcement and compliance roadmap for ensuring goods made with forced labour do not enter the U.S. market.
- The document contains essential policy requirements that also demand advanced technological capabilities from importers. Companies must present "clear and convincing evidence" to prove their goods were not made by entities or located in the Xinjiang region to avoid a forced labour presumption.
- The strategy gained additional importance when DHS announced the largest UFLPA Entity List expansion by adding 37 PRC-based companies in January 2025.
- Businesses need to implement flexible technology-based compliance systems that can rapidly respond to regulatory modifications.

Case Study 2: Enhancing ERP-Based Compliance Systems with AI Platform [12]

Organisations implement enterprise resource planning (ERP) systems, integrating global trade management (GTM) functions to handle regulatory compliance under the UFLPA. The systems provide capabilities for country-of-origin validation, restricted entity screening, document management, and automated customs workflows. The UFLPA-specific controls in ERP platforms enable organisations to prevent transactions with flagged suppliers, geographies, or products unless required documentation is attached. A GTM-enabled ERP system underwent customisation to implement Entity List screening logic and workflow-based document checks for supplier certifications and traceability evidence. The system implementation assists importers in fulfilling UFLPA's "clear and convincing evidence" requirement through automated document retrieval, alert generation, and audit trail maintenance during compliance procedures. ERP platforms excel at enforcing transactional rules and policy regulations, yet they do not provide workforce-level labour risk visibility, which includes essential information about recruitment practices and employment conditions for UFLPA and human rights due diligence. Organisations can address this gap through the integration of Verité's CUMULUS Forced Labour Screen™, which uses AI technology to perform labour risk assessments. The CUMULUS platform enhances ERP systems by delivering social compliance intelligence, which standard trade platforms do not provide by default.

- The CUMULUS Forced Labour Screen™ is a membership-based digital platform designed to detect, assess, and address forced labour and unethical recruitment practices in cross-border labour supply chains.
- It leverages data analytics and patented technology to:
 - Map supply chains and workforce demographics.
 - Identify International Labour Organisation (ILO) forced labour indicators.
 - Monitor and verify employer compliance with the Employer Pays Principle.
 - Facilitate remediation, audits, and due diligence aligned with OECD guidance.

Discussion

The case studies show that AI and machine learning can boost compliance with the UFLPA by making supply chain activities easier to monitor, analyse risks, and make better decisions.

- **Application of AI/ML in Compliance Enforcement:** Verité's CUMULUS Forced Labour Screen™ applies AI to spot risk factors related to ILO standards, map out supply chains, and direct actions to take next. This platform reveals how technology helps companies achieve UFLPA objectives by applying effective screening and using thorough data analysis.
- **Challenges in Deploying AI/ML:** Many barriers continue to block the full use of AI/ML in this field. Important challenges related to this type of logistics are: Limited access to correct information about Xinjiang, as the government blocks any clear public statement or interactive reporting. Some firms, SMEs, cannot use AI-based compliance systems because of their resistance and limited technical staff.
- **Opportunities and Potential Benefits:** The case studies also highlight promising opportunities: Enhanced supply chain visibility and traceability via AI-enabled dashboards and analytics tools. Real-time insights for regulatory bodies and companies, allowing faster intervention and preventive actions. Scalable models that could be expanded beyond current sectors to other industries with forced labour risks, improving global ethical standards.

Conclusion and Recommendations

This study has examined the evolving role of artificial intelligence (AI) and machine learning (ML) technologies in enhancing compliance with the UFLPA. Through a descriptive case study approach, it highlighted how AI-driven platforms, such as Verité's CUMULUS Forced Labour Screen™ and data-informed strategies deployed by U.S. Customs and Border Protection (CBP), are being used to improve transparency, traceability, and accountability within global supply chains.

Key Insights and Contributions

AI and ML tools are currently being applied to:

- Conduct automated risk assessments of suppliers and sub-suppliers.
- Support predictive analytics for identifying forced labour risks.
- Facilitate regulatory due diligence by integrating trade, labour, and customs data.

These applications confirm that emerging technologies can be critical enablers of regulatory compliance and ethical sourcing, especially in complex and opaque supply chain networks.

Practical Recommendations

To strengthen the implementation and effectiveness of AI/ML tools under the UFLPA, this study makes the following recommendations:

For policymakers, it is essential to promote open-data initiatives and establish cross-border data-sharing protocols to improve the availability and quality of supply chain information, particularly from high-risk regions such as Xinjiang. For supply chain managers, AI/ML solutions should be integrated into supplier vetting and audit processes, with a particular focus on extending due diligence practices to indirect and tier-2 suppliers. For technology developers, it is critical to prioritise the transparency and interpretability of AI models to foster user trust and ensure that compliance outcomes can be clearly explained

Challenges to address

The progress achieved has not eliminated several essential obstacles. The lack of dependable data and the inability to authenticate information in dangerous areas like Xinjiang prevent risk assessments from being accurate. The integration of AI tools into existing legacy supply chain systems faces challenges because these systems often lack the necessary flexibility or infrastructure to support advanced analytics. The implementation of AI tools faces substantial ethical and operational challenges because of algorithmic bias, automated decision-making risks, and data privacy threats, which need proper governance and oversight.

Future Research Directions

Future research should involve primary data collection, such as interviews or field studies to evaluate the real-world effectiveness and limitations of AI/ML tools in supply chain settings; explore cross-sector applications of AI-enabled compliance mechanisms beyond textiles and electronics; and assess the long-term scalability and governance of these technologies in addressing forced labor and broader sustainability challenges in global trade.

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Dual Supply Chain Design: Innovation, Sustainability and Resilience through Supply Chain Cooperation

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Purpose of this paper: Introduction

Transport Logistics and Supply Chain Systems are determined by materialism, a theory that argues that all (mental) phenomena are fundamentally physical [1]. Materialism theory considers, as discussed in Alter et al. [1], the mind a physical phenomenon. It is a machine and its operations “produce” thinking, perception, and consciousness.

Materialism in the field of Transport Logistics and Supply Chain Systems is represented in strict production processes, time schedules, and process designs – thus supporting efficient flows of goods and minimising transaction costs among the supply chain entities. Deviations can get penalised and – at the very least – result in a loss of trust and reputation in the causing system entity.

Although Transport Logistics and Supply Chains are well thought out down to the smallest detail, and the application of advanced technology increases their efficiency and effectivity, in this paper we hypothesise that many Supply Chain Systems fail of the materialism-based perspective. We argue that innovation, creativity, co-creation, cooperation, and collaboration are the factors of a profitable, sustainable, and resilient Supply Chain. This paper is based on the research question about which factors are relevant having a more efficient supply chain with the aim to demonstrate the importance of dualism, the opposing theory to materialism, in Supply Chain Systems.

Design/methodology/approach:

To provide a response to the paper’s hypothesis and research question, we make use of the Beer Distribution Game (BDG). The BDG is a management simulation designed to illustrate the complex interdependencies within a four-stage supply chain as well to highlight the importance of system thinking. The players of the BDG are a manufacturer of beer (factory), its distributor, wholesaler, and retailer that commonly serve and satisfy the customer’s need. The objective of each player is materialistic: minimising costs and increasing efficiency. However, the information exchange between the individual players is limited (i.e., by using order cards) and occurs with a time delay. This results in the focus being placed on one's own situation, as it is the only one that can be significantly influenced.

The Beer Distribution Game was executed as part of the Erasmus+ SMARTER week (2-6 Sept 2024) at the South East Technological University in Ireland. Participants were ten international students from Argentina, Austria, Finland, Romania, and Spain, including heterogeneous scholarly backgrounds and different levels of work/industry experience. The students were divided into four groups that represent the players of the game.

In total, the game was played for five hours, applying different sets of execution. The first hour was used to introduce the BDG, to present the game’s rules, production processes, and time schedules as well as to perform some tests. The remaining four hours were used to play the game under competitive conditions, separated on the 2nd and 3rd Sept 2024 á two hours each.

Table 1: Schedule

Day	Hour	Topic
2 nd Sept 2024	1h	Introduction
2 nd Sept 2024	2h	Playing under competitive conditions, application of strict rules: decentralised gameboard, suppression of all communication between the players; strict monitoring
3 rd Sept 2024	2h	Playing under competitive conditions; centralisation of the gameboard; fostering of communication, interaction, and information exchange

As presented in Table 1, in the first session under competition (2nd Sept 2024), the players experienced as much pressure as possible. In doing so, we split the gameboard into four pieces and have placed the players in different places in the lecture room. We encouraged the students to proactively discuss the upcoming orders, moves and strategies within their group but strictly prohibited oral communication and information exchange between the remaining players.

In the second session under competition (3rd Sept 2024), we relocated the players to a central place in the lecture room. On this game day, we encouraged the players to proactively communicate with each other and exchange information about the upcoming orders, moves, strategies, etc.

Value:

The players experienced several supply chain related phenomena, such as the bullwhip effect, cost inefficiency, increase of costs for warehousing and backlogs, etc. while being thrilled to be efficient at the same time. The execution of the game was accompanied by recurring feedback rounds with the aim to capture the feedback (i.e., complaints, arguments, ...) of the players. Due to the setting of the game in the first session under competition, the feedback was mostly "negative". For example, the players complained about information and communication gaps between the remaining players, intransparency, as well as arguments (within the groups and beyond). The players' feedback on the second session was more "positive". To satisfy the customer's needs, the players reported collaborative behaviours, accompanied with the implementation of coordination measures, increased communication, and cooperation. At a glance, the players shifted from a pure materialistic perspective to a dualistic perspective and let innovation happen through cooperation, collaboration, and communication.

Research limitations/implications:

In addition, the students were asked to respond to a quantitative questionnaire (mandatory) as well as invited to interviews (voluntary). Based on the players' experiences, these questionnaires and interviews are used to identify the factors are relevant having a more efficient supply chain. These factors serve as data to provide implications for managers and organisational decision-makers in the field of supply chain management.

Practical implications:

With this paper, we identify the factors that are relevant for a more efficient supply chain. Our research paper identifies the limitations of the materialist perspective – shifting away for purely engineered rather than to cooperative and collaborative supply chains. This paper identifies the importance of communication and interaction in Supply Chain Systems. Interaction and communication foster the positive development of the overall system in both qualitative and quantitative characteristics of the system. Communication and interaction, for example, decreases the transaction costs of the overall systems and enables the entities for advanced planning and the anticipation of events. Restricted

communication and focus on one's own situation have the consequence that, when there are too many or too few orders, these can have a significant influence on the entire supply chain. This phenomenon is particularly evident when there are greater fluctuations upstream of the supply chain. This phenomenon is known as the "bullwhip effect".

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Development of a Simulation Model for Assessing Policy Impacts in Thailand's Economic Corridors

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Purpose of this paper:

Despite extensive research on economic corridor development, existing studies reveal several gaps that this research seeks to address. Many policy impact models lack a multidimensional approach, often focusing on isolated factors without integrating economic, social, environmental, and infrastructural aspects (Verburg et al., 2011). Spatial accessibility and regional disparities remain underexplored, with limited use of GIS-based spatial analysis to capture geographic variations in market access and infrastructure investments (Barrett, 2008). Furthermore, dynamic simulations and scenario analyses are rarely employed to assess long-term policy impacts, limiting policymakers' ability to anticipate and mitigate risks (Hering & Poncet, 2010). There is also a notable absence of corporate decision-making and competency factors in current frameworks, leading to incomplete assessments of market-driven behaviours and their influence on economic performance (Harris, 1954). This study contributes a holistic, data-driven simulation model that enhances decision-making for policymakers and stakeholders involved in Thailand's economic corridor development by addressing these gaps.

The primary objective is to design and construct a comprehensive spatial impact assessment model that integrates multidimensional data, including economic, social, environmental, and infrastructural factors. The model is intended to serve as a decision-support tool for policymakers and planners, enabling them to forecast and analyse the outcomes of policy proposals in a holistic manner. By leveraging advanced modelling techniques, this research seeks to enhance policy formulation and strategic planning by providing empirical evidence on the potential consequences of infrastructure development and investment decisions within economic corridors.

The research addresses how infrastructure investments influence spatial accessibility and economic performance. This approach considers regional economic theories and market accessibility frameworks, focusing on how geographic factors affect economic opportunities and competitiveness (Harris, 1954; Barrett, 2008). The simulation model aims to project potential outcomes of infrastructure projects by incorporating dynamic interactions between transportation networks, economic activities, and spatial development patterns. This study also emphasises the significance of reducing economic disparities between central and peripheral regions through inclusive development strategies (Verburg et al., 2011).

Design/methodology/approach:

The research methodology begins with an extensive literature review of policy impact assessments within economic corridors, both domestically and internationally. The theoretical foundation incorporates concepts such as Market Accessibility and Regional Economics, which are used to analyse key factors influencing market accessibility and economic potential. The study adopts the EPIC-D Framework, which examines Economic (E), Political (P), Infrastructure (I), Competency (C), and Corporate Decision (D) factors.

The developed simulation model employs the EPIC-D framework to assess the policy impacts on economic corridor development in Thailand. Economic factors (E) influence investment and trade growth, while political factors (P) determine budget allocation and policy direction for infrastructure development (I), which drives market accessibility and logistics efficiency. Additionally, logistics competency (C) is crucial in reducing costs and enhancing competitiveness, whereas corporate decision-making (D) is influenced by investment feasibility, infrastructure availability, and supportive policies. The model integrates GIS, Discrete Choice Modelling, and Regression Analysis to evaluate multidimensional policy impacts, enabling policymakers to make data-driven and strategic decisions for sustainable and inclusive economic development.

Data is collected from reliable sources, including the National Economic and Social Development Council (NESDC), the Customs Department, and transport-related agencies. Geographic Information Systems (GIS) are employed to process spatial data and visualise transportation network structures and economic factors. The simulation integrates Discrete Choice Modelling to analyse decision-making behaviour and Regression Analysis to estimate the coefficients of significant variables affecting decision-making and policy impacts. Variables such as GDP, investment rates, transportation costs, and policy intervention levels are analysed using Maximum Likelihood Estimation (MLE) to ensure accurate coefficient estimations.

The model also incorporates scenario analysis and dynamic simulation techniques to assess the long-term implications of infrastructure development. The use of spatial distribution mapping through GIS allows for visualising how different policy choices can alter market accessibility, economic integration, and regional competitiveness over time.

Findings:

The developed simulation model serves as an analytical tool for assessing spatial impacts, reflecting various policy development scenarios through dynamic analysis. It enables policymakers to evaluate potential policy effects across multiple dimensions under different assumptions. The model is structured to incorporate scenario analysis and long-term economic and social changes within economic corridors.

The framework is designed based on five core variables:

- **Economy (E):** Gross Domestic Product (GDP), Gross Provincial Product (GPP), household income changes, investment rates, and trade volume.
- **Politics (P):** Policy support, budget allocations, and transportation-related projects.
- **Infrastructure (I):** Transportation network quality, including roads, railways, ports, and airports.
- **Competency (C):** Logistics cost models and border efficiency indices.
- **Corporate Decision (D):** Business decisions influenced by cost, time, and transport reliability.

The model applies Utility Theory to analyse business behaviour, assuming that firms select the most beneficial transport and investment options (Hering & Poncet, 2010). The Discrete Choice Model predicts transport mode selection based on utility maximisation, incorporating cost, time, and reliability factors.

Additionally, the simulation captures complex interactions among economic, social, environmental, and infrastructural factors. For instance, improvements in infrastructure directly enhance economic performance by reducing transportation costs and improving market accessibility. These changes can stimulate social development by increasing employment opportunities and access to essential services. However, economic expansion can pressure the environment, leading to increased resource consumption and potential

pollution. Conversely, environmental constraints can influence infrastructure planning by necessitating sustainable development strategies. The model allows scenario testing incorporating these interactions, enabling policymakers to anticipate trade-offs and synergistic effects between economic growth, social equity, environmental sustainability, and infrastructural improvements.

Spatial distribution maps and heatmaps generated through GIS reveal significant disparities in market accessibility across regions. The model also demonstrates how peripheral regions with limited infrastructure face higher transportation costs and longer delivery times, limiting their economic growth potential.

The interconnectedness of economic and infrastructural factors emphasises the need for integrated policy interventions to address regional disparities effectively.

Value:

This study contributes to policy development by offering a structured tool for assessing the spatial impacts of infrastructure investments and economic policies. The simulation model enhances the capacity of policymakers to predict policy outcomes, reduce risks associated with ineffective strategies, and promote inclusive and sustainable economic development. It serves as a strategic planning tool for infrastructure and logistics development, minimising economic disparities between central and peripheral regions.

The model offers a framework for evaluating trade-offs between different infrastructure investment strategies by applying advanced analytical techniques. It allows for better allocation of resources by identifying regions that can benefit the most from infrastructure upgrades, thereby enhancing national competitiveness and promoting balanced economic growth.

Research limitations/implications:

Despite its comprehensive design, the model has limitations in evaluating qualitative impacts such as community and socio-cultural effects, which may require additional qualitative research. The accuracy of the model is dependent on the completeness and reliability of statistical data sources. Moreover, external factors such as global economic fluctuations and unforeseen policy changes could influence the model's outcomes, highlighting the need for continuous model updating and calibration.

Practical implications:

The findings provide practical insights for policymakers, allowing them to anticipate policy impacts and refine infrastructure planning strategies. The model's application can help mitigate economic disparities, optimise logistics networks, and support evidence-based decision-making in economic corridor development. It also serves as a valuable tool for private sector stakeholders, enabling them to assess the feasibility of investments based on projected changes in infrastructure and accessibility.

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A Dynamic Decision Support Tool for Optimising Textile Waste Recycling Supply Chains

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Purpose:

The textile waste recycling industry, dealing with both post-consumer and post-industrial waste, faces critical challenges such as high operating costs, unstructured resource planning and greenhouse gas (GHG) emissions due to transportation. With 92 million metric tons of textile waste generated annually—ranking as the fourth highest-pressure category and the fifth largest contributor to GHG emissions—there is an urgent need for an intelligent decision support tool to optimise recycling supply chains. Despite significant research on textile waste management, no such tool currently exists to support data-driven decision-making for network design in recycling systems.

This research presents a supply chain network design model, integrating key recycling stages including collection centres, sorting facilities, recycling plants, and manufacturers. The tool aims to minimise overall supply chain costs—encompassing capital, operational, and transportation expenses—while simultaneously reducing emissions from processing operations and logistics. By balancing economic and environmental factors, this study provides practical insights for stakeholders on optimal facility locations, facility selection, inter-facility flows, and connectivity within the recycling supply chain. The proposed framework enhances operational efficiency, facilitates sustainable practices, and promotes a circular economy by transforming unstructured planning methods into a cost-effective and environmentally responsible supply chain design.

Design/Methodology/Approach:

The research employs an optimisation model to design an efficient textile waste recycling supply chain. The model integrates material flow analysis with supply chain network optimisation techniques, ensuring mass balance across collection, sorting, recycling, and manufacturing stages. Key decision variables include Optimal facility locations, Waste flow allocation between supply chain nodes, and Minimisation of both supply chain costs and emissions. A Mixed-Integer Linear Programming (MILP) model is formulated, using industry-relevant data to establish an optimised network. The model's validation will be further conducted through industry case studies, incorporating real-world data from recyclers, sorting centres, and collection centres. The core focus remains on cost and emission optimisation, while future work may explore dynamic adjustments of load sharing between different stakeholders through rolling planning horizons.

Findings:

The initial results indicate that the decision support tool effectively identifies optimal facility locations and material flow allocations, leading to significant cost reductions and lower emissions compared to conventional, non-integrated approaches. The model showcases how optimised network configurations improve facility connectivity, reduce transportation distances, and enhance resource utilisation. Even under varying cost and emission scenarios, the proposed network consistently outperforms traditional unstructured supply chain setups. These findings reinforce the practical value of an integrated decision support tool in stabilising planning processes, reducing operational inefficiencies, and driving sustainability in textile recycling supply chains.

Value:

This research presents the first decision support tool tailored for textile waste recycling supply chains, filling a critical gap in the application of existing supply chain network design methodologies. By optimising costs and emissions concurrently, it provides industry stakeholders, policymakers, and sustainability advocates with a robust framework to make data-driven decisions. The model's integration into industry will be tested in collaboration with recycling partners, ensuring its real-world applicability. The study contributes to the circular economy by reducing textile waste, lowering operational costs, and decreasing environmental impact, setting a foundation for future advancements in sustainable supply chain management.

Practical implications:

The use of this decision support tool provides immediate benefits to textile recyclers, producers, and logistics providers in waste management. This tool will assist practitioners in creating a systematic integration of supply chain networks for resource planning, operational efficiency, and sustainability. It provides real-time data-driven decision-making, allowing firms to choose the best facility sites, cut wasteful transportation costs, and minimise carbon emissions while remaining profitable. The model provides policymakers with an evidence-based framework for developing sustainable recycling legislation and incentives. This instrument contributes to waste reduction and circular economy objectives in the textile sector by optimising procedures.

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BUILDING RESILIENCE FOR SUPPLY CHAINS

Ensuring Robust and Resilient Industrial Symbiosis Network: A Case of the Dairy Industry

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Purpose of this Paper:

Industrial Symbiosis Networks (ISNs) are collaborative systems wherein three or more firms exchange secondary resources, such as by-products or waste, as inputs, forming a closed-loop network that supports resource efficiency and environmental sustainability (Chertow, 2007). However, when involving perishable by-products, such as in dairy, ISNs become acutely vulnerable to logistics, operations, and coordination disruptions (Chopra and Khanna, 2014; Fraccascia, Albino and Garavelli, 2017) which can rapidly destabilise symbiotic flows, triggering ripple effects (Ivanov, Sokolov and Dolgui, 2014). ISNs are a subset of SCNs, sharing structural foundations such as inter-firm coordination, material flow continuity, and systemic interdependencies (Herczeg, Akkerman and Hauschild, 2018). While SCNs emphasise economic efficiency and resilience in the sharing and transfer of primary resources like raw materials and finished products, ISNs pursue ecological value through the sharing and exchange of secondary resources such as wastes and by-products. These exchanges in ISN demand further refinement in infrastructure, tighter temporal alignment, and greater adaptability than SCNs. Despite differing objectives, resilience and robustness in both network types are underpinned by similar principles. In SCNs, resilience is studied through recovery dynamics, ripple effects and robustness is linked to structural redundancy and buffering capacity (Gunasekaran, Subramanian and Rahman, 2015; Simchi-Levi, Wang and Wei, 2018). Theory from these studies is applied to study ISN resilience and robustness. However, existing ISN resilience studies largely adopt macro-level perspectives and overlook how firm-level operational vulnerabilities can trigger disruptions in this highly connected type of network. To address the research gap, in this study, we developed a structured method for analysing firm-level disruptions and identifying strategic interventions to enhance the resilience and robustness of ISN.

Design/methodology/approach:

This study employed a research approach based on the development of a theory-informed framework development, followed by empirical data collection, and process-based simulation modelling.

A comprehensive literature review was conducted to identify ISN-specific vulnerabilities, disruptions and strategies that can be used to keep ISN robust and resilient. These findings informed the adaptation of the SCN robustness framework by Vljajic, Van Der Vorst and Haijema (2012). Further, we investigated the literature on waste valorisation for possible symbiotic partners for dairy processors and producers. We selected those who already operate in Northern Ireland and are candidates for a real ISN in the region.

Empirical data were collected through industrial site visits and semi-structured interviews with stakeholders across the dairy sector in Northern Ireland. Interviews were conducted to obtain (1) network and process characteristics essential for ISN scenario modelling; (2) quantitative data for parameterising the simulation model and disruption scenarios.

A process-based simulation model was developed to evaluate disruption impacts within an illustrative dairy ISN. The model employed a hybrid of Discrete Event Simulation (DES) and Discrete Rate Simulation (DRS) libraries from ExtendSim Pro 10 software. Key operational stages included milk collection, storage, processing, and downstream transportation. Emphasis was placed on the by-product flow and processes related to it, whose symbiotic flow was analysed using three ISN indicators – quantity coverage,

temporal coverage (Kosmol et al., 2021) and the technical exchange efficiency of the network (Fraccascia, Albino and Garavelli, 2017). These were mapped back against the ISN framework to determine phase-specific strategies, ensuring targeted interventions to ensure ISN robustness and resilience.

Findings:

The findings showed how different disruption types and severities influenced the stability of symbiotic flows and the overall performance of the ISN. Disruptions were classified using the developed vulnerability framework, identifying causes such as infrastructural fragilities, coordination breakdowns, and process constraints. Each disruption scenario was subsequently mapped to phase-specific intervention strategies - prevention, concurrent, and recovery. Firm-level disruptions within dairy operations, including cooling failures, valve malfunctions, and leakages, were identified as critical in triggering a ripple effect across the ISN. Further, through the lens of these indicators, the findings demonstrated that targeted strategic interventions during the concurrent stage sustained flow continuity, reflecting robustness, while interventions during the recovery stage re-established operations, evidencing the resilience of ISN.

Value:

This study presents a framework for robust and resilient ISNs, which enhance decision-making by linking firm-level vulnerabilities to targeted strategies across disruption phases – anticipation, concurrent, and recovery. Unlike prior ISN research focused on network-level disruptions, this study shifts the focus to firm-level disruptions and their propagation across the network, measured through its impact on ISN performance indicators. This approach aligns with the ripple effect concept in SCN literature but contextualises it within ISNs. The study also highlighted that perishability exhibits unique sensitivities to disruptions, requiring timely strategic interventions. While sector-specific in application, the framework is transferable to other industrial settings.

Research limitations/implications:

The empirical modelling in this study focused primarily on the firms anchored around dairy producers. While critical, this scope may underrepresent the role of smaller or peripheral firms whose disruptions can also affect overall network stability. Additionally, although the framework addresses firm-level and inter-firm dynamics, broader systemic resilience in real-world ISNs is also shaped by enabling policy environments. Future research should therefore expand the modelling scope to incorporate diverse network actors and policy-level interventions.

Practical implications:

Proposed dairy-centred ISN has value for the local agricultural sector, especially in Northern Ireland, where it contributes approximately 31% of total gross agricultural output and generates 2.5 billion litres of milk annually (Dairy Council, 2020). Given the volume of by-products and waste, operationalising ISNs in this context could transform regional sustainability practices by enhancing resource efficiency, reducing waste, and advancing circular economy principles.

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Demystifying the Fruit and Vegetables Supply Chain Complexities

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Purpose:

Many global businesses have recently experienced severe supply chain disruptions, which have brought new challenges, complexities and understanding of the need to restructure the operations of our supply chains. This calls for deeper inquiries into how supply chains, and more specifically food supply chains, are formed, structured and designed, what level of flexibility and responsiveness is currently considered within these chains, and what opportunities are there for further developing sustainable and resilient operations.

The food supply chain is key for human survival, therefore needs to be sustainable and resilient, bringing minimum impact on the environment it operates in, leading to social development and innovation, and being financially viable. Building on such aspirations, this paper aims to take a closer look at supply chain design by analysing the Fruit & Vegetables (F&V) supply chain from the point of its origin to the final destination.

Fruit and vegetables are crucial to the human diet, with health organisations like the World Health Organisation (WHO) recommending a minimum daily intake of 400 grams per person to promote overall health. Perishability is a key factor in the fruit and vegetable sector, and it increases the importance of effective planning and management. Each year, over two billion tonnes of fruits and vegetables are produced worldwide, which is enough to meet the global recommendations. However, nearly half of these perishable goods are lost or wasted, with 22% lost in the supply chain after harvest and during distribution (Moraes et al., 2020). As a result, the availability of F&V is insufficient to meet the global demand for healthy and sustainable diets for everyone.

Design/ methodology/ approach:

Given the complexity of F&V supply chains and their potential similarities, this paper analyses the supply chain of F&V by answering the question **RQ: How can resilience and sustainability in the F&V supply chains be built by drawing on FSC complexities and opportunities for innovation?** To do so, the case of F&V supply chain is analysed from their typical structure by taking a detailed look at the level of complexity. A supply chain complexity framework is proposed for this analysis, detailing implications for resilience and sustainability together with opportunities for innovation. The framework of supply chain complexity (Tipi, 2021) brings in characteristics such as the number of entities in the chain, the types of interactions, the predetermined attributes, the way in which a chain is evolving, together with operations complexity (suppliers, producers, transporters, warehouse, retailers), and consumer expectations.

Findings:

Findings highlight patterns for each of the selected supply chains, propose actions to overcome challenges in the face of complexity and innovative solutions for the operations of these chains. The resilience and sustainability of these supply chains are vital as they support the year-round availability and affordability of a wide range of fruits and vegetables, which are integral to a healthy diet and the economy.

The complexity of F&V supply chains can escalate at each tier, as illustrated in Figure 1 (based on various studies as detailed in the figure's source). There are a number of stakeholders that form part of the chain (suppliers, farmers, growers, transporters, wholesalers, warehouses, processing facilities, retailers, open markets, and consumers), as well as each case brings new complexities in operation that may impact F&V to reach their destination in a short period of time while preserving their quality and freshness.

In some instances, fresh produce that does not meet the standards for fresh sale is redirected as inputs for processing; however, in many other cases, this becomes waste. Another factor to consider is that, although government regulatory bodies influence all supply chain stakeholders, they are especially important before exportation, as they must approve F&V's sanitary and phytosanitary conditions.

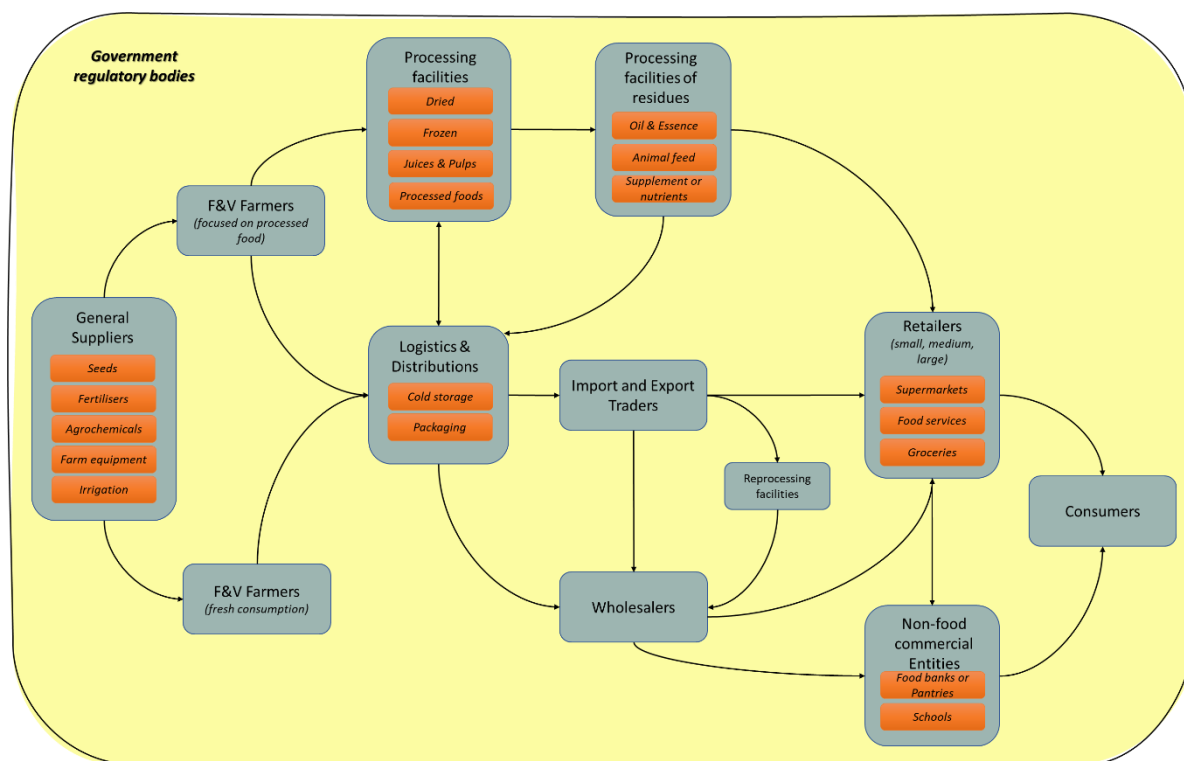


Figure 1. F&V complexity supply chain

Source: Based on several studies, such as Fernandez-Stark et al. (2011), Munhoz and Morabito (2014), Frankowska et al. (2019), Spiker et al. (2023), Vicario et al. (2023)

Value:

This work brings insights into how supply chain complexity (through innovation and challenges) could benefit the F&V supply chain by incorporating elements of resilience and sustainability in operations. The developed analysis framework can be used to a range of different supply chains.

Research implications:

In exploring the broad scope of supply chain complexity to build resilience and sustainability operations (Pereira & Yurt, 2024), a research agenda is developed that points out avenues where future studies could investigate different perspectives and opportunities that F&V supply chains could potentially bring to theory and practice.

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Enhancing Supply Chain Resilience for SME Food Producers: A Case Study From North East of England

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Purpose of this paper:

This study examines the implications of supply chain disruptions on supply chain resilience (SCRes) among small and medium-sized enterprise (SME) food producers, a critical yet under-researched area in the literature. While prior research has extensively explored SCRes in large firms, particularly during the Covid-19 pandemic, SMEs—despite their vital role in food supply chains—have received limited attention. Addressing this gap, the study focuses on SME food producers in the North East of England, a region where food production is economically significant but academically overlooked (NELEP, 2023).

The research aims to investigate how SME food producers adapted to Covid-19-induced disruptions, employing Complex Adaptive Systems (CAS) Theory (Van Yaroson et al., 2021) to analyse resilience strategies. By exploring both short-term responses and long-term adaptations, this study contributes to a deeper understanding of SME resilience mechanisms, offering insights for policymakers and business leaders seeking to strengthen supply chains in volatile environments.

Design/methodology/approach:

This study adopts a qualitative research design, utilising semi-structured interviews to capture the lived experiences of SME food producers in the North East of England. The phenomenological approach (Henriksen et al., 2022) ensures a nuanced exploration of how SMEs navigated supply chain disruptions during the pandemic. Data was collected via telephone interviews, balancing flexibility and consistency (Kallio et al., 2016), while mitigating logistical constraints.

A convenience sampling strategy was employed, with 25 SME owners participating—sufficient to achieve data saturation (Weller et al., 2018). Thematic analysis, supported by NVivo, was used to identify key patterns aligned with the research questions. The application of CAS Theory (Christopher and Holweg, 2011) provides a structured framework for analysing resilience as an adaptive response to disruptions, distinguishing between external pressures, internal dynamics, and coevolutionary outcomes.

Findings:

The study found that SME food producers faced severe supply chain disruptions during the pandemic, including material shortages, extended lead times, price fluctuations, and sudden demand collapses. Many experienced critical delays in key inputs like glass imports, while widespread stockouts forced production halts. Simultaneously, hospitality sector closures triggered catastrophic revenue declines, with some SMEs losing 80% of sales virtually overnight.

In response, SMEs deployed multiple resilience strategies. Many diversified sales channels through e-commerce and social media, while others increased supplier flexibility by localising procurement networks. Several firms demonstrated adaptive innovation, such as repurposing production lines for hand sanitiser manufacturing. Most transitioned from just-in-time to safety stock inventory models, reflecting a fundamental shift in supply chain philosophy.

Post-pandemic analysis revealed these adaptations became permanent operational improvements. Contrary to prior assumptions about financial constraints (Tong et al.,

2020), SMEs successfully implemented digital solutions and expanded supplier networks. Notably, resilience was achieved primarily through horizontal peer collaboration rather than vertical supply chain partnerships, challenging existing frameworks (Marusak, 2021). These findings suggest SME resilience mechanisms differ significantly from larger firms, emphasising the need for context-specific theoretical models and policy interventions to support smaller enterprises in future crises.

Value:

This study contributes original insights into SME-specific SCRes strategies, addressing a critical gap in the literature. By focusing on a geographically underrepresented region and employing CAS Theory, it provides a novel perspective on adaptive resilience. The findings challenge prior assumptions about SME limitations in digital adoption and collaboration, offering actionable recommendations for policymakers and business support organisations.

Research limitations/implications:

The study's reliance on convenience sampling and a single geographic context may limit generalizability. Future research could expand to other regions or incorporate quantitative methods for broader validation. Additionally, exploring sector-specific resilience strategies (e.g., perishable vs. non-perishable goods) could yield further insights.

Practical implications:

The findings highlight several critical implications for practice and policy. First, targeted policy interventions should facilitate SME digital transformation and strengthen localised supply chain networks. Second, comprehensive business training programs must be developed to enhance SMEs' capabilities in market diversification and risk mitigation strategies. Third, structured financial incentive mechanisms should be implemented to encourage SME investment in resilience-enhancing infrastructure and technologies. Collectively, these measures would significantly improve SMEs' capacity to maintain operational continuity during systemic disruptions, thereby contributing to more robust and sustainable supply chain ecosystems.

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Resilience of the Logistics Service Providers (LSPS) Industry: Exploring Drivers and Barriers

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Purpose of this paper:

The expansion of global business operations has significantly increased the complexity and length of supply chains. At the same time, larger-scale supply chain disruptions are occurring more frequently, caused by a broader range of sources (Hosseini et al., 2019; Ivanov, 2022). The pandemic has recently caused a prolonged crisis for supply chains. Additionally, geopolitical issues, such as wars erupting in various regions and the US-China trade war, have increased concerns. As a result, supply chain disruptions have become the new norm for businesses (Blessley and Mudambi, 2022), leading to a greater focus on the concept of supply chain resilience. Given this background, the resilience of logistics service providers has become an important aspect, as logistics operations play a crucial role in supply chain management and help mitigate vulnerabilities and risks (Song et al., 2022). Building on this significance, this study seeks to develop a conceptual framework that identifies the drivers and barriers of resilience in the logistics service providers (LSPs) industry and to create an index for firms operating in this sector.

Design/methodology/approach:

This study employs a mixed-method research strategy given its explorative nature. Principal component analysis is applied as a quantitative technique after qualitative methods of focus group and questionnaire implementation. The research methodology is illustrated in Figure 1. The research strategy consists of three main interactive phases: construct search, conceptual framework/metric development procedure, and empirical application. The research begins with an extensive review of the relevant literature and sector reports to identify constructs and associated items. Following this, a focus group study will be executed with experts from the Turkish Forwarding and Logistics Association (UTIKAD), which is the most comprehensive non-governmental organisation in the Turkish LSPs business. Achieving full consensus among experts on each construct and item serves as the legitimisation criterion. The subsequent steps involve developing a questionnaire and conducting a pilot test with the focus group to refine the survey instrument. An online questionnaire will be distributed to all 737 members of UTIKAD, aiming for a minimum response rate of 25 percent. Once data collection is complete, principal component analysis will be conducted in R to reduce the dimensionality of the variables. Assigning subjective average weights to each item complicates the accurate representation of their actual impact on the composite index to be developed (Pan et al., 2022). To address this challenge, principal component analysis is utilised as an objective method to consolidate the number of correlated indicators into a smaller set of comprehensive indicators. The robustness of the study will be assessed through reliability and validity tests. Ultimately, a conceptual framework and the Logistics and Transportation Resilience Index will be developed. In the final phase, the numerical values of the sub-components and the overall resilience value will be discussed with the companies in the focus group for validation. Additionally, a comparative analysis will be conducted to identify similarities and differences among the companies across various dimensions.

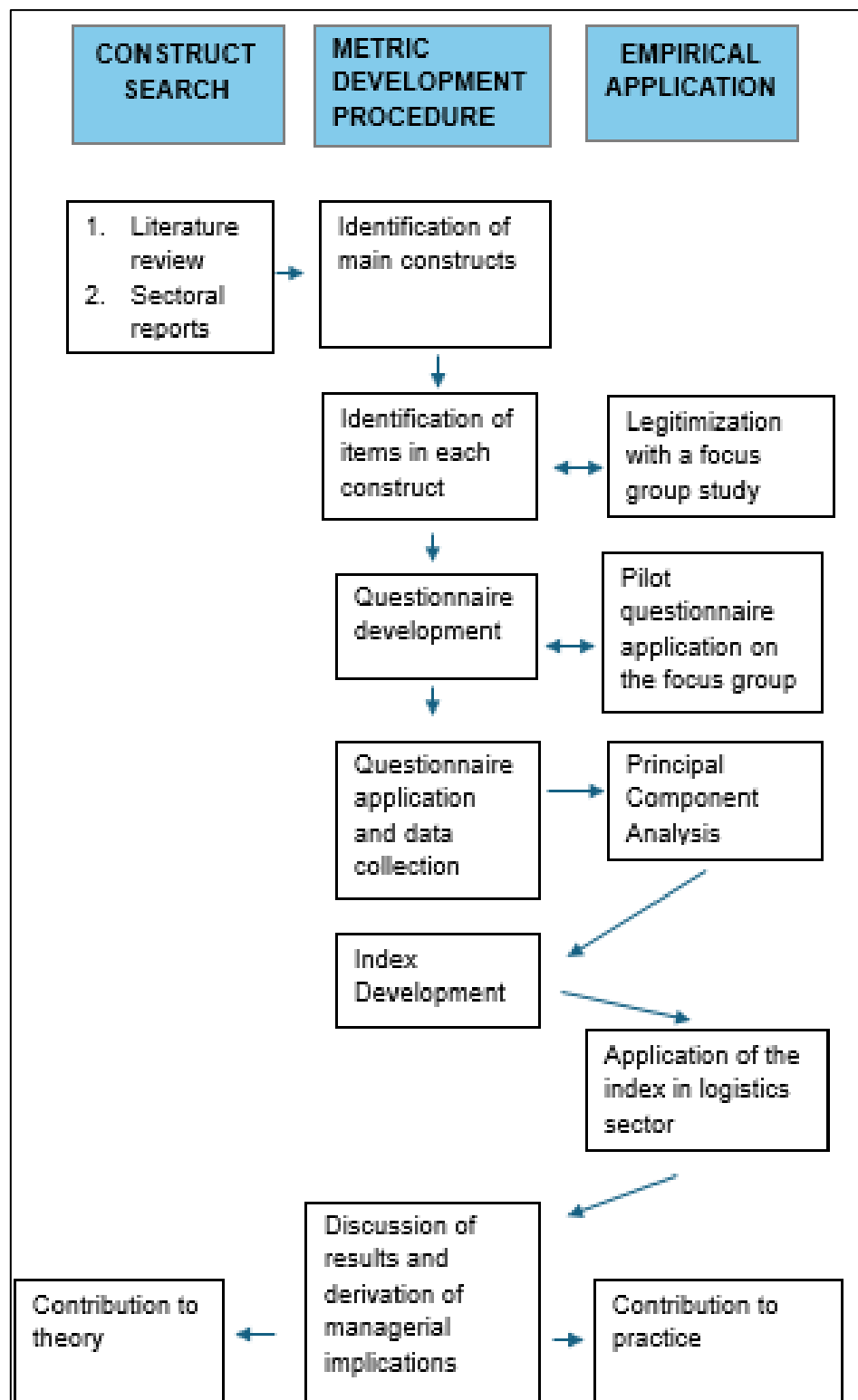


Figure 1. Research Method

Findings:

After conducting an initial literature review, the constructs and items related to the factors that enable and hinder resilience in a supply chain context were identified. In Table 1, the driving factors are organised into five constructs: management, strategy, supply chain integration, information, and organisation. Additionally, the barriers are categorised into

four constructs—relationships, supply chain integration, organisation, and macro environment—as shown in Table 2.

CONSTRUCTS	MAIN SOURCES
Management	
Resilience Culture	Christopher and Peck (2004)
Risk Management Culture	Christopher and Peck (2004), Sheffi and Rice (2005), Scholten et al. (2014)
Top management support	Ponomarov and Holcomb (2009)
Strategy	
Agility	Christopher and Peck (2004), Sheffi and Rice (2005), Ponomarov and Holcomb (2009), Scholten et al. (2014), Hosseini et al. (2019), Rajesh (2017)
Redundancy	Sheffi and Rice (2005), Dolgui et al. (2018), Jüttner and Maklan (2011)
Flexibility	Sheffi and Rice (2005), Ponomarov and Holcomb (2009), Pettit et al. (2010), Dubey et al. (2019b), Hosseini et al. (2019), Dolgui et al. (2018), Rajesh (2017), Jüttner and Maklan (2011)
Supply Chain Restructuring	Christopher and Peck (2004), Scholten et al. (2014), Rajesh (2017)
Adaptability	Pettit et al. (2010), Jüttner and Maklan (2011)
Standardization	Rajesh (2017)
Postponement	Rajesh (2017)
Dynamic Pricing	Rajesh (2017)
Strategic Stock	Rajesh (2017)
Dynamic Planning	Rajesh (2017)
Supply Chain Integration	
Collaboration	Christopher and Peck (2004), Ponomarov and Holcomb (2009), Pettit et al. (2010), Dubey et al. (2019a), Scholten et al. (2014), Hosseini et al. (2019), Rajesh (2017), Jüttner and Maklan (2011)
Information Sharing	Ponomarov and Holcomb (2009), Dubey et al. (2019a), Hosseini et al. (2019)
Logistics Integration	Ponomarov and Holcomb (2009)

Logistics Competitiveness	Ponomarov and Holcomb (2009)
Visibility	Pettit et al. (2010), Dubey et al. (2019a), Hosseini et al. (2019), Jüttner and Maklan (2011)
Supply Chain Connectivity	Dubey et al. (2019a)
Trust	Dubey et al. (2019a)
Robustness	Dolgui et al. (2018)
Velocity	Jüttner and Maklan (2011)
Information	
Big Data Analytics	Dubey et al. (2019b), Ivanov et al. (2018)
Anticipation	Pettit et al. (2010)
Knowledge Management	Scholten et al. (2014)
Organization	
Capacity	Pettit et al. (2010), Rajesh (2017)
Financial Strength	Pettit et al. (2010)
Efficiency	Pettit et al. (2010)
Recovery	Pettit et al. (2010)
Security	Pettit et al. (2010)
Organizational Structure	Pettit et al. (2010)

Table 1: Drivers of Supply Chain Resilience

CONSTRUCTS	MAIN SOURCES
Relationship	
Lack of Tier Visibility and Control	Doetsch and Huchzermeier (2024)
Limited Technological Capabilities of Partners	Doetsch and Huchzermeier (2024)
Supply Chain Integration	
Sensitivity	Pettit et al. (2010)
Complexity	Pettit et al. (2010), Cohen et al. (2022), Doetsch and Huchzermeier (2024)

Limited Supply Chain Redesign Options	Cohen et al. (2022)
Product Complexity	Doetsch and Huchzermeier (2024)
Lack of Internal Acceptance	Doetsch and Huchzermeier (2024)
Supplier/Customer Behavioural Uncertainty	Pettit et al. (2010), Dubey et al. (2019a)
Lack of Cross-Functional Teamwork	Doetsch and Huchzermeier (2024)
Lack of Data Visibility	Doetsch and Huchzermeier (2024)
Efficiency	Cohen et al. (2022), Doetsch and Huchzermeier (2024)
Organisation	
Resource Scarcity	Pettit et al. (2010), Cohen et al. (2022)
Financial/Budget Constraints	Cohen et al. (2022), Doetsch and Huchzermeier (2024)
Lack of Digital Capabilities and IT Infrastructure	Doetsch and Huchzermeier (2024)
Macro Environment	
External Pressures	Pettit et al. (2010)

Table 2: Barriers to Supply Chain Resilience

Value:

Supply chains face a variety of events that could interrupt operational activities and compromise performance (Hosseini et al., 2019; Ivanov, 2022). After large-scale disruptions severely impacted supply chains, firms are exploring ways to create more resilient supply chains for future turbulence. While there has been significant focus on factors that enhance supply chain resilience, the barriers have been overlooked in current research (Agarwal and Seth, 2021; Ali and Gölgeci, 2019). Therefore, empirical analysis of both positive and negative factors may provide new insights into achieving and maintaining supply chain resilience (Ali and Gölgeci, 2019).

In addition, measuring resilience has become a top priority for fully understanding an industry's resilience and managing disruptions. However, modelling efforts focus on supply chain risks rather than on quantifying resilience (Raaymann and Spinler, 2024). A brief review of some of the limited number of papers that develop resilience metrics is provided below:

Sahu et al. (2017) analyse the resilience drivers using fuzzy theory and present a multi-level framework for obtaining an appraisal index for industry resilience. A case study from an Indian automobile company confirms the effectiveness of the methodology.

Kumar and Anbanandam (2019) develop a tool to measure resilience for a manufacturing company in India using an integrated Delphi-fuzzy logic approach that considers various resilience drivers. Additionally, they identified the main obstacles to building resilience for the case company through a separate research process.

Agarwal et al. (2022) develop a model to quantify supply chain resilience by examining the interactions between resilience enablers using a graph theoretical approach. This model is applied to an Indian four-wheeler manufacturer.

Raaymann and Spinler (2024) quantify supply chain resilience using key performance indicators derived from the literature through text mining.

Borbon-Galvez et al. (2025) propose a new composite indicator with the enabling factors for the combined evaluation of resilience and sustainability, using primary and secondary data for the Italian industrial sector.

Narassima et al. (2024) use fuzzy logic to evaluate 33 enablers of supply chain resilience in 37 organisations across 22 industries and introduce a new coexistent resilience index based on mutualism.

Based on the existing research examined above, two primary gaps can be identified:

- i. Further research is needed to identify both drivers and barriers for the conceptualisation and measurement of resilience.
- ii. Quantifying resilience in the service industry is essential, as previous focus has primarily been on the manufacturing sector.

To fill these gaps, this study aims to develop a framework including both drivers and barriers of resilience for the LSPs industry and to propose a procedure to quantify resilience. In addition, this study proposes a convenient and practical tool for logistics and supply chain managers in the industry, which can be used to monitor resilience for self-assessment or benchmarking purposes. As a service business, the resilience of LSPs sector is an important component of resilient supply chains due to the urgent need for sophisticated logistics capabilities for disruptions (Song et al., 2022). Thus, this study makes another contribution by exploring a timely topic for a critical service business.

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Innovation Management and Strategic Collaboration in Supply Chains: Challenges and Opportunities in Colombia

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Purpose of this paper:

The purpose of this paper is to explore how digital transformation influences organisational success, with a particular focus on small and medium-sized enterprises (SMEs) operating in emerging economies such as Colombia. In an era marked by rapid technological evolution and heightened market volatility, organisations are increasingly required to adopt and integrate digital technologies to maintain competitiveness, enhance resilience, and foster innovation (Henríquez-Calvo et al., 2024). This study investigates the critical dimensions of business digitalisation—such as strategic alignment, operational efficiency, data-driven decision-making, and value creation—and evaluates their role in shaping firm-level performance outcomes. Beyond assessing technological uptake, the paper also examines the organisational capabilities, cultural factors, and leadership dynamics that underpin successful digital transformation processes.

The research aims to bridge the gap between theoretical frameworks—particularly those related to dynamic capabilities and socio-technical systems—and practical implementation strategies employed by SMEs. By analysing how digital tools and platforms contribute to increased agility, improved customer engagement, and sustained growth, the study provides an integrated perspective on digital maturity and organisational effectiveness. It also explores barriers such as resistance to change, limited digital competencies, and structural constraints, offering recommendations for overcoming them. Ultimately, the paper contributes to the growing body of literature on digital transformation in the Global South and provides actionable insights for business leaders and policymakers seeking to drive sustainable development through technological innovation.

Design/methodology/approach:

This study adopts a quantitative, correlational, and confirmatory research approach aimed at empirically testing the relationships between innovation management capabilities, strategic collaboration, continuous improvement processes, and supply chain performance in Colombian organisations. A structured online survey instrument was developed and disseminated via Google Forms, targeting professionals working in supply chain-related roles such as logistics, procurement, operations, and innovation management across various industries. The instrument included items adapted from validated scales in the literature and was structured using five-point Likert-type response options.

Data were collected from a diverse sample of professionals to ensure sectoral and organisational variety. Descriptive statistics were used to profile the sample, followed by Exploratory Factor Analysis (EFA) to confirm construct validity. Confirmatory Factor Analysis (CFA) was conducted to verify the factor structure, and Structural Equation Modelling (SEM) was employed to test the hypothesised relationships between latent variables and assess the model's overall fit. SEM fit indices included CMIN/DF, GFI, AGFI, CFI, TLI, and RMSEA, with results showing acceptable to strong levels of model fit.

This rigorous empirical methodology allows for robust validation of theoretical constructs and provides evidence-based insights into how dynamic capabilities affect supply chain performance in an emerging economy. Ethical approval for the research was obtained, and participant anonymity was maintained throughout.

Findings:

The study's empirical analysis, based on structural equation modelling (SEM), reveals nuanced insights into the interplay between innovation management, strategic collaboration, continuous improvement, and supply chain performance within Colombian organisations. The strongest and most statistically significant relationship was found between innovation management capabilities and continuous improvement processes. This result highlights that firms with stronger innovation practices—such as market sensing, knowledge integration, and collaborative development—are better positioned to systematically enhance their internal processes and adapt to dynamic conditions (Patiño Torres & García Pardo, 2024).

Strategic collaboration and information sharing also exhibited a positive, albeit weaker, influence on continuous improvement, suggesting that inter-organisational communication and trust-based partnerships support learning and operational refinement, though contextual barriers (e.g., regulatory and infrastructural constraints) may limit their full impact (Saunila et al., 2023).

In contrast, the expected direct relationships between innovation management, collaboration, and overall supply chain performance were not statistically supported (H3–H5 rejected). This implies that while these capabilities and practices are foundational, they do not automatically translate into measurable performance gains without further organisational maturity, ecosystem support, and integration. The findings suggest a pathway of indirect influence—where innovation supports performance primarily through its effect on continuous improvement (Kumar et al., 2014).

Overall, the study confirms that dynamic capabilities must be embedded in conducive environments and supported by long-term strategic alignment to yield tangible improvements in supply chain performance.

Value:

This paper offers original empirical evidence on the complex dynamics of innovation management, strategic collaboration, and continuous improvement within supply chains in an emerging economy context, specifically Colombia. Unlike prior studies that predominantly focus on developed markets, this research highlights how contextual barriers—such as regulatory inefficiencies and infrastructure deficits—mediate the impact of these capabilities on supply chain performance. The paper's value lies in its integration of a confirmatory structural equation model with context-specific variables, providing a nuanced understanding of how dynamic capabilities operate under institutional and economic constraints. It is especially valuable for supply chain managers, policymakers, and researchers seeking to design more effective innovation and collaboration strategies in Latin America and other emerging regions. By identifying indirect pathways—such as the mediating role of continuous improvement—the study also contributes theoretically by challenging linear assumptions in dynamic capabilities theory and offering practical guidance for capability-building in constrained environments.

Research limitations/implications:

This study presents several limitations that should be acknowledged to inform future research. First, the research is cross-sectional, which limits the ability to observe changes over time or to infer causality between dynamic capabilities and supply chain performance. Longitudinal studies would be valuable for examining the evolution of innovation and continuous improvement practices and their long-term effects. Second, the analysis relies on self-reported survey data, which may be subject to response bias or social desirability effects, particularly concerning organisational capabilities and performance. Third, the sample is geographically limited to Colombian firms, which, while offering important context-specific insights, may constrain the generalizability of findings to other emerging markets or institutional settings. Additionally, the study's rejection of direct performance

effects suggests that contextual factors—such as regulatory barriers, infrastructure gaps, and limited technological readiness—may overshadow organisational capabilities, yet these contextual variables were not directly measured in the model. Future research should integrate these external environmental variables into a more comprehensive framework. Finally, while the study applies a robust structural equation modelling approach, the complexity of interactions between constructs such as innovation, collaboration, and performance suggests the potential benefit of multi-method or qualitative approaches to deepen understanding of causality and underlying mechanisms.

Practical implications:

The study offers several important practical implications for supply chain professionals, organisational leaders, and policymakers in emerging economies, particularly Colombia. First, it underscores that innovation management capabilities are essential for strengthening continuous improvement practices, even if they do not directly translate into immediate performance gains. This suggests that managers should prioritise innovation not merely as a technological upgrade, but as a strategic process integrated with learning, problem-solving, and process enhancement. Organisations are encouraged to invest in building innovation-oriented cultures through cross-functional teams, training, and internal knowledge-sharing mechanisms.

Second, although strategic collaboration and information sharing did not show a direct effect on performance, their positive influence on continuous improvement implies that firms should strengthen trust-based, long-term partnerships with supply chain stakeholders. This includes developing interoperable information systems, establishing formal collaboration protocols, and participating in joint planning and innovation initiatives.

Third, the findings indicate that performance improvements may depend more on the maturity and depth of internal practices than on isolated capability deployments. Managers should focus on embedding continuous improvement into core operations and ensuring alignment between innovation, collaboration, and supply chain strategies.

For policymakers, the study highlights the need to address structural barriers such as regulatory inefficiencies and infrastructure deficits that currently limit the effectiveness of collaborative and digital initiatives in supply chains.

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Disruption Management in the South African Apparel Industry – Current Practices and Opportunities for Improvement

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Purpose of this paper:

South African apparel organisations are characterised by extended, international supply chains. These supply chains make them vulnerable to global disruptions resulting from events such as geo-political instability, natural disasters, and pandemics. Within the context of this research, a supply chain (SC) disruption was defined as any occurrence that disrupts the normal flow of goods and creates immediate and/or long-term negative consequences (Bode & Macdonald, 2017:837).

Some research has been performed on supply chain risk and disruption management within the South African context. This includes research with a focus on grocery manufacturers (Simba, Niemann, Kotzé & Agigi, 2017), grocery retailers (Hove-Sibanda, Motshidisi & Ingwe, 2021), 3PLs and their clients (Nel, De Goede & Niemann, 2018), omni-channel retailers (Weber, 2021), and the effectiveness of risk mitigation strategies in dealing with Covid-19 related supply chain disruptions (Nel, 2024). A gap in research was, however, found when it comes to the South African apparel industry, or a similar industry with extended, international supply chains.

The main aims of this research were to uncover current challenges when it comes to disruptions and the management thereof within South African apparel organisations, and to determine the extent to which they build resilience into their supply chains. The overall aim was to work towards identifying industry best practices and potential shortcomings when it comes to disruption management.

Design/methodology/approach:

A deductive approach to theory development was followed, using Macdonald and Corsi (2013) as foundation for the structure of the research. An exploratory case study on the South African apparel industry was utilised for the research strategy, focusing on large apparel retailers and their Tier 1 and Tier 2 supply chain partners (as well as logistics service providers).

Qualitative data was collected through 18 semi-structured interviews with an average time of 54 minutes per interview; the sample size and interview length being in line with research performed by Weber (2021). Purposive, expert sampling was utilised to include experienced industry role-players in mid to senior management or executive positions. Participants had to work in either a buying, planning, warehousing, logistics, manufacturing or exco position. The interviews focused on answering the four main research questions of this study. Participants were asked:

- 1) What are the most common disruptions within South African apparel SCs?
- 2) What impact do disruptions have on South African apparel SCs?
- 3) How are these disruptions managed and mitigated?
- 4) What SC management strategies are used to achieve SC resilience?

Interviews lasted between 35 and 120 minutes. All interviews were recorded and transcribed. Where clarification was required, it was obtained via email from research participants.

The data was analysed using a thematic analysis approach. The initial coding template was theory-driven, and later refined as data collection unfolded. Coding of the interview data took place in Atlas.ti with three levels of codes being applied.

Findings:

The research found that, in general, apparel role-players are more vulnerable to external or macro disruptions than to internal disruptions. The most common disruptions mentioned by participants were loadshedding (an interruption of electricity supply when the demand for electricity is greater than can be supplied), delayed product deliveries, and delays related to port operations. This is a reflection of the ongoing electricity supply crisis in South Africa, and the poor ranking of South African ports in the container port performance index (World Bank, 2023).

The reported impacts of supply chain disruptions were mainly related to increased costs, lost sales, and reputational damage. When it comes to the classification of disruptions by impact, only two participants mentioned that they classify and rank disruptions based on their impact on the financial bottom line. This is concerning, as the determination of financial impact gives an organisation greater clarity on the appropriate level of action that a disruption (or similar future disruptions) would require.

Current evidence shows that disruptions are largely managed on a case-by-case basis through reactive management strategies. There is great reliance on the experience of senior members of staff, with little focus on formalisation into institutional knowledge. Few role-players could identify the improvements/changes they had implemented in their supply chains due to past disruptions.

All research participants shared that they have implemented steps to improve the resilience of their supply chains, with the re-evaluation of sourcing strategies (and increased push for onshoring) and collaboration with supply chain partners being the most common.

Value:

This study expands on the current knowledge of supply chain disruptions and resilience, specifically as they apply to South African apparel supply chains. Industry case studies from developing countries are scarce, when it comes to disruption management. The findings provide valuable insight into the importance of understanding the disruptions that South African apparel organisations are vulnerable to and proactively putting measures and strategies in place to hedge against similar disruptive occurrences in the future. These would be of importance to new entrants to the market, especially those that are not familiar with the unique challenges that developing markets can pose.

Research limitations/implications:

The results reflect the explorative nature of the research and are mainly of a qualitative nature, in that they describe the current status quo of supply chain disruption management. Future research could focus on quantifying the impact of supply chain disruptions to the South African apparel industry as a whole. Quantifying the impact could serve as a motivating factor for the industry to collaborate in finding more sustainable solutions to frequently occurring disruptions.

One of the new questions that emerged from the research, namely, "Why do so few apparel role-players have limited or no visibility upstream into their supply chains?", would also be worth investigating.

Practical implications:

The recommendations propose that South Africa apparel role-players and their supply chain partners should implement a more formal supply chain risk management strategy, enhance visibility and increase flexibility, agility and redundancy within their supply chains. At the very least, role-players should use lessons learned from previous disruptions to enhance their knowledge of how to react to similar future occurrences.

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Enterprise Resources and Performance for Supply Chain Resilience of Machine Tool Industry in Taiwan

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Purpose of this paper:

In recent years, the pandemic, wars, and geopolitical tensions have created numerous challenges for businesses. For example, during the pandemic, border closures disrupted the smooth flow of raw materials and products between countries, putting supply chains at risk of collapse and threatening business survival. According to the COVID-19 recovery survey from McKinsey & Company (McKinsey & Company, 2020), 39% of manufacturers believed it would take 2 to 3 months to restore their supply chains to their original state, while as many as 54% estimated that full recovery would require 6 to 12 months. These issues have prompted companies to rethink how they can swiftly prevent and respond to unexpected disruptions, further emphasising the growing importance of supply chain resilience.

While previous studies have identified numerous complexities influencing supply chain resilience, such as digital resources, organisational flexibility, adaptive capacity and so on (Yadav & Cherian, 2022), these factors have rarely been systematically organised. Most research has focused on the impact of individual factors rather than examining how their interactions affect resilience.

Additionally, past studies have often assessed supply chain resilience as a whole, without breaking it down into specific business functions. Moreover, the measurement of supply chain resilience includes various indicators, such as financial performance, reputational performance, and supply chain performance (Paul & Saha, 2024). However, past studies have predominantly treated resilience as a holistic concept rather than analysing it at the level of specific business basic functions.

Design/Methodology/approach:

To address these gaps, this study applied resource dependence theory to categorise five factors into internal organisational resources and supply chain-integrated resources. Furthermore, it incorporated "supply chain performance"—one of the key performance indicators of supply chain resilience—within the framework of five basic functions (McGrath & Hoole, 1992). The objective was to explore how the alignment between internal and external resources influenced each of these business functions individually.

The questionnaire of this study was developed based on the original survey from the DR.SCR Supply Chain Resilience Enhancement Assessment Platform, jointly established by the Industrial Development Administration Ministry of Economic Affairs and the Industrial Technology Research Institute. A focus group was applied to refine and tailor it to the fitness of this research.

In total, 35 completed questionnaires were collected, with respondents consisting of business owners or senior executives from the machine tool industry in Taiwan, ensuring a certain level of reliability in the responses. This study adopts a two-stage correlation analysis as its research methodology. The first stage identified the relationships between internal organizational resources and supply chain integration resources. In the second stage, the correlated internal and external resources were paired and analysed against the resilience of the five business functions. This second-stage correlation analysis aimed to determine how resource alignment influences the resilience of each business function.

Findings:

Based on the analysis results, it was found that four significant correlations emerged in the first stage: digital resources and organisational flexibility from internal organisational resources, and information sharing and collaborative capability from supply chain integration resources. In the second stage, these four resource alignments formed nine impact pathways with the resilience of the five business functions: Product Development, Demand Management, Purchasing, Production, and Order Fulfilment.

By tracing back through correlation coefficients, the importance ranking of the four resources was determined as follows: collaborative capability, information sharing, digital resources, and organisational flexibility. Similar to past studies, Alzoubi et al. (2020) highlighted that collaboration within the supply chain has been regarded as a top priority for many manufacturing firms operating globally.

Overall, these four resource alignments each had varying degrees of impact on the resilience of the five business functions, demonstrating that the internal and external resources identified in this study were closely linked to overall business operations. Among them, the alignments of "digital resources and collaboration capability" had the most extensive influence, showing significant correlations with four out of the five business functions, with the exception of demand management. The alignments of "organisational flexibility and information sharing" showed significant correlations with demand management, purchasing, and order fulfilment.

Values:

These research findings provide valuable guidance for managers by offering a foundational understanding of the relationship between internal organisational resources and supply chain integration resources. This helps managers identify which internal resources should be prioritised to create synergies with supply chain partners. Additionally, the study presents empirically validated impact pathways, enabling managers to refer to these findings when optimising specific business functions and gaining deeper insights into the factors influencing resilience.

The two main contributions of this research aim to help businesses allocate limited resources more effectively by focusing on key factors that enhance supply chain resilience, ultimately maximising resource value and supporting the sustainable operations of companies.

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LOGISTICS CONNECTIVITY

Locker Systems in Sharing Models: Integrating Business Customers into Distribution Logistics

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Purpose of this paper:

The “Open B2B Sharing Economy” research project is investigating the integration of corporate customers into distribution logistics processes within sharing models. The focus is on the question of how companies can be integrated into the logistics process of sharing platforms in order to realise efficiency gains, reduce costs and promote sustainable transport solutions.

Although sharing has been used for many decades, the scientific focus is still on the B2C market (*Rojanakit et al., 2022*). Studies on logistical processes in the sharing economy and their implications for sustainability parameters, for example, are also insufficiently considered (*Moncef & Monnet Dupuy, 2021*). The same applies to the use of locker systems, which have so far been used almost exclusively in the B2C sector (*Sawik, 2024*). It can be argued that there are also players in the B2B sector for whom such a solution - particularly for the flexible and asynchronous transfer of goods - could represent an efficient and economically attractive alternative to traditional direct delivery.

A central objective of the study is to analyse the economic and logistical effects of asynchronous delivery via locker systems in the B2B sector. Locker systems represent an innovative solution for the last mile by improving flexibility of goods collection and reducing the need for individual deliveries.

The study looks at the following key aspects:

- What logistical challenges arise when using locker systems in B2B sharing models?
- Which influencing factors determine the acceptance of such systems by corporate customers?
- What economic threshold makes the implementation of a locker system profitable for companies?
- To what extent can the bundling of delivery flows via locker systems reduce traffic volumes and CO₂ emissions in urban areas?

Design/methodology/approach:

The research project “Open B2B Sharing Economy” is based on a mixed-methods approach that combines qualitative and quantitative methods to enable a comprehensive analysis of the integration of corporate customers in distribution logistics sharing models.

First, a comprehensive market and literature research was conducted to analyse existing sharing processes, platform structures and logistical requirements. The core research questions were defined on this basis.

This was followed by an empirical survey in two phases:

1. qualitative interviews with micro-enterprises, platform operators and logistics service providers to identify the key challenges and potentials of the sharing economy. Particular emphasis was placed on acceptance factors, economic thresholds and logistical requirements.
2. quantitative survey of a larger sample of companies to validate the qualitative findings and identify generalizable patterns. Among other things, the frequency of

use, perceived benefits and challenges and willingness to pay for logistics solutions were surveyed.

A key component of the research design was the exploratory field study, in which a locker system was tested as an alternative to traditional direct delivery. Companies were able to exchange goods via a locker system in order to analyze the effects on delivery times, flexibility and customer satisfaction. Challenges such as location selection, accessibility and organisational hurdles were empirically investigated.

In addition, a transport economic analysis was carried out to assess whether the bundling of traffic flows via locker systems can lead to a reduction in inner-city delivery traffic and CO₂ emissions.

This multi-stage research approach enabled both theoretical models and practical findings to be generated, which serve as a basis for future sharing models in the B2B sector.

Findings:

The “Open B2B Sharing Economy” research project provided valuable insights into the integration of corporate customers into distribution logistics processes within sharing models.

A key finding was that the acceptance of sharing models depends heavily on trust and organisational effort. While many companies see access to shared resources as a potential advantage, there are concerns about the availability, condition and return of the shared goods. In the B2B sector in particular, there is a greater reluctance to lend than to borrow, as there is concern that borrowed items will be returned damaged or incur unexpected maintenance and repair costs.

The logistical implementation showed that locker systems can be a useful addition to traditional direct delivery, especially in urban areas with limited access to delivery. However, the study showed that the acceptance of lockers depends heavily on the proximity to the company's location and opening hours. The time flexibility and the ability to receive and return goods outside regular business hours were particularly appreciated.

Another key finding was that economic factors play the biggest role for companies. While sustainability benefits were perceived as positive by many respondents, companies primarily opted for sharing models if they could reduce costs or achieve efficiency gains.

In addition, the transport economic analysis showed that the use of locker systems can reduce the number of delivery trips, provided that locations are chosen strategically. However, a final assessment of the environmental impact could not be conclusively made.

Overall, the results underline that effective sharing models in the B2B sector can be successfully implemented through a combination of trust, flexibility and economic benefits.

Value:

The “Open B2B Sharing Economy” research project sets itself apart by investigating the integration of corporate customers in distribution logistics processes within sharing models - an area that has so far been researched primarily in the B2C sector.

A key innovation was the testing of locker systems as a logistics solution for the B2B sharing sector. While such systems are already widely used for end customers, their potential for sharing between companies has hardly been investigated to date. The study provided valuable insights into the conditions under which locker systems are economically viable and what requirements companies place on such systems.

The project also combined economic, logistical and transport ecology perspectives in order to holistically assess the impact on operational efficiency, costs and sustainability.

The practical field test enabled real usage patterns and challenges to be identified, providing new impetus for the design of sustainable sharing models in the B2B sector.

Research limitations/implications:

The research was restricted by a limited field study, as delays in the implementation of the locker system could affect the generalizability of the results. In addition, the analysis is based on a small sample of micro-enterprises, which limits transferability. The long-term effect on traffic flows could not be conclusively assessed. Finally, the study focused on smaller companies, which means that the findings are not directly transferable to larger companies. Future research should consider a broader database and longer study periods in order to make robust statements about B2B sharing models.

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Bridging Sustainable Intent and Action: A Comparative Study of E-Commerce Consumers in Turkey and South Korea

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Purpose of this paper:

The rapid growth of e-commerce has transformed consumer shopping behaviours worldwide. In Turkey, e-commerce adoption has surged, with 51% of internet users engaging in online shopping according to Turkstat 2024. Moreover, South Korea is a major e-commerce market with a 94% internet usage rate among its population. However, the integration of sustainability into e-commerce platforms remains a challenge. This study investigates Turkish and Korean consumers' purchase intentions for sustainable e-commerce and examines how contextual cues influence their decision-making processes. Contextual cues, such as eco-labels, green packaging, carbon-neutral shipping, online promotions, and social reviews, shape consumer perceptions and trust in sustainable online shopping. Despite the growing literature on e-commerce consumer behaviour, research on sustainability as a determinant of purchase intention remains scarce. Understanding consumer behaviour is essential to drive sustainable consumption patterns and inform businesses and policymakers on effective sustainability strategies. This study aims to bridge this gap by providing qualitative insights into consumer behavioural patterns related to sustainable e-commerce.

Design/methodology/approach:

A qualitative research methodology was adopted using a snowball sampling technique. Data were collected through semi-structured interviews with Turkish consumers and Korean consumers who exhibit varying levels of engagement in sustainable e-commerce. The interviews were conducted via Zoom and other online communication platforms and face to face, allowing for broader participation and flexibility in data collection. This approach provided rich insights into consumer awareness, preferences, and decision-making processes regarding sustainability in online shopping. The collected data were analysed using thematic analysis, which enabled the identification of key patterns and recurring themes across participants' narratives. By employing qualitative analysis, the study effectively captured the complexity of consumer perspectives and behavioural patterns. The chosen methodology allowed for a flexible and detailed exploration of underlying factors influencing purchasing decisions, ensuring a deeper understanding of consumer attitudes toward sustainable e-commerce.

Findings:

This study represents one of the first attempts to explore Turkish and Korean consumers' perceptions of sustainable e-commerce. By conducting qualitative research, we gained an in-depth understanding of how consumers perceive and engage with sustainability in online shopping. The findings offer a nuanced perspective on consumer awareness and attitudes, which can be compared to previous studies conducted in other contexts. This research provides valuable insights into the current state of consumer perceptions in Turkey and Korea, highlighting both existing challenges and opportunities for promoting sustainable consumption in e-commerce. The study also underscores the role of digital platforms in shaping consumer attitudes toward sustainability. Additionally, the findings suggest that increasing consumer awareness through targeted marketing strategies and educational initiatives could enhance sustainable purchasing behaviours.

Participants in both countries identified a significant information gap regarding sustainability—they wished they knew more about what constitutes genuinely sustainable products. Price sensitivity was a common barrier to sustainable choices. Turkish consumers showed higher scepticism and mistrust toward green claims, alongside greater price sensitivity. Korean consumers, in contrast, expressed more trust in certifications and institutional support. They also emphasised convenience and fast delivery as key reasons for preferring online shopping, which often outweighed sustainability considerations. These differences reflect how cultural and supply chain contexts shape consumer narratives around sustainable e-commerce.

Value:

This study provides nuanced insights into sustainable e-commerce by comparing consumer perceptions in both a developing market (Turkey) and a digitally advanced economy (South Korea). Drawing on rich qualitative data, it reveals how emotional triggers, price sensitivity, institutional trust, and visual sustainability cues jointly shape online purchase behaviour. Rather than assuming a rational, information-based decision process, the study highlights the importance of embedding sustainability within familiar consumer heuristics—such as convenience, health consciousness, and visual trust. For businesses, it offers practical guidance on how to align sustainability messaging with culturally specific values and emotional motivators. For policymakers, the findings underscore the urgent need for credible labelling standards, consumer education, and platform-level transparency to reduce the belief-behaviour gap and promote sustainable consumption in e-commerce environments.

Research limitations/implications:

The study is based on qualitative interviews with a limited sample of Turkish and Korean consumers, which may not fully capture the diversity of consumer behaviours across different demographics and regions. Future research could expand the sample size and incorporate quantitative methods to validate findings. Additionally, longitudinal studies could explore how consumer attitudes toward sustainable e-commerce evolve over time.

Practical implications:

Sustainability strategies in e-commerce should reflect cultural contexts. In Turkey, where trust in certifications is low, emotionally framed messaging—focused on health, family, and moral values—is more persuasive than technical eco-labels. Trust-building requires locally resonant storytelling and transparent, relatable claims. In Korea, visual clarity, platform credibility, and speed dominate consumer priorities. Embedding sustainability into fast delivery services or top-rated products—using simple, trusted symbols—can improve engagement. Formal certifications are more effective here, especially when tied to seamless user experiences. Across both markets, personalised, culturally sensitive messaging, improved visibility of credible sustainability cues, and integration with reviews and social proof can help close the belief-behaviour gap. Policymakers should support these efforts through standardised labelling, required disclosures, and public education to build long-term trust in sustainable e-commerce.

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Adjustment of the Logistics Services in the Rail Transport System to the Current Challenges in the Hungarian/Slovak-Ukrainian Border Area

(Phase 1: HU-UA)

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Purpose of this paper:

Border areas are an important part of any national economy in any latitude/longitude. They are also important because of the special demand for logistics services that are performed for internationally traded goods. When an area adjacent to a national border is additionally also the end/beginning of a separate customs and functional area, the importance of smooth operation and handling of flows becomes crucial (Anderson et al. 2003; Decoville et al. 2013; Sousa 2013).

After the start of the current phase of Russian aggression against Ukraine (February 24, 2022), ensuring the logistical availability of the economy and armed forces has become a critically important element, and most of the related tasks have fallen to Poland, Slovakia and Hungary. This is because these countries have well-functioning transport networks linked to the European system, capable of handling West-East flows. The EU-Ukrainian border area is of particular importance also from the point of view of Ukraine's accessibility (in a broad, multi-vector sense). Entities from the Transport & Logistics sector operating in there fulfil important economic functions related to logistic security (regional, national, and cross-border).

The Hungarian/Slovak border junction with Ukraine is peculiar in that it operates in somewhat different geopolitical conditions than Poland. Both countries (Slovakia and Hungary) are not as unequivocally pro-Ukrainian as Poland, which results not only in different operating conditions for entities serving border crossings with Ukraine, but also in specific challenges for the entire rail transport system of those countries (Donski-Lesiuk 2022).

The main goal of the research is the identification of desired adjustment of the logistics market to current challenges related to economic and security changes (mainly of geopolitical nature) in the Visegrad countries and neighbouring countries. The analysis of:

- 1) what has changed over the last three years?
- 2) what directions of changes are desirable from the point of view of the efficiency of the rail transport system connecting the three countries (HU, SK, UA)?

seems to be appropriate, reasonable and purposeful as it is important for each of these countries and for each of the regions directly adjacent to the border.

Design/methodology/approach:

Various data acquisition techniques were used in the research. At the stage of verifying the current conditions under which the activities of Hungarian rail transport sector entities and their affiliates are carried out, a library search and literature analysis were carried out by the methodology described by W. Czakon (2015). Databases, contents of documents, including business development plans of the logistics sector were analysed, which allowed:

- a) to verify of the acquired data as to the subject and entity scope of the projects declared by the stakeholders (government bodies, companies, logistics operators),
- b) to collect participatory observation data, made possible by the presence "on the ground" and interviews with experts – employees of the Hungarian TSL sector specialising in the sphere of railway transport and cross-border cooperation.

With regard to qualitative data collection, it is crucial to have multiple sources (Gephart 2004) and then exploit them by confronting the source and informants in order to decipher clear trends and/or patterns. Just as importantly, the subordinate exploration, intentionally staged way of collecting data, and triangulation of their sources, helps minimize the likelihood of randomness in empirical data collection (Canter 1977; Miles 1979). The use of such an approach to data acquisition and verification will make it possible to realistically increase the level of final conclusions, while confronting the results of the Delphi study conducted with experts, which was achieved through interviews with experts.

The research was conducted in November-December 2024 during a research visit to Miskolc (Hungary).

Findings:

Selected conclusions, revealed in the study:

- There has been a significant decline in shipments across the Ukrainian-Hungarian state border after 2022;
- Transport & Logistics sector companies operating in the Hungarian-Ukrainian border area are struggling to find their way in the changed, severely constrained market reality, including reorganisation/change in the scope of the implemented processes;
- Experts do not agree on when to expect a change in the current unfavorable situation for the railroad sector;
- All players in the rail logistics services market are anticipating the change in current conditions and will welcome the intensification of processes for handling flows across the national border, regardless of their origin.

In addition, and worth noting, it proved quite problematic to find experts willing to participate in the study. While geopolitical issues, as a rule, tend to be associated with a certain point of view and/or affiliation with supporters/opponents of certain political options or parties, not in all countries is the willingness to express one's own opinions on issues that concern the state's foreign policy or its consequences.

The survey revealed a different openness of respondents in Hungary compared to the Polish or Slovakian reality (yet all three countries are part, along with the Czech Republic, of the Visegrad Group), however this finding is not an assessment of reality, but only its description.

Value:

The study includes phases corresponding to each of the Hungarian-Ukrainian (phase 1) and Slovak-Ukrainian (phase 2) border areas. There is currently a research gap in the literature related to the long-term effects of the changing of the geopolitical circumstances in the region, which used to be called *the Eastern Europe* and is now associated more often with *the Eastern external border of the European Union*.

While it may seem on the surface that the subject matter of the research outside of strict operational logistical thinking dictates, the value of the study and taking up the topic seems to be its connection to the market dimension of the operation of entities belonging to the Logistics (or, using another understanding, Transport & Logistics) sector and the spatial-political scope in which these entities operate. Such an approach does not seem to be popular, but gives, after all, a direct reference to the efficiency dimension of international SC systems.

Research limitations/implications:

A major limitation is the relatively small number of experts who agreed to take part in the survey (nine). Unfortunately, this is more a product of a number of objective factors, the author's influence on which is severely limited.

Potentially valuable addition to the whole picture will be the juxtaposition of the research conclusions with those that will be revealed in the Slovak-Ukrainian borderland (phase two), scheduled for the second half of 2025 (these will be the subject of a separate paper).

Practical implications:

Cooperation with Ukraine, which in the logistics sector is mainly based on operations related, on the one hand, to the supply of goods (including dual-use goods) to Ukraine, and on the other hand, to the reception of goods shipped from Ukraine in the Western direction, which are the results of its export activities; in the perspective of a potential change in the geopolitical situation, it will be focused on servicing the increased demand for goods used in the reconstruction of the Ukrainian economy. Both at the current and next stages, the effective functioning of the rail sector and the availability of the necessary resources required to provide freight exchange services at the desired level is a prerequisite for the economic development of any participant in international trade relations.

Cross-border economic interaction, which is rooted in the essence of establishing lasting functional ties between entities from different countries operating in border areas, is an important area relating to, among other things, the search for determinants of competitive advantage or the creation of networks of cooperative entities (Martens 2013; European Court of Auditors 2021). And since the level of development of border areas is linked to the economic and social characteristics of larger areas (Şlusarciuc 2015; Cappellano et al. 2022), identifying and understanding the real conditions of businesses is a tool for explaining reality.

Answers to questions:

- (1) Are the current projects effective? What still needs to be done?
- (2) Are the directions of infrastructure/market development sufficient? Will they serve the assigned goals of the border area cooperation?

which will be obtained through the implementation of the both phases of the research, will have a concrete impact on the functioning of the logistics entities of the border region.

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Unpacking Inventory Record Inaccuracy: Metrics, Contexts, and Implications

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Purpose of this paper:

Inventory record inaccuracy (IRI) is a pervasive problem in the retail sector, with significant implications for operational efficiency, product availability, and financial performance (DeHoratius and Raman, 2008). Despite its importance, research has thus far not explored how retailers measure IRI, evaluate the effectiveness of their measurement practices, or integrate these metrics into broader organisational processes. This paper addresses this gap by examining the metrics used to quantify IRI, the organisational contexts in which these metrics are applied, and additional dimensions such as reporting relationships and IRI maturity. By providing insights into these underexplored areas, the paper seeks to advance both academic understanding and practical approaches to inventory management.

Design/methodology/approach:

The research adopts a qualitative approach, centred on an in-depth interview study conducted with 25 retail professionals. Informants were selected using the principle of maximum variation and the replication logic to ensure a diverse and representative sample across retail segments, business models, and geographical locations. Semi-structured interviews allowed for a combination of predetermined questions and exploratory follow-ups, enabling the collection of rich, detailed insights. The interviews were transcribed and analysed using conventional content analysis, with categories and themes emerging iteratively from the data (Eisenhardt, 1989; Hsieh and Shannon, 2005). In addition to the interview study, the research synthesizes existing literature to contextualize its findings and highlight gaps in current knowledge.

Findings:

Our findings suggest significant variability in how IRI is perceived, measured, and addressed across the retail sector. Commonly used metrics include binary, absolute, and relative measures. However, we also identified inconsistencies in metric application and significant gaps in their integration with operational and strategic decision-making. Beyond metrics, the research highlights the importance of reporting relationships, organisational culture, and the concept of IRI maturity in shaping how retailers address inventory inaccuracies. These findings underscore the need for standardised measurement practices and a more holistic approach to managing IRI.

Value:

We make a novel contribution by systematically investigating IRI measurement practices and their organisational contexts. Our research is among the first to evaluate how metrics are used in practice while also exploring broader dimensions, such as IRI maturity and reporting structures. The insights provided are valuable for both academics seeking to expand theoretical frameworks on inventory management and practitioners aiming to improve their measurement and management of inventory inaccuracies. By bridging these domains, the paper offers actionable strategies for enhancing inventory record accuracy in the retail sector.

Practical implications:

The findings of this study have direct implications for retail practice. By identifying common metrics and their limitations, the research provides a basis for developing more effective measurement tools. Additionally, the emphasis on organisational contexts, such as reporting relationships and IRI maturity, offers practical guidance for integrating these metrics into decision-making processes. Retailers can leverage these insights to improve inventory accuracy, enhance product availability, and reduce operational costs.

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AI-Powered Automation in Yard Management: Enhancing Efficiency, Security, and Throughput with Smart Gate Check-in Systems and Precheck Applications

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Purpose of this paper:

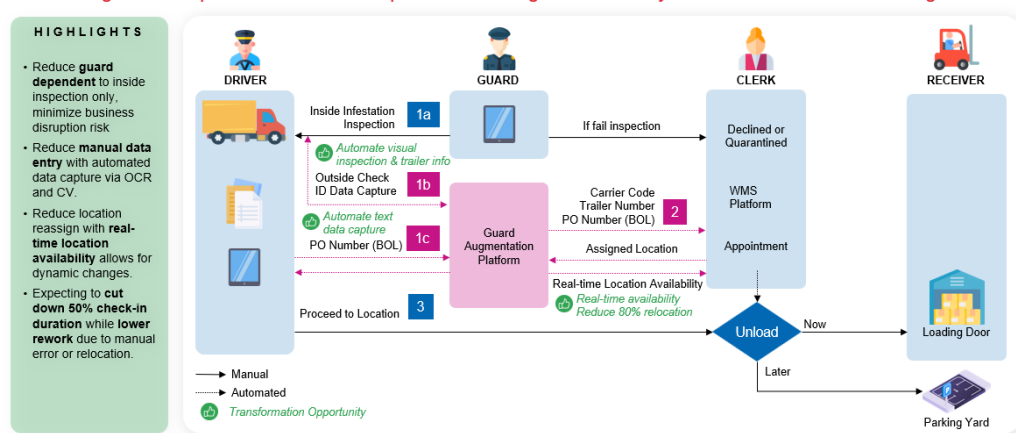
This research looks at how AI-based automatic gate entry and driver verification systems are designed and made available through a design science approach. The paper studied the problems with old manual check-in methods and showed how repeated design updates and organisational feedback played a role in building a solution that yard management could scale. Researchers not only discuss the products made in the research but also explain how the research was done and how it might be applied beyond one project. At the start, the initial prototypes were tested in controlled settings as part of a design science methodology. Advice from yard staff, IT workers, and operations supervisors helped to make the system faster, more accurate, and better integrated. By going through these stages more than once, the solution fits well with actual production conditions such as varying lights and changing trailer markings. The research also focused on what changes must be made in the organisation to help support adoption, such as updating staff training and altering the process at the gates. Often, depending on these mainstream methods can result in greater expense and more risks, so new solutions are required. The research looks at how AI cameras use computer vision and machine learning to spot trailers, trailer numbers, and license plates in real-time, easily match with the Yard Management Systems (YMS), and offer reduced dependence on manual actions. Furthermore, the paper studies how precheck applications help by allowing drivers to pass detailed information ahead of time, thus making the entry and exchange of details faster so the operation runs smoothly. One manufacturing company using these technologies as a case study saw substantial

savings, faster check-ins, and increased yard performance. As a result, this research directs companies on how to use AI to modernize their yard management, making their supply chain operations more efficient and protected. According to Montoya-Torres et al. (2016) (Pavel Cimili et al., 2024),

Design/methodology/approach:

This study uses technological tools to evaluate how bringing together driver precheck and automated gate check-ins can help with yard management. To start, it becomes clear that manual check-in methods can lead to data errors, major delays, risks to security, and poor overall efficiency, making an automated system needed. Next, the study explains how computer vision, OCR, and machine learning support an AI-based check-in system to recognise and confirm trailer details with no manual input. Such technology is even more effective because it is integrated with standard Yard Management Systems, making data always reliable and processing simple.

Automating check-in process to reduce dependencies on guards and rely on clerks for accurate management



The research also explores installing a driver precheck application, so that drivers can supply the required information prior to arrival, making manual gate verification unnecessary and improving how things are completed. A detailed analysis of a top manufacturing firm discusses improvements in time to check-in goods, greater yard efficiency and how much money it saved. The information in the paper helps organizations improve their supply chain operations with the help of AI (Song et al., 2020).

Findings:

The manufacturing company's case study showed that trimming the time spent processing check-ins by 30 minutes enabled them to handle 30% more deliveries in their yard. Yards can now be managed by artificial intelligence with the help of automated check-in and driver precheck apps. Cameras and apps that check people and use AI help employees work more easily, lower the facility's expenses and decrease security worries. The use of AI helps OCR in trailers guarantee high accuracy, especially in demanding conditions, while AI at the same time ensures that an AI can confirm up-to-date visits to stop unwanted stops (Song et al., 2020).

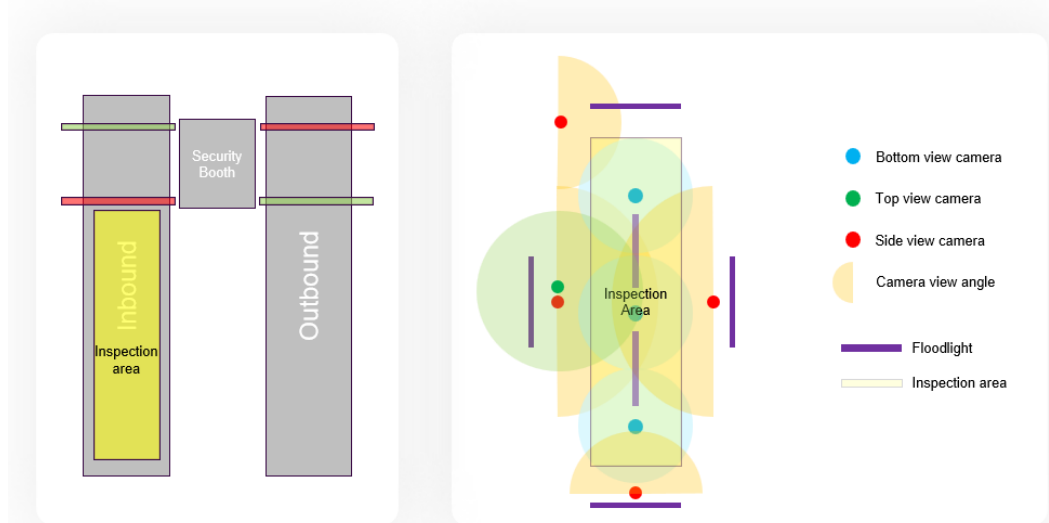


Additionally, the precheck application improves the company's operations by allowing drivers to share their information early, use speedy verification codes, and receive swift updates. All these improvements ensure smoother operations, fewer bottlenecks, greater savings, and greater profit. All in all, the approach proposed in this research gives valuable guidance to organisations focused on improving yard efficiency, security, and how the entire supply chain performs. As well as numerical benefits, the study uncovered key understandings about how the system's design has changed. Initially, identifying trailers and shooting well at night were problems, but researchers solved them by using adaptive learning models and brighter lights. To use the system, the organisation had to change how greeters check visitors in and how those roles were assigned. Solving these issues is important for adapting these approaches in other areas of industry.

Value:

The research provides a solution and a repeatable way to design AI-assisted systems for an efficient yard. Because the study captures how design, stakeholder engagement, and technical details changed over time, it offers practical advice for anyone putting such a solution into practice in different situations. Computer vision, OCR, and the integration with the real-time Yard Management System (YMS) make trailer check-ins quicker, more secure, and more efficient and tackle the challenges seen in traditional manual methods.

Check-in gate with possibility of self check-in





Using a real-world example, it was found that the system caused a 30% increase in yard activity and led to major cost savings. Thanks to the findings, logistics managers and technology experts have useful direction in encouraging technology advancements for their companies.

Research limitations/Practical implications:

While AI-powered gate check-in systems and driver precheck applications offer substantial benefits for yard management, several limitations must be acknowledged. These technologies require significant upfront investment in both hardware and software, posing challenges for smaller businesses with limited budgets. Their accuracy is heavily dependent on data quality—issues such as poor lighting or obstructions can impair performance. Additionally, real-time data exchange raises cybersecurity concerns if robust encryption measures are not in place. The study's insights are primarily drawn from a single case study, highlighting the need for broader validation across diverse industries. Future research should aim to expand case studies, explore advanced AI capabilities like predictive analytics and anomaly detection, and integrate IoT and blockchain technologies for improved operational visibility. Conducting cost-benefit analyses for SMEs is also essential. In practice, these systems can reduce check-in times from 30 minutes to under a minute; enhance security through real-time validation, and lower operational costs, benefiting industries such as retail, manufacturing, e-commerce, and third-party logistics (Song et al., 2020).

The research is constrained by its focus on a single industrial setting. However, the design science methodology adopted lays a foundation for future iterative studies across different organizational environments. Future research should apply the development framework in varied industries to validate adaptability and improve system robustness under diverse operational conditions.

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Operating a Parcel Locker Network with Mothership and Subship Drones for Last-Mile Delivery

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Purpose of this paper:

With the rapid growth of urban logistics delivery demands and the increase in the complexity of the last mile delivery, traditional delivery methods face significant challenges in areas with high population density. Stationary parcel lockers and home delivery solutions often face many challenges, such as inefficiency(Grabenschweiger et al. 2021), resources waste(Che et al. 2022) and environmental pollution(Ranieri et al. 2018, Demir et al. 2022). To solve these problems, this research aims to propose an innovative parcel locker delivery system that uses large-capacity mothership and small subships to operate together to develop a flexible, efficient and low-carbon urban logistics solution. In the new delivery system, large transport drones (i.e., motherships) are modified to incorporate the functionality of parcel lockers, serving as temporary aerial delivery stations that can dock in areas with concentrated customer demand. Simultaneously, motherships can carry and coordinate multiple small delivery drones (i.e., subships) to accomplish precise last mile deliveries for customers at longer distances. In this system, the mothership acts as both a delivery hub, replacing the ground-based capability of transporting parcels to autonomous parcel lockers (APLs), and a temporary aerial parcel locker, supplementing the delivery capacity of stationary parcel lockers. The main goal of this study is to supplement ground delivery capabilities by utilizing air resources, optimize the last mile delivery process, reduce energy consumption, shorten delivery time and improve service coverage.

Design/methodology/approach:

To achieve the research objectives, this study adopts a multi-stage approach. First, the K-means-based optimisation model is used to select the landing points of the mothership. By combining historical logistics data, geographical information and regulatory restrictions, a set of landing points is defined. At the same time, the K-means clustering algorithm is used to spatially group customer demand points that need to be delivered. Subsequently, the final landing point is selected by a mixed-integer linear programming model(MILP). This stage minimises the distance between the mothership and customer demands while ensuring the subship flight range and load capacity constraints, thereby reducing the energy consumption and time cost of subsequent distribution. After the mothership has completed its landings, this study further solves the Travelling Salesman Problem (TSP) to plan the optimal flight route of the mothership and determine the order of visiting each landing point. For the delivery operations of subships, the Vehicle Routing Problem (VRP) model is used to schedule the delivery tasks at each landing point to ensure efficient and timely completion of the "mothership-to-APL" package delivery within the operational restrictions. The entire system is simulated through Python, combining factors such as flight distance, energy consumption, landing time and delivery time constraints. This comprehensive approach allows detailed analysis of system performance and its potential to solve the last mile delivery problem.

Findings:

In the simulation experiments, we used randomly generated candidate landing points, customer demand data, and pre-defined model parameters to comprehensively validate and evaluate the performance of the entire system. First, by applying the K-means clustering algorithm to the customer demand data, we successfully divided the delivery demands within the city into several regions. Using MILP model, we selected the optimal

landing points from the pre-defined candidate set. The results showed that the selected landing points significantly reduced the distance to customer demand clusters, providing an efficient starting point for subsequent subship delivery tasks and lowering the flight distance and energy consumption of the subships. During the mothership route planning phase, we constructed and solved a TSP model to successfully plan a mothership landing route with the shortest total flight distance. This route not only covered all selected landing points but also demonstrated high operational efficiency in the simulated multi-region delivery scenario. Furthermore, in the subship route planning, we employed a VRP model with time window constraints to address the customer groups corresponding to each landing point. The experimental results indicated that, under the constraints of maximum flight distance and payload capacity, all subship delivery routes were able to complete tasks within the shortest delivery time, significantly reducing the overall delivery waiting time.

Value:

The innovation of this paper lies in the first proposal and implementation of an aerial delivery system based on the collaborative operation of motherships and subships, which organically integrates traditional parcel lockers and ground-based delivery models. By utilising large-capacity motherships as aerial stations and incorporating optimisation models such as customer demand clustering, mixed-integer programming, TSP, and VRP, the system achieves multi-objective optimisation of delivery routes, energy consumption, and waiting times. The system can flexibly select optimal landing points based on the logistics demands of different urban areas and efficiently complete last mile deliveries using subships, significantly reducing overall delivery costs and environmental impact. This research not only provides a novel solution for last mile logistics but also holds significant theoretical and practical value for logistics companies, urban planners, and academic researchers.

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HUMANITARIAN LOGISTICS

A Two-Echelon Truck Travelling Salesman Problem with Drone for Flood Disaster Response

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Purpose of this paper:

The truck-drone coordination distribution model was first proposed by Murray and Chu (2015). This model is growing rapidly, including the presence of a new vehicle type, such as an inflatable boat for flood disaster response, which is introduced by Ramadhan et al. (2025). Different from a prior paper, this study aims to develop a novel relief distribution model using truck-drone-boat vehicles to deliver items from a warehouse to shelters in multiple flooded regions. The proposed model provides several new aspects, such as the presence of multiple drones, multiple boats, multiple flooded regions, and multiple hub facilities. The truck carried items from a warehouse that will be dropped at multiple hubs. Each flooded region consists of one hub and one boat. After that, the boat will deliver the items to the shelters. At the same time, multiple drones can be utilised to deliver items directly from the warehouse to the shelters. As boats have more capacity than drones, boats can transfer the items with multi-visit movements in one trip, while drones can only make single-visit movements. This concept is designed as a two-echelon distribution model. We refer to this model as a Multi-Hub Multi-Region Truck Travelling Salesman Problem with Drone and Boat (MHMR-TSP-DB). The aim is to minimise the maximum return time to the depot for the truck and drones, where the hub is for boats. We refer to this objective as completion time.

Design/methodology/approach:

In this study, we developed the MILP model. We solve the model using an exact method (EM) to obtain the solution. As the complexity of the model is high, we also developed a matheuristic-based approach by combining EM and simulated annealing methods to produce a better solution quality, especially for the large-sized datasets. We refer to the proposed solution method as a Matheuristic-based Simulated Annealing (MSA). The proposed MSA is developed by performing several procedures. First, we use the framework of simulated annealing by iterating the procedures based on the temperature condition. Inside the iterations, a local search is performed by implementing swap inter-route and new drone-boat allocation routing procedures. In this new procedure, we aim to produce a good solution for drone allocation, followed by implementing a nearest insertion procedure for the multiple boat routes solution. In addition, we combined this procedure with EM to solve the timing coordination constraints among vehicles. In the last step, an additional shaking procedure is also developed to find other combinations by implementing the reverse route, 2-opt, and 1-0 insertion procedures for the truck route. To validate the solution quality, the MSA result is compared with the EM in terms of objective and solving time.

Findings:

In computational experiments, first, we adapted the datasets from Agatz et al. (2018), where the remaining parameters are generated randomly. There are three types of datasets such as small-sized (7, 8, 9, 11, 12, and 13 nodes), medium-sized (24 and 54 nodes), and large-sized (80 and 105 nodes) datasets. In small-sized datasets, EM can obtain the optimal solution with fast computational time (CPU) at 0.31 seconds. The MSA method can also obtain the optimal solution with a fast solving time of 1.26 seconds. In the medium-sized, EM starts to face difficulty, where the deviation of the solution quality is at 3.81% compared to the best-known solution with 1001.33 seconds in CPU time. On

the other hand, MSA outperformed EM, where the deviation is 0.00% and the CPU time is much faster at 6.11 seconds. This condition also happened in large-sized datasets, where EM deviation is at 7.57% with 1046.16 seconds of CPU time, while the MSA deviation is 0.00% within 12.36 seconds. Overall, the MSA has a better result than the EM, where the average deviation is 0.00% with the CPU at 4.45 seconds. The proposed model and method are also tested using case study instances from Jakarta's flood disaster in Indonesia. The results also show that the MSA can obtain good solutions with fast CPU time at around one second. To sum up, the findings show that the MSA is a powerful approach to solving the model.

Value:

This study proposed a novel vehicle tandem-based model for flood disaster response that is not discussed in the previous literature. In the prior study, Ramadhan et al. (2025) introduced the truck-drone-boat coordination model for flood disaster with only a single vehicle for each type. Moreover, that prior study only considers one flooded region without any hub facility. On the other hand, the presence of multiple flooded regions and hub facilities sometimes happened in real conditions, so that the proposed MHMR-TSP-DB model provides new values and insights about how to implement the effective vehicle tandem-based model in flood disaster response.

Research limitations/implications:

This research has a few limitations. For the model, the multi-warehouses, multi-trucks, and stochastic aspects are not considered, so that those aspects can be identified further for future research. To accommodate the stochastic model, in future research, another suitable solution method can be used, such as combining the simulation and optimisation methods to solve the related model.

Practical implications:

Flood disaster is one of the dangerous disasters, where 23% of the global population is directly at risk of flooding (Zhao et al., 2024). Therefore, an effective disaster response, such as utilising a truck-drone-boat relief distribution model, is very useful for stakeholders. This study provides an experiment on a realistic case study, followed by practical managerial implications that can help the decision-makers, such as a national authority of disaster management, to handle the flood disaster response faster with effective results.

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Humanitarian Supply Chain Operations and the Roles of Data-Driven Innovations

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Purpose:

The COVID-19 pandemic revealed a poor level of preparedness by the manufacturing sector in building a resilient smart operations and logistics framework to respond to severe global supply chain disruptions. This research focuses on the effectiveness of data-driven innovation strategies in mitigating the impacts on humanitarian operations of Covid-19 related supply chain interruptions. It is supported by the outcome of a comprehensive overview of the major conceptual issues in the literature. This review uncovered two main topics of debate notably (i) the significant role of big data analytics and Artificial Intelligence in boosting firm performance by untangling supply chain disruptions and (ii) the paucity of research in this emerging area of literature. The paper explores how humanitarian, and emergency operations faced many obstacles, ranging from lack of real-time information or communication with the disaster victims, to poor predictability of demand, improper coordination of supply and inability to achieve last time operations. These obstacles range from insufficient data, lack of real-time visibility for effective coordination among stakeholders, scaling problems of environmental hazards, limited data analytics capabilities, to traditional supply chain management (SCM) system. Clearly, these technologies enhanced collaborative arrangement across local, regional and interorganisational space in the context of supply chain operations.

Design:

This paper proposes a conceptual model for humanitarian supply chain operations to highlight how big data analytics and AI technologies could be deployed by firms to gain a competitive advantage by responding promptly and effectively to severe disruptions akin to those experienced during the recent COVID-19 pandemic. The critical functions of the model indicate that a swift and competent application of big data analytics and AI technologies improve resiliency, visibility, and responsiveness within supply chain networks, which in turn strengthens the coordination among major stakeholders. Due to these complexities, frameworks for data-driven analytics and decision-making are now highly needed, and only cutting-edge technologies such as blockchain, IoT, big data analytics (BDA), 3D printing and artificial intelligence (AI), which are becoming increasingly intricate and linked in SCM can mitigate these drawbacks. The theoretical model described in this paper also makes meaningful contributions to the operations management literature. These effects could materialise into the short or long term. These negative impacts obviously will make sustainability in HSCs a challenging, as well as an important topic to study. Prior to COVID-19 pandemic, companies have focused on reducing cost through contract manufacturing and lean manufacturing, offshoring, and outsourcing, as strategies sustainable supply chains disruption.

Findings:

Most scholars believe that in disaster management cycle, Humanitarian Supply Chain is the major backbone in amending disruption physically for the following reasons: 1) it serves as a bridge between disaster preparedness and response, and between procurement and distribution; 2) it is crucial to the effectiveness and speed of response for major humanitarian programs, like health, food, shelter, water and sanitation; 3) it can be one of the most expensive parts of relief efforts and operations. Big data analytics identify general trend and correlations, since several authorities such as governments, large corporations including general publics are often subjected to extensive analysis based on the use of algorithm. For instance, where aid agencies switched to remote data collection and relied heavily on use of telecommunications and digital tools, such as phone

calls, online survey, SMS, and messaging app (such as WhatsApp and Signal). Big data analytics support aid-relief agencies in epidemic surveillance and response. Literature reveals limited number of studies focusing on the management of supply chain disruptions using advanced technologies, despite strong evidence that consequence of the covid-19 pandemic is that a growing number of firms are shifting their operations online supported by big data analytics and AI technologies.

Value:

It is a general believe that the success of any humanitarian operation is a direct function of efficiency and effectiveness of coordination and management in getting the key stakeholders, including the supplies to the right place as quickly as possible. The key stakeholders comprise of established suppliers, operators of pre-positioning centres, operators of local distribution points, ad hoc suppliers, government agencies, aid/relief organisation, and donors including local, regional or international entities. Therefore, any poor humanitarian supply chain management will result in a continued suffering of the victims resulting in major negative impact on the social and economic conditions of the receiving community, countries or regions. Example is the refugee crisis that often characterised this unfortunate invest. Refugee crises among other man-made disastrous events such as arm conflicts, epidemics, famine, are the direct result of humanitarian emergency experienced by several countries. These man-made disasters, particularly refugee crises have contributed significant risks to health, safety and well-being on the receiving communities.

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SUPPLY CHAIN SKILLS, TRAINING AND EDUCATION

Gamification, Creative Thinking, and Lego® Serious Play: Transforming Supply Chain Education in Higher Learning

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Purpose:

With growing challenges related to sustainability and the increasing influence of technology on operations and supply chain management (e.g., digital twins, blockchain), learners require a comprehensive skill set in problem-solving, as well as an analytical and creative mindset to understand and contribute to solutions for emerging business challenges (e.g., Dyke et al., 2012). The World Economic Forum has identified analytical skills, creative thinking, AI/Big Data, and systems thinking as core competencies for the workforce of 2030 (World Economic Forum, 2025). For Supply Chain and Operations Managers – who often navigate complex environments, from overseeing daily operations to managing global supply chains – a diverse skill set is essential. However, from an educational perspective, teaching complex systems while developing soft skills and subject knowledge alike, requires innovative and engaging approaches (e.g., Deif, 2023).

Experiential learning is a pedagogical approach that actively engages with learners. Gamification, a tool within this approach, enhances participation through interactive game elements (Manzano-Leon et al., 2021; Deif, 2023). As an interactive tool, LEGO® Serious Play (LSP), promotes innovation and problem-solving by enabling participants to express ideas, achieve objectives, and think creatively using LEGO® bricks (Blair et al., 2016). LSP supports diverse learning approaches through both individual and collective builds. While existing literature explores LSP's use in a diverse range of business management environments (e.g. Wheeler et al., 2020; Deif, 2023), no study has combined it with other business and problem-solving approaches to create a holistic learning experience. This research aims to explore the impact of LSP as an innovative teaching tool and examines the effects of combining the problem-solving method 'Lightning Decision Jam' (LDJ) with LSP in business management education.

Design/Methodology/Approach:

This research employs a longitudinal design guided by Interpretative Phenomenological Analysis (IPA), a qualitative approach that explores how participants contextualise and interpret personal experiences (e.g., Braun & Clarke, 2013; Wheeler et al., 2020).

A comparative case study approach was adopted, involving four cases conducted over two years within the MSc Logistics and Operations Management Programme and the Executive MBA Programme. In the first year, two cases implemented LSP as the sole pedagogical tool, aiming to strengthen critical thinking and introduce design thinking principles through individual and collective building strategies. In the second year, two cases integrated LSP with LDJ to examine how combining these two innovative methods influenced learning outcomes. This approach provided insights into the effects of integrating LSP and LDJ, offering an understanding of their combined impact on learning.

Findings:

Findings from the first year revealed that the majority of students found the LSP-based workshop effective in understanding and applying creative thinking skills through hands-on activities and practice-based learning. Key elements of LSP, such as active building, storytelling, and reflection, enhanced engagement and allowed learners to explore strategic concepts beyond the traditional gamification elements of points, badges, and leaderboards. This approach also promoted inclusivity, as LSP was perceived as more engaging and accessible compared to other gamification methods (e.g., simulation games),

ultimately allowing learners with varying learning styles (visual, kinaesthetic, and auditory) to express their viewpoints. Further findings showed that the different levels of LSP (individual and collective builds) enabled learners to better understand team dynamics and fostered creativity. Learners particularly appreciated the prototype building and 3D visualisation, which provided a unique experience compared to other methods. Overall, the structured nature of LSP helped reinforce learning and effectively connected theoretical concepts to practice.

Building on these results, the second year aimed to explore whether combining LSP with other creative and innovative learning methods would further enhance learning outcomes. In this phase, LSP was integrated with LDJ methodology to explore the impact of combining these approaches. Findings from the second year indicate that the combination of LDJ and LSP enhances problem-solving by blending structured decision-making with creative prototype building. While LDJ kept learners focused and provided a clear framework for decision-making, LSP encouraged creative thinking and open-ended exploration. Key advantages of this combined approach included improved creativity, increased engagement, and greater inclusivity, allowing for serious discussions in a playful environment. The combined method also promoted effective team collaboration, clear problem definition, and democratic decision-making. However, some challenges were noted, including potential distractions and scalability issues when applied to larger groups or organisations. Overall, the integration of LDJ and LSP helped to improve problem understanding, solution development, and group participation.

Value:

This research highlights the value of gamification in higher education for developing soft skills like critical thinking, creativity, and teamwork. LSP is seen as innovative approach. Combining it with LDJ enhances learning by integrating structured decision-making with creative problem-solving. The combined approach increases engagement, fosters collaboration, and helps learners to apply theoretical knowledge to real-world challenges. It also provides educators with valuable insights into student interaction, decision-making, and team dynamics, aligning with gamification and experiential learning to promote active learning and reflection.

Research Limitations:

The study acknowledges the limitation of using empirical data from four cases with postgraduate cohorts. Future research would benefit from expanding to include undergraduate cohorts, allowing for a comparative analysis of how learning through this gamification tool is perceived across different educational levels. Additionally, broadening the scope of data collection to include more qualitative methods could provide deeper insights into the effectiveness of the approach.

Practical Implications:

LSP offers a valuable alternative to traditional simulation games in operations and supply chain management. To maximise its impact, careful consideration of learning objectives, build questions, and reflective tasks is needed. The combined approach of LSP and LDJ further enhances the learning experience by integrating structured decision-making with creative problem-solving, benefiting both learners and educators.

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No One Left Behind: Supply Chain Skills for an Inclusive Transition to a Circular Economy

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Purpose:

This research investigates what are the skills and competencies that the supply chain management (SCM) literature identifies as relevant in the transition to circular supply chains (CSCs). More specifically, it *explores what SCM literature reports on low-skill and high-skill requirements for implementing restorative supply chains, focusing on the technical cycle of the circular economy*. This project also adopts a *just transition approach* by paying especial attention to the skills and competencies suggested by SCM literature required for low-skilled workers.

The transition to a Circular Economy (CE) cannot happen without the support of supply chains, which must also undergo transformations. SCM functions are central to facilitating the CE transformation thanks to their cross-functional roles in coordinating the needs of suppliers, customers, and business operations (Zils et al., 2023). Current CSC shifts include procurement strategies that emphasise leasing and service models, cascaded material flows requiring cross-chain collaboration, and expanded networks that integrate untraditional stakeholders (De Angelis et al., 2018). These changes come with requirements for both high and low skilled jobs (Govindan & Hasanagic, 2018). High-skilled professionals will need competencies such as the ability to build cascades and reverse cycles (EMF, 2014), and the ability to foresee and manage transition challenges like cannibalisation (Bressanelli et al., 2019). Meanwhile, labour-intensive processes—e.g. recycling and waste management—will drive demand for low-skilled workers (Alvis & Avison, 2021; Govindan & Hasanagic, 2018).

While scholars have acknowledged the relevance of new or updated competencies and skills for the CE with a few notable cases (Beducci et al., 2024; Burger et al., 2019; De los Rios & Charnley, 2017; Sumter et al., 2021), the topic is still in its infancy (Hofmann Trevisan et al., 2024; Straub et al., 2023), particularly so within the SCM literature. A few SCM papers addressed skills as levers for dealing with CE-specific challenges (Bressanelli et al., 2019), as a capability to promote the CE (Chari et al., 2022), or as a hindering factor when absent (Govindan & Hasanagic, 2018), yet none focus explicitly on CE skills. Literature on CE implementation and implications for SCM is still scarce (De Angelis et al., 2018). It comes as no surprise that skills and competencies in this area have received far less attention. Given the crucial role of SCs supporting and driving changes towards closed- and open-loop cycles (EMF, 2014), more research is needed on the implementation of CSCs at large scale and supporting factors such as skills and competencies. Considering this gap in the literature, the first aim of this project is to *understand what has been reported so far by the SCM literature on skills and competencies for implementing restorative supply chains through a systematic literature review*.

This research also adopts a 'just transition' approach in examining the skills for transitioning to CSCs. Existing studies have largely focused on high-skilled jobs (e.g. designers, engineers), while research on low-skilled workers remains insufficient. Insights into inclusive transitions have been primarily provided by policy and government institutions (Cambridge Econometrics et al., 2018; Circle Economy, 2021; European Economic and Social Committee, 2023), while SCM scholars have not given due attention to the topic with the exception of Karaosman et al. (2024). Looking at just the transition from the SCM standpoint, these scholars emphasise the integration of lower-tier and marginalised SC stakeholders. Low-skilled workers face significant vulnerability due to economic shifts related to the circular transition; thus, understanding pathways for

reskilling, upskilling, and redeployment in new, alternative settings is essential (Karaosman et al., 2024). Embracing this call, the current project also aims to *understand how just transition thinking in skills and competencies for restorative supply chains has been addressed by the SCM literature*.

Research design:

This study focuses on the skills essential for the technical cycle in restorative SCs, encompassing both reverse SCs that enable closed-loop cycles of products and components, and forward open-loop cycles that support cascading material flows beyond the original SC. The technical cycle has been selected because the inner loops and extended circulation entail processes that require both low- and high-skilled jobs, in line with the aims of this paper.

Following well-known reviews at the intersection of SCM and the CE, this study adopts a systematic literature review (SLR) approach (Tranfield et al., 2003) to explore the current state of SCM literature. This method allows to map, consolidate and identify gaps in the existing SCM body of knowledge.

Using Scopus and Web of Science databases, papers that include selected key terms relevant to the CE, SC functional areas, and skills, are extracted. Cross-refencing helps in identifying any relevant papers left out to later apply exclusion criteria before moving to full-paper analysis.

Findings:

This SLR is in progress at the moment. Preliminary findings will be presented in the symposium.

Value :

A very limited number of studies in the SCM have paid attention to the competencies and skills required to support the transition to CSCs. In most of these cases, skills are not the focus of the research. Moreover, even fewer studies pay attention to competencies in low-skilled workers, yet the transition to CE should be just and inclusive by nature. This research aims to contribute to both gaps in knowledge.

Limitations :

Competencies and skills tend to be linked to industries, sectors and are usually context specific (EMF, 2021). On many occasions they are also linked to the economic activity of a geographical region. Requirement for skills might be also linked to local infrastructure. These conditions pose challenges for generalisations. However, this research is focused on SCM literature for now, so it can still extend our broad understanding of competencies and skills relevant in different scenarios of transitioning SCs.

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SECTION TWO: FULL PAPERS

CIRCULAR SUPPLY CHAIN

Supply Chain Capabilities and Drivers Shaping Circular Product Design Adoption in the Clothing Industry

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Abstract

The clothing industry (CI) faces increasing pressure to adopt circular practices due to CI's significant environmental impact, particularly in waste generation and resource consumption. Circular product design (CPD) plays a pivotal role in reducing both waste generation and resource consumption by enabling circular supply chains (CSCs) via product longevity, recyclability, and sustainable material use at the design stage. Despite CPD's potential, however, research has primarily focused on technical aspects, leaving its strategic orchestration at the supply chain (SC) level underexplored. This study addresses this gap by investigating the key SC capabilities that support CPD adoption and the external drivers shaping CPD capabilities in the CI. Using dynamic capabilities (DC) and stakeholder theory (ST) as theoretical lenses, this study employs a qualitative case study approach, analysing five Australian clothing firms integrating CPD practices. The findings identify three core CPD capabilities: supply capabilities, manufacturing capabilities, and material recovery partnerships. These capabilities are shaped by three key external drivers: regulatory & policy, market, and technological forces. This study makes three key contributions to CPD research. First, it extends DC theory by identifying key resources SCs adapt to respond to external CPD forces. Second, it advances ST theory by showing that CPD requires multi-stakeholder coordination across the SC, reinforcing circularity beyond firm boundaries. Third, it provides industry-specific insights, revealing that material complexity, circular supply alignment, and recovery technologies are critical enablers of CPD adoption in the CI.

1. Introduction

Despite the key role CI plays in our everyday lives and in the world economy, the global CI is facing scrutiny due to its extensive environmental impact. For instance, the global textile industry sends 92 million tons of waste to landfills every year, where 90% of that waste still has value as reusable and recyclable material (Moazzem et al., 2021). In Australia, near 300 kilotons of clothing waste are sent to landfill annually (Gbor and Chollet, 2024). Thus, the urgent need for changing the way the industry designs and manages its products' lifecycles. As a response, the circular economy (CE) model is becoming a possible path to decouple economic growth from resource depletion supported by CSCs.

Circular economy (CE) is gaining increasing attention due to the growing environmental and social impacts of unsustainable production and consumption. Unlike the traditional linear economy, where products follow a "take, make, use, dispose" lifecycle, the CE envisions closed-loop systems in which resources are continually reused, remanufactured, or recycled, minimising waste and environmental degradation (Montag, 2023). CE is therefore a transformative model that seeks to decouple economic growth from resource consumption (Brummelhuis and Marinelli, 2022).

The structural backbone of a CE lies in the development of CSCs. CSCs extend beyond traditional SCs by incorporating an expanded network of actors, material loops, supporting technologies, and production and recovery activities (Montag, 2023). CSC models suggest that various actors, producers, consumers, scavengers, and decomposers, must work collaboratively in a closed-loop system to create integrated value chain (Bals et al., 2022). Despite its theoretical promise, the implementation of CSCs in real-world industries is still in its early stages. Firms encounter several capability-related obstacles to adopting CSCs, including a lack of technical expertise and design constraints (Kazancoglu et al., 2022), insufficient SC coordination and integration, the complexity of products with mixed materials, challenges in tracking and tracing materials, and the high volatility of pre-

consumer and post-consumer waste volumes (Saccani et al., 2023). These factors underscore the need for further research to establish practical strategies for overcoming these barriers and to make CSCs a viable framework for advancing CE principles in industry.

While the opportunities CE represent vary depending on industry, it promises value at large-scale adoption (Lacy et al., 2020). Within CSCs, CPD plays a pivotal role in making CE feasible. CPD focuses on designing products with their entire lifecycle in mind. It integrates resource efficiency, longevity, and ease of disassembly, reuse, repair, remanufacturing, and recycling at the product's conception phase. To implement CPD and enable CSC however, there are several challenges that need to be addressed. One of the main challenges is the complexity of materials used in products. This is, particularly critical in the CI, where biological (e.g., cotton, wool) and technical (e.g., polyester, nylon) materials are often combined, making material separation and recycling difficult and limiting the circularity of its products. Additionally, firms may face high upfront costs in adopting CPD principles with unclear long-term benefits, such as cost savings from material recovery and waste reduction.

Despite these, there is little research that investigates how firms can orchestrate CPD, especially in a CI context. Studies have highlighted the challenges firms face, such as the high upfront costs of adopting circular design principles, lack of collaborative frameworks, and difficulty in coordinating SC stakeholders. This research seeks to address these gaps by examining how Australian clothing brands are integrating circularity into their product design processes and identifying the key capabilities, strategies, and external forces driving this transition. The research is guided by two key questions: *1) What key supply chain capabilities support CPD within supply chains, and how do they contribute to CPD? 2) What are the external drivers influencing CPD capabilities in supply chains, and how do these drivers shape CPD capabilities?* From a theoretical perspective, this study builds on existing research on DC and ST, applying these theories to the context of CPD. In the context of CPD, this study explores how firms develop and utilise capabilities to transition from linear to circular design processes. ST highlights the importance of collaboration and stakeholder engagement in the implementation of circular practices, recognising that firms cannot transition to a CE in isolation. This research contributes to these theoretical frameworks by examining how stakeholders, including designers, manufacturers, and policy makers, work together to enable CPD within the SC.

2. Literature Review

2.1 Circular product design

CPD has emerged as a vital area of research within the broader field of CSC. CPD aims to minimise waste, extend product life cycles, and promote the R-strategies (Burke et al., 2021). The design stage is vital as it establishes the product's full life cycle, influencing how resources are used, how waste is overseen, and how products can be reintroduced into the SC. CPD plays a pivotal role in advancing the objectives of CSC by redefining the conventional limits of product development with a preventive approach. Unlike traditional design methods, which predominantly focus on product functionality and aesthetics, CPD features the full product lifecycle. CPD is considered as one of the main foundations of CSCs (Bakker et al., 2014), as it allows reshaping the complete lifecycle of products by making them compatible with CSC systems, highlighting features such as disassembly, recycling, and reuse. Additionally, CPD also offers commercial benefits by lowering material costs through the R-strategies and establishing new business prospects through product-service systems. CPD incorporates two design methodologies: design for closing material loops, where products are designed to stream in inner loops; and product durability, where products are repairable, thus the lifetime of product use can be extended through upgrades (Ellen MacArthur Foundation, 2024). The move from linear design models to circular approaches is enhanced by a combination of technological innovations, regulatory pressures, and evolving consumer preferences. While CPD activities have been detailed in literature, the scalability of these activities remains a big challenge for SCs. Research

demonstrate that executing CPD at scale is restricted by SC complexity, cost, and technological limitations (Denizel and Schumm, 2024). Further research is required to investigate how firms can get pass these barriers to scale CPD practices into global SCs. Existent CPD literature lacks practical studies that focus on the specific internal capabilities essential for firms to successfully adopt to CPD. DCs to react to environmental challenges, have been highlighted as central in general CE research, yet their exact role in CPD remains underexplored. While some studies have examined broader CSC capabilities, there is a limited understanding of the organisational knowledge, skills, and resources necessary for firms to adopt in CPD practices.

2.2 Circular economy

The central pillars of CE are elimination of waste and pollution, recirculating products, and materials into closed-loop streams with the objective of keeping value and regenerating nature (Kirchherr et al., 2023). CE is grounded on the creation of loops within the production cycles that result in material recovery, product life extension and waste reduction. CE aims to eliminate negative environmental impacts while stimulating new business opportunities. The Ellen MacArthur foundation CE definition is one of the most referenced in literature: *"The CE is a system where materials never become waste and nature is regenerated. In a CE, products and materials are kept in circulation through processes like maintenance, reuse, refurbishment, remanufacture, recycling, and composting. The CE tackles climate change and other global challenges, like biodiversity loss, waste, and pollution, by decoupling economic activity from the consumption of finite resources"* (Ellen MacArthur Foundation, 2024, p. 1). In the CI, CE studies have focused on three main themes. First, systemic transformation processes from linear to CEs influenced by consumer behaviour, regulatory and stakeholder forces as drives (Abdelmeguid et al., 2022). Secondly, there is an interest on innovative approaches in product design, manufacturing and waste management using R-strategies and emphasising the role of new technologies and materials (Abbate et al., 2024). Finally, stakeholder collaboration appears as a key theme (Mishra et al., 2021), focusing on the role of collaborative spaces and multi-stakeholder collaboration to overcome SC complexity.

2.3 Circular supply chains

CSCs represent a change of paradigm in how resources are managed during the entire lifecycle of products, embodying a cradle-to-cradle model within the SC that starts from material extraction to product development, manufacturing, supply, product use and subsequent recovery (Montag, 2023). CSCs are designed to eliminate waste, foster resource efficiency, and maximise recycling, creating a closed-loop system. The concept of CSCs is still building, with definitions ongoing refining. However, despite progress, scholars mention that a CSCs definition is not universally agreed upon yet, ending with fragmented interpretations in the literature. Closed-loop systems, which simulate material loops of nutrients and energy found in natural ecosystems, are a foundation of CE (Braungart and McDonough, 2009) and they are materialised as CSCs. CSC involves connecting two or more phases of the SC using R-strategies (recycle, reuse, recover, etc). The investigation of the topic in the CI has concentrated on operations management application strategies, and collaboration as well as challenges and opportunities around CSCs. A core trend in clothing CSC research is the focus on stakeholder collaboration and engagement, which are central for reaching circularity. Additionally, resource orchestration and technological innovation also enable material recovery (Bansal et al., 2024). In clothing CSCs, successful implementation depends on supportive legislation, collaboration among SC partners, and the development of automated sorting or waste-management technologies (Ki et al., 2020). On the other hand, research uncovers major challenges in promoting collaboration, specifically between strategic stakeholders, such as recyclers and manufacturers (Bals et al., 2022). Scholars have investigated the obstacles to CSC adoption, providing insights into the difficulties faced by companies trying to implement

circular principles into their SCs. Commonly identified challenges include the lack of technical knowledge, product design constraints, and issues with material traceability.

2.4 Theoretical underpinning

A variety of theories have been used to explore the field, including DC, ST, resource-based view (RBV), natural resource-based view (NRBV), and institutional theory (Zhang et al., 2023). Specifically, institutional theory has been valuable in understanding firms' responses to regulatory frameworks supporting sustainability and circularity (Magnano et al., 2024). Yet, its emphasis on external compliance limits its ability to explain the internal processes of adaptation, learning, and innovation that firms must undergo to transition toward circularity. Given that CPD is an emergent and evolving area of both academic and practical interest, it demands firms to develop adaptive capabilities to respond to changing conditions. In this context, DC theory (Teece et al., 1997) offers a robust lens to explain how firms can reconfigure their internal resources to innovate, redesign products, and seize opportunities to advance circularity. However, CPD extends beyond the boundaries of individual firms. CE practices are inherently collaborative, requiring coordinated value creation across stakeholders. Therefore, ST becomes essential for understanding the inter-organisational dynamics and the orchestration of capabilities across actors in the SC. In the CE context, regulators are not only enforcers but also co-creators of policies, learning from firm-level practices to support broader CPD adoption (Shah and Bookbinder, 2022). The integration of DC and ST thus provides a complementary theoretical foundation. While DC highlights the internal DCs needed for firms to embed circularity in design, ST captures the external stakeholder collaboration required within the broader CSC. This dual lens enables a systemic understanding of CPD as both an organisational transformation and a collaborative endeavour.

3. Methodology

This study investigates the capabilities required for firms transitioning to CPD within the Australian CI. To achieve this, a multiple-case study approach was employed, analysing five Australian clothing brands and interviewing key decision-makers responsible for production processes. The research integrates both deductive and inductive reasoning. The study begins with a first stage, including a literature review to establish theoretical foundations, followed by a second stage with sample case study identification, qualitative data collection and analysis using an inductive approach, in the final stage findings are used to elaborate on theory (See Figure 1). Given the complexity and dynamic nature of circular transitions, a qualitative case study methodology was deemed appropriate, as it provides in-depth, context-specific insights into firms' CPD adoption processes.

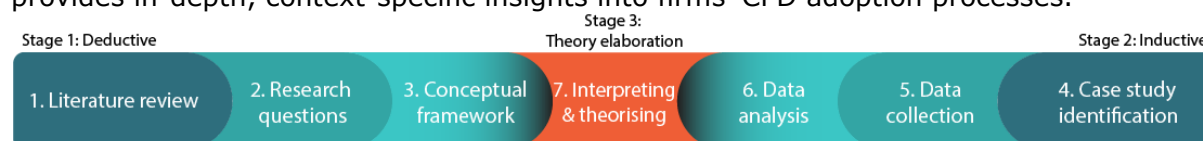


Figure 1. Research design of the study

3.1 Research Context and Sample

The study focuses on the Australian CI, which is under increasing pressure to adopt circular CE principles. Clothing is a fundamental human necessity, but it also serves as a means of self-expression and cultural identity. The demand for apparel is highly dynamic, influenced by factors such as seasonal changes, cultural shifts, and evolving fashion trends. These factors contribute to high consumption and disposal rates, particularly in fast fashion models, which prioritise low-cost production and frequent turnover of new styles. This consumption pattern has been identified as a significant contributor to textile waste and environmental degradation. The complexity of clothing products presents a unique

Table 1. Summary of the cases and interviewees

Case	Case description	Participant description
Brand A	Firm branded as a “lifestyle” recycled brand. Its range of products are made using recycled items. It is an omnichannel brand. With three years on the market and workforce size of six.	Co-Founder & Business Strategist. Eight years in the CI.
Brand B	Firm that produces products for people with temporary and long-term movement impairment with sustainable materials. Recovers product for recycling. It is an omnichannel brand. With five years on the market and workforce size of ten.	Founder & designer. Ten years in the CI.
Brand C	This firm offers made-to-order and ready-to-wear garments using sustainable materials. It is an online brand. With eight years on the market and workforce size of twelve.	Production lead & designer. Twelve years in the CI.
Brand D	Sustainable underwear brand. Uses bio-based materials in its products. It has a take back program. It is and omnichannel brand. With ten years on the market and workforce size of seventy.	Product lead. Five years in the CI
Brand E	Middle market clothing brand with operations in Australia, New Zealand, and South Africa. It designs clothes using sustainable fabrics. It is and omnichannel brand. With fifty years on the market and workforce size of six thousand.	Designer & materials manager. Four years in the CI.

challenge for circularity. Unlike industries where materials predominantly follow either biological or technical cycles, the CI incorporates both. Many garments are made from blended fabrics, which are difficult to separate and recycle efficiently without quality loss. Additionally, the globalised nature of the clothing SC complicates circular transitions. While garment production is concentrated in low-cost manufacturing hubs in South Asia, consumption rates are highest in developed economies such as Australia, the United States, and Europe. As a consequence, a high rate of consumption and disposal in Australia has risen, clothing is bought cheaply and rapidly disposed of after minimal use, thus adding 300 kilotons of waste in landfills every year. In Australia, the CI is highly fragmented, dominated by small and owner-operated companies with no firm holding more than 5% of the market share (Wheeler, 2023). Approximately around 80% of Australia’s clothing imports came from Asian countries due to their low-cost production (Payne et al., 2024). Australian CI is thriving sector with an increasing attention on sustainable fashion. For instance, the Seamless National Clothing Product Stewardship Scheme aims to achieve clothing circularity by 2030. The sampling strategy employed purposive sampling, targeting firms actively engaged in CPD practices. Details of the selected cases are shown in Table 1. The selected firms represent the CI in Australia. The firms involved have shown knowledge and commitment towards CE practices, including CPD. Moreover, they have engaged with their stakeholders to offer products that show some level of circularity, some of them outsourced their production to factories while the rest own their production facilities. This case sample thus serves as a representative microcosm of the broader CI, including material recovery, sustainable sourcing, and extended product lifecycles, ensures that the sample provides meaningful insights into CPD implementation within the industry.

3.2 Data Collection

This study adopts an exploratory qualitative approach to examine the emerging phenomenon of CPD adoption. Primary data was collected through semi-structured interviews conducted between June and November 2024. Interviews targeted key stakeholders within each firm, including designers, production managers, and senior executives, to capture multiple perspectives on CPD implementation. This was essential, as product design decisions are largely driven by firms, with upstream SC stakeholders playing a reactive role in this process. The interview protocol was designed to elicit insights on CPD capabilities and external influences. Specifically, questions targeted firms' ability to sense opportunities, seize resources, and reconfigure processes for CPD (DC attributes). Simultaneously, the protocol explored stakeholder identification, engagement, and mutual value creation (ST attributes). Sample questions included: How does your organisation incorporate circular strategies, such as closing material loops or slowing down material cycles, into the product design process? What external factors influence your company's decision to adopt CPD? Why? To ensure data reliability, interviews were recorded and transcribed. Follow-up questions were used to clarify responses and deepen the exploration of key themes.

3.3 Data Analysis

Thematic analysis was employed following Clarke and Braun (2013) six-step process. This approach facilitated the identification of recurring patterns and empirical themes within the case study data. The analysis was conducted iteratively, beginning with an open coding process to extract first-order concepts. These were subsequently grouped into second-order themes, which were cross-referenced with existing literature. Finally, higher-order aggregate dimensions were developed to encapsulate the core capabilities and external forces shaping CPD adoption. The resulting themes and dimensions provided the foundation for the study's conceptual framework, illustrating the interplay between CPD capabilities and external drivers. By adopting this methodological approach, the study ensures a robust examination of the key factors influencing CPD adoption within the CI. The data and themes related to CPD capabilities and external forces are presented in Figure 2.

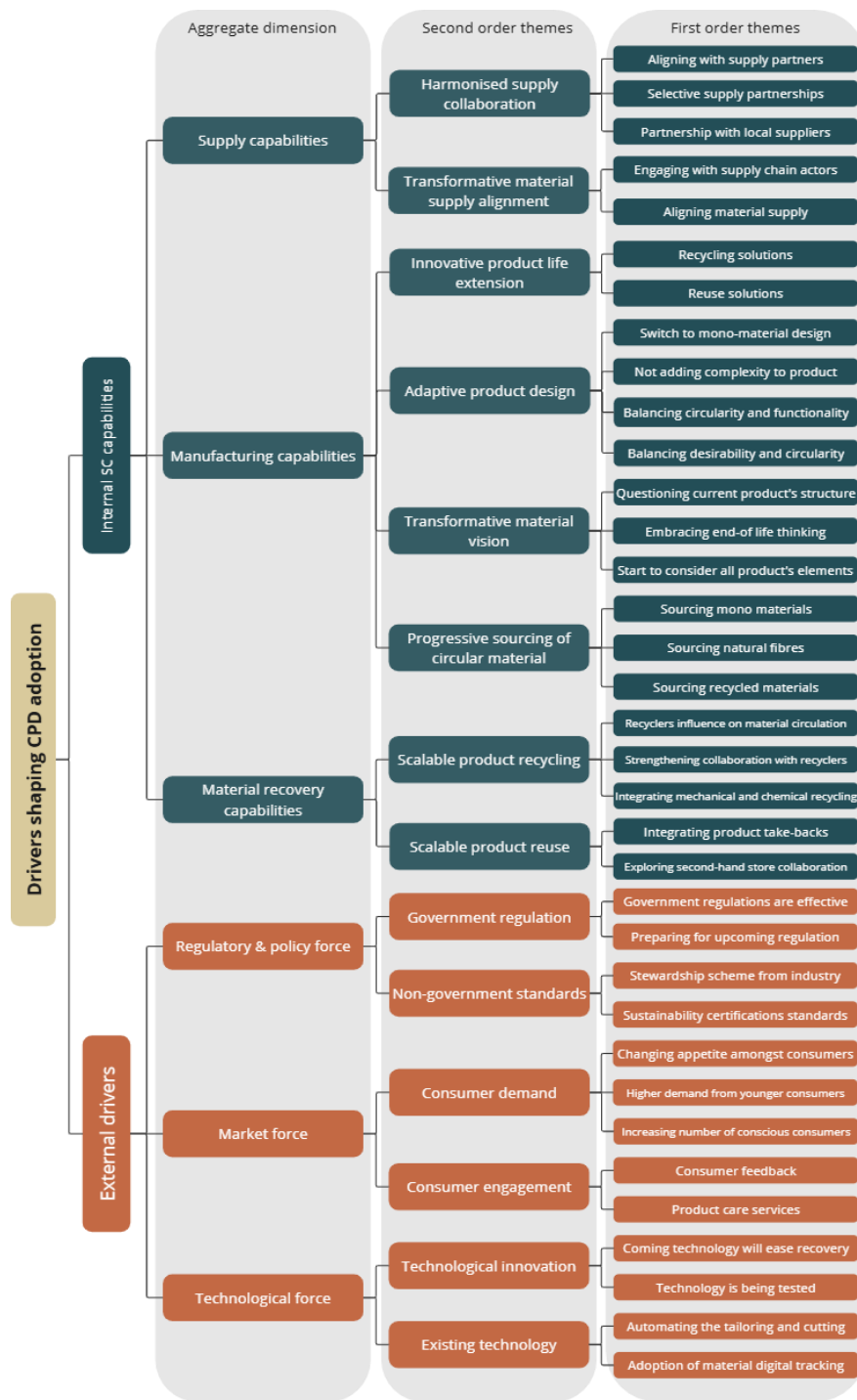


Figure 2. Thematic structure of interview data

4. Findings & analysis

Analysis of the data shows the following three core SC capabilities that support CPD adoption in CI.

(i) *Supply capabilities*: The findings highlight two key themes around supply capabilities, these play a fundamental role in enabling CPD, these are harmonised supplier collaboration and transformative material supply alignment. Harmonised supplier collaboration emerged as essential for CPD implementation, with firms highlighting the interdependence and

alignment of expertise across supply networks. One participant noted, *"No one person or company [alone] is going be able to come up with a solution. It's very much about relying on different expertise and different companies to come together"*. Beyond collaboration, transformative material supply alignment capability was identified as critical for aligning CPD objectives with sourcing practices. A participant described how early communication with supply partners ensures compliance with circularity requirements, stating, *"It's very important that from the start of our relationship, we understand each other, so the factory knows [why] we need 100% recycled materials."*

(ii) *Manufacturing capabilities*: The findings highlight four key themes around manufacturing capabilities: innovative product life extension, adaptive product design, transformative material vision and progressive sourcing of circular material. Designing for end-of-life emerged as a central practice, with firms prioritising recyclability and reuse in their design strategies. One participant explained, *"Designing for end of life is critical... so enabling circularity and making it easy for consumers to access it [circular economy]"*. Adapting product design to balance functionality with recyclability is a capability that needs to be mastered. A participant noted, *"So, one [item] with clips and trims and hardware versus a product that's got none of that, so [the second] can be much more straightforward to take back and recycle, but it's probably...not very supportive"*. Additionally, a forward-looking vision for circularity guides design decisions, with one participant emphasising the need to evaluate every component's potential for recovery and reuse before their use: *"We consider the lifespan beyond the garment... knowing how to decommission it at the end of its life"*. Also, firms are sourcing materials that are regenerative and recovered, one participant mentioned, *"All of our clothing is made entirely from 100% recycled materials, so not just the fabrics, but the trims, the thread, the embroidery, the buttons, the zippers, the swing tags, the care labels, everything"*.

(iii) *Dynamic material recovery capabilities*: The study found two critical themes related to material recovery capabilities, scalable product recycling and scalable product reuse. One participant described the firm's engagement with a long-term recycler partner, stating, *"We work with recyclers who chop fabric waste into smaller staples, re-spin it into new yarn, and make new jersey fabric"*. These partnerships also extend to reuse capabilities, where firms partner with second-hand marketplaces to extend product lifecycles. A participant shared, *"We've been connected to [second-hand shop's name] for a long time... facilitating product resale and reuse."*

Study identified three external forces support CPD adoption in CI, in the following we discuss these forces.

(i) *Regulatory and policy forces*: Regulatory and policy forces were identified as key external enablers of CPD, the two main themes being government regulation and NGO's standards. Government regulations play a pivotal role in driving industry-wide practices, with firms recognising the need for regulatory enforcement to catalyse change. One participant stated, *"The industry will need some sort of regulation from the government... because market or shareholder action alone won't drive brands to change [to a CE]"*. Beyond governmental mandates, NGOs contribute to CPD advancement through voluntary stewardship programs. One such example is the Australian Fashion Council's Seamless scheme, which participants highlighted as an influential framework for guiding CPD practices: *"The Seamless project could provide long-term direction for firms, similar to how tariff regulations shaped past industry practices"*.

(ii) *Market forces*: Market forces emerged as an important driver of CPD, particularly through shifting consumer demand and consumer engagement. Consumer preferences for transparency and accountability were frequently cited as triggers for CPD adoption. One participant noted, *"A lot of our customers certainly look to us because they know that's our practice [circularity]. I mean, they're very environmentally minded, they are conscious about where they spend their money"*. This need for circularity has driven firms to offer repair and take-back services, aligning with circular principles and ensuring a reverse flow

of materials. One participant mentioned, "We can repair it [product], or we can dispose it, we can also give guidance to the customers on the best way of ending that garment's life cycle, ... So, we do free repairs for life".

(iii) *Technological forces*: Technological forces are pivotal in enabling CPD capabilities by improving traceability, recycling processes, and design adaptability. Technological innovation emerged as a key theme, with firms looking into new traceability technologies to simplify material identification. One participant shared: "There's so much technology and innovation in that space [traceability], there are companies that are doing incredible things with transparency and traceability". In parallel, technology adoption was the second theme found to support internal operational changes that enhance CPD practices. A participant shared their firm's investment in algorithm-driven design tools, stating, "We've written an algorithm that customises patterns to fit customers, optimising material use and extending product lifespan". At this stage of CDP adoption, economic or financial drivers for CPD transition were not found.

5. Discussion

Building on our analysis, we propose a framework illustrating that CPD capabilities in CSCs depend on supply, manufacturing, and material recovery capabilities within a collaborative ecosystem, with external drivers such as regulatory forces, market pressures, and technological advancements shaping their development (see Figure 3). These findings reinforce the idea that CPD is not an isolated function within firms but an integrated SC capability that necessitates collaboration and support from multiple skilled stakeholders.

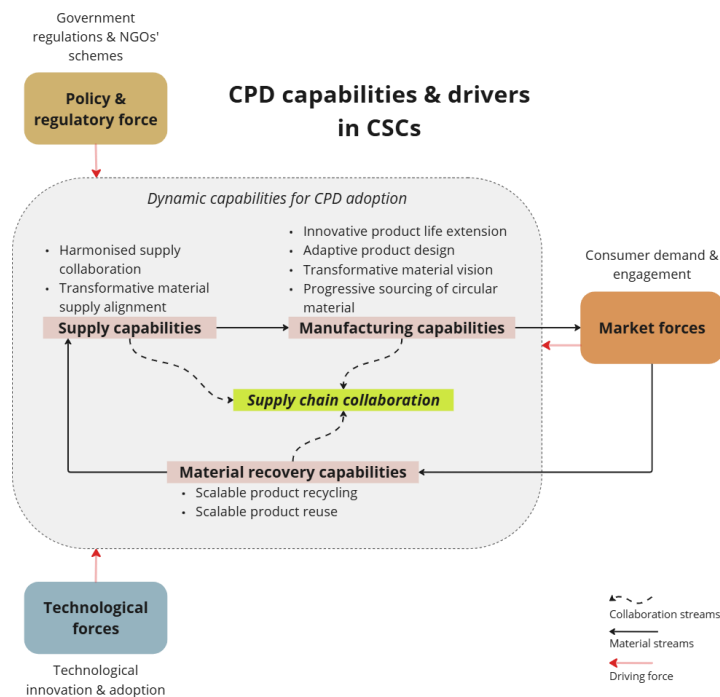


Figure 3. A framework of CPD adoption in clothing CSCs

5.1 Supply chain capabilities

(i) Supply capabilities, including harmonised supply collaboration and transformative material supply alignment, are essential for sourcing materials that comply with CPD requirements. The findings reveal that suppliers and manufacturers must develop partnerships with recyclers, to ensure a reliable stream of regenerative materials. This

aligns with ST, where collaborative relationships among SC stakeholders drive CPD adoption by balancing shared goals and requirements. The study found that supply collaboration involves transformative material supply alignment to ensure materials are either durable for reuse, recyclable, or free from complex material blends that hinder recovery, thus enabling a departure from linear SCs. This entails a DC that enables firms to constantly seek and find sourcing opportunities in their partners. (ii) Manufacturing capabilities play a critical role in CPD implementation, requiring firms to balance circularity with product functionality and profitability. The findings highlight that designers must integrate circular principles into product development by extending lifespans, using recyclable materials, and reducing product complexity. This reconfiguration process aligns with DC theory, as firms must continuously adapt product designs to meet circular requirements while ensuring that materials remain functional and desirable for consumers. Furthermore, manufacturers and designers need to know how to design products for circularity, this means following design strategies, such as design for recyclability, and build closed loop systems that involve SC partners. Additionally, the study underscores the importance of traceability technologies in manufacturing, as firms must verify material origins and recovery potential. (iii) Material recovery capabilities are fundamental for ensuring circularity of materials in CSCs. The findings indicate that recyclers serve as suppliers of recovered materials and the scalability of these are crucial for enabling firms to secure circular raw materials for CPD. This further reinforces the interconnected nature of CSCs, where firms must actively engage with recyclers to ensure material compatibility, especially in the CI, where mixed fabrics represent a recovery challenge. Second-hand markets also play a role in extending product lifespans, demonstrating that CPD strategies must account for both reuse and recycling streams.

5.2 External forces driving CPD capabilities

The study identifies three key external drivers shaping CPD capabilities: regulatory, market, and technological forces. These external stakeholders drive incentives for firms to adopt CPD by SC collaboration, manufacturing strategies, and material recovery initiatives.

(i) Regulatory forces from external stakeholders play a crucial role in shaping CPD adoption by providing policy direction and industry-wide sustainability expectations. The findings indicate that government regulations and NGO-led stewardship programs are starting to drive firms toward circularity, however there is a hint of an absence of strict circular regulations. Companies are engaging in voluntary compliance initiatives; the CI in Australia is beginning to autoregulate facing pressures from conscious consumers. (ii) Market forces, particularly consumer demand and engagement, are significant drivers of CPD. Firms recognise that consumer awareness of sustainability is increasingly influencing purchasing decisions and brand loyalty. The findings indicate that brands are embedding circular design to comply with consumer requirements, responding to evolving market expectations. Additionally, firms are going further by offering product care and repair services for their client base, suggesting a switch from fast fashion towards long lasting fashion. (iii) Technological forces facilitate CPD by enabling innovation in circular material use, product traceability, and automated design processes. Companies are researching and developing digital traceability systems, material sorting technologies, and automation tools to enhance product recyclability and improve SC transparency. For the CI, this represents an opportunity to ease material verification and compatibility with their product design. The findings highlight that technological advancement supports the integration of CPD within supply networks, reinforcing its role as a key driver of circular adoption.

6. Conclusions

This study demonstrates that CPD adoption in the CI is primarily driven by regulatory, market, and technological forces, which shape firms' capabilities in supply collaboration, manufacturing adaptation, and material recovery partnerships. The findings emphasise that external forces are accelerating CPD adoption, with firms responding to evolving policies, consumer expectations, and technological advancements to align with CE

principles. The study reinforces that CPD is not an isolated function but an integrated SC capability, requiring strategic collaboration across suppliers, manufacturers, and recovery stakeholders. The research contributes to DC and ST by highlighting the resources firms need to adapt in collaboration to respond to external forces. From a practical perspective, firms should strengthen partnerships with suppliers for circular materials and invest in material development and automation technologies to scale CPD implementation. Policymakers should focus on developing clear and consistent CPD regulations, alongside financial incentives to accelerate industry-wide adoption. To enhance the generalisability of this study's findings across industries and regions, further research is needed. Such future studies should, amongst others, examine the long-term impact of technology adoption on CPD adoption, especially for material sorting and recovery.

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Mixed Method Driven Agri Food Supply Chain Food Security Policy Evaluations in the UAE

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INTRODUCTION

Agrifood supply chain creates an eco-system that strengthens food security of a country and food security pillars. According to the United Nations Food and Agricultural Organisation (FAO), the food security pillars are classified into four types, namely, 1. Food Availability, 2. Food Accessibility, 3. Food Utilisation and 4. Food stability (Fao, 2016 and worldbank, 2025). These four pillars are derived from the agrifood supply chain stages of farm to fork in terms of food supply, food production, food import and export, food utilisation and healthy food consumption. Though this remains as a complex concept, the drive to ensuring food security of residents by all means seemed to be the prime target of countries such as the UAE. This paper focused on the food security drivers and policies based on an extensive search of academic and industrial archival records for the development of policies in the UAE.

Food security has emerged as a pivotal policy priority in the United Arab Emirates (UAE), which has one of the highest rates of food insecurity in the Gulf region at 8.9% according to 2019 statistics (FAO, 2021). The complex geopolitical dynamics of the Middle East, rapid economic development of Gulf states, and rising populations have amplified food security challenges in the Arab region (Aldababseh, 2018). The UAE faces persistent food security challenges including inadequate availability, affordability, nutrition and supply stability (Ali et al., 2022). The UAE's inhospitable desert climate, scarce arable land, and minimal renewable freshwater resources constrain domestic agricultural production capacity. As a result, the country relies heavily on food imports, with over 90% of requirements met through foreign supply sources (Hanieh, 2022). The UAE has utilised its oil wealth to invest in overseas land acquisitions and agriculture ventures in locations as diverse as Sudan, Serbia, Vietnam, and South America to secure food supplies (Chemingui and Roe, 2018; Ammar et al., 2024). However, an overdependence on global food import chains creates risks of external disruptions. Domestically, food production is limited to greenhouses and energy-intensive desalination supported systems with very high costs (Wakeford & EFM, 2020). This research gap has been attempted to study in the ongoing funded research in the UAE and this research presents seminal findings of the policy assessment from thereof.

RESEARCH METHODOLOGY

The research has conducted several reviews of academic, food industry, government, and NGOs websites and reviewed articles to capture the existing food policies around food security. Earlier, at stage 1, Wahbeh et al. (2022) have identified 34 food security drivers and 17 major policy recommendations, addressing food insecurity in the UAE, through a systematic literature review. However, the findings were not validated by primary research. Therefore these 34 food security drivers and 17 food policy actions and recommendations are needed to be validated in the context of the UAE in particular by using the Delphi technique. At stage 2, the research team has formed and conducted two rounds of Delphi approach-based stakeholders' meetings in 2023 and 2024 to validate those identified policies to be able to develop policy reforms and new policy developments.

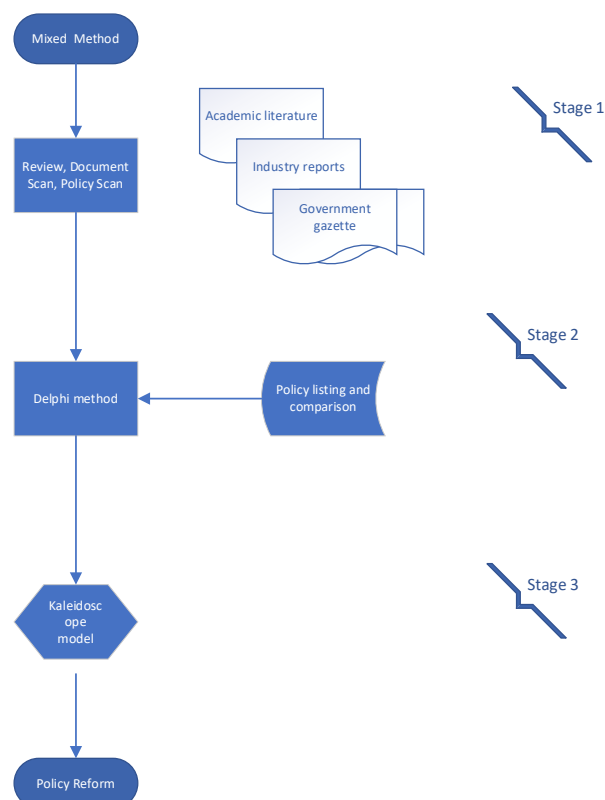


Figure 1. Research design and implementation [Authors own sketch]

As indicated in the research design, at stage 2, the research applied the Delphi-EKE method to validate the major food security drivers and policy recommendations by conducting two rounds of Delphi driven Stakeholders meetings and policy evaluations. Delphi-EKE is used in the literature to obtain parameter estimates in situations where data is lacking (e.g. Ali et al., 2021; Pashaei Kamali, 2015). In this regard, an online survey administered in the Qualtrics Platform, was used to collect data from food system stakeholders. In total, we obtained 55 responses during March 2023, of which 27 were fully completed responses. These collected policies about food security are assessed and sorted and validated in the Delphi meetings during 2023 and 2024. The findings are shown in Table 1 and Table 2 for policy reforms in the UAE.

The findings are then mapped in the multi-ring Kaleidoscope model in stage 3 for future policy reforms and policy implementations from short terms action to long term action plans.

RESULTS AND DISCUSSION

The rankings of the food security drivers by the experts are somehow different from the rankings based on the literature review outcome. Looking at the top 10 drivers, the experts identified the following drivers in their top ten lists: *Formulating food supply chain risk management policies* (3rd), *Measuring food security by applying valid and reliable indicators that take the four dimensions into account* (6th), *Strengthening food distribution infrastructure/logistics including transportation and storage facilities* (8th), and *Formulating integrative food-energy-water policies (Nexus)* (9th) whereas these drivers were respectively ranked 14th, 29th, 24th and 25th according to the literature review result of Wahbeh et al. (2022).

Table 1. Results of validation of food security drivers

Drivers	Delphi-EKE Score		Expert Rank	Literature Rank (Wahbeh et al., 2022)
	Mean ^a	SD ^a		
Formulating national food security objectives and policies	6.48	0.63	1	2
Reducing food loss and waste	6.44	1.03	2	1
Formulating food supply chain risk management policies	6.15	0.93	3	14
Raising adoption of modern agricultural technologies by supply chain actors (e.g. high-yield seed varieties, digital technologies, biotechnology, nanotechnology, blockchain)	6.11	1.03	4	3
Raising domestic/local food production	6.11	1.29	5	6
Measuring food security by applying valid and reliable indicators that take the four dimensions into account	5.96	0.92	6	29
Enhancing food safety, by formulating food safety policies and practices	5.96	0.92	7	8
Strengthening food distribution infrastructure/logistics including transportation and storage facilities	5.93	1.18	8	24
Formulating integrative food-energy-water policies (Nexus)	5.89	1.13	9	25
Formulating environmental policies including gas emission reduction policies, fertilizer application policies, climate change policies	5.89	1.37	10	10
Strengthening agricultural infrastructure (e.g. governments' expenditure on R&D, irrigation and soil preservation technologies, extension services, early warning systems)	5.81	1.16	11	23
Increasing the government's role in food supply chain operations (e.g. investing in agriculture)	5.81	1.54	12	8
Enhancing communication among all the food supply chain stakeholders	5.78	0.99	13	13
Reducing farm yield volatility, for example, through raising adoption of agricultural technologies (e.g. irrigation and water-saving technologies)	5.78	1.17	14	18
Formulating food import policies	5.74	1.11	15	15
Managing national food reserves (e.g. grain stock management)	5.74	1.38	16	21
Educating consumers about sustainable consumption and healthy diet	5.70	1.24	17	12
Designing public programs to influence consumers' diets in a healthy manner	5.67	1.36	18	16

Table 2. Results of validation of food security policies

Policies	Delphi - EKE Score		Expert Rank	Literature Rank (Wahbeh et al., 2022)
	Mean ^a	SD ^a		

Food safety policies	6.37	0.73	1	3
Food loss policies	6.19	1.09	2	9
Food security policies	6.15	1.30	3	1
Food waste policies	6.07	1.44	4	2
Water use policies	6.07	0.98	5	12
National food reserve policies (e.g. grain stock management policies)	6.04	1.17	6	13
The food-energy-water integrative policies (nexus)	6.00	0.98	7	14
Food supply chain risk management policies	6.00	1.25	8	11
Environmental policies	5.93	1.05	9	5
Food surplus policies (i.e. policies to manage food surplus at any point along the supply chain)	5.93	1.09	10	8
Policies aimed at increasing traceability across the entire food supply chain	5.89	1.17	11	10
Policies promoting consumer education about sustainable and healthy consumption	5.70	1.21	12	15
Food import policies	5.70	1.44	13	6
Urban agricultural policies	5.52	1.26	14	17
General trade (import-export) policies	5.33	1.41	15	4
Dietary standards policies	5.07	1.44	16	16
The European Union's Common Agricultural Policy (CAP)	4.59	1.62	17	7

^a The Mean scores and Standard Deviations are derived from the ratings of the 27 experts on a scale of 1 (no effect at all) to 7 (very strong effect).

The rankings of the policy recommendations according to EKE and the literature review results are identified as, *Food safety policies*, *Food security policies*, *Food waste policies*, *Environmental policies*, and *Food surplus policies* were included in the top 10 major policy recommendations for achieving sustainable food security. These results imply that on top general food security policies, policies addressing food safety, food waste, food-energy-water nexus, food surplus and food supply chain risk management are critical for enhancing the sustainability and resilience of food security in the UAE region.

Kaleidoscope theory

The research applied Kaleidoscope approach developed by Resnick et al. (2018) to design and evaluate the identified policies and present them for reform. These policies are short term to long terms action plans that the UAE government will implement in their national food security strategies agenda 2051.

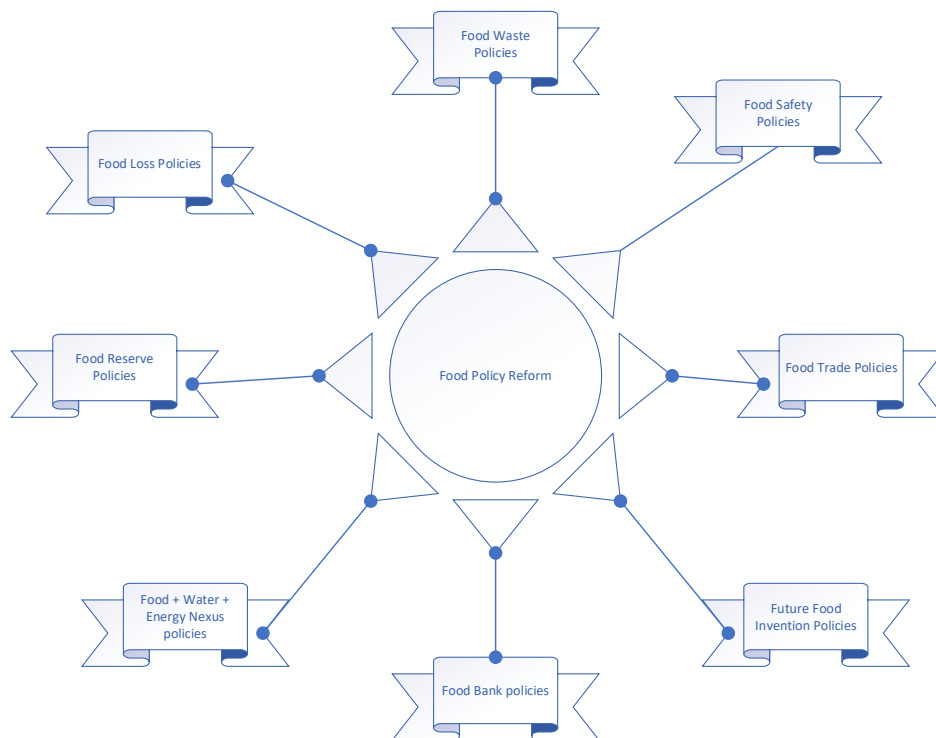


Figure 1. Agrifood supply chain Food policy reform based on Kaleidoscope theory
[Designed by authors]

CONCLUSIONS

The research studied an important area of sustainable food supply chain, food security and being able to develop resilient agrifood systems. By mixing three methods, the research validated several key food security policies and developed actions plans. Achieving sustainable food security requires understanding of the major drivers of food security, and designing appropriate policies. According to the experts, especially, the integrative food-energy-water policies could help to address the multitude challenges faced by the region related to water, environment, and food production.

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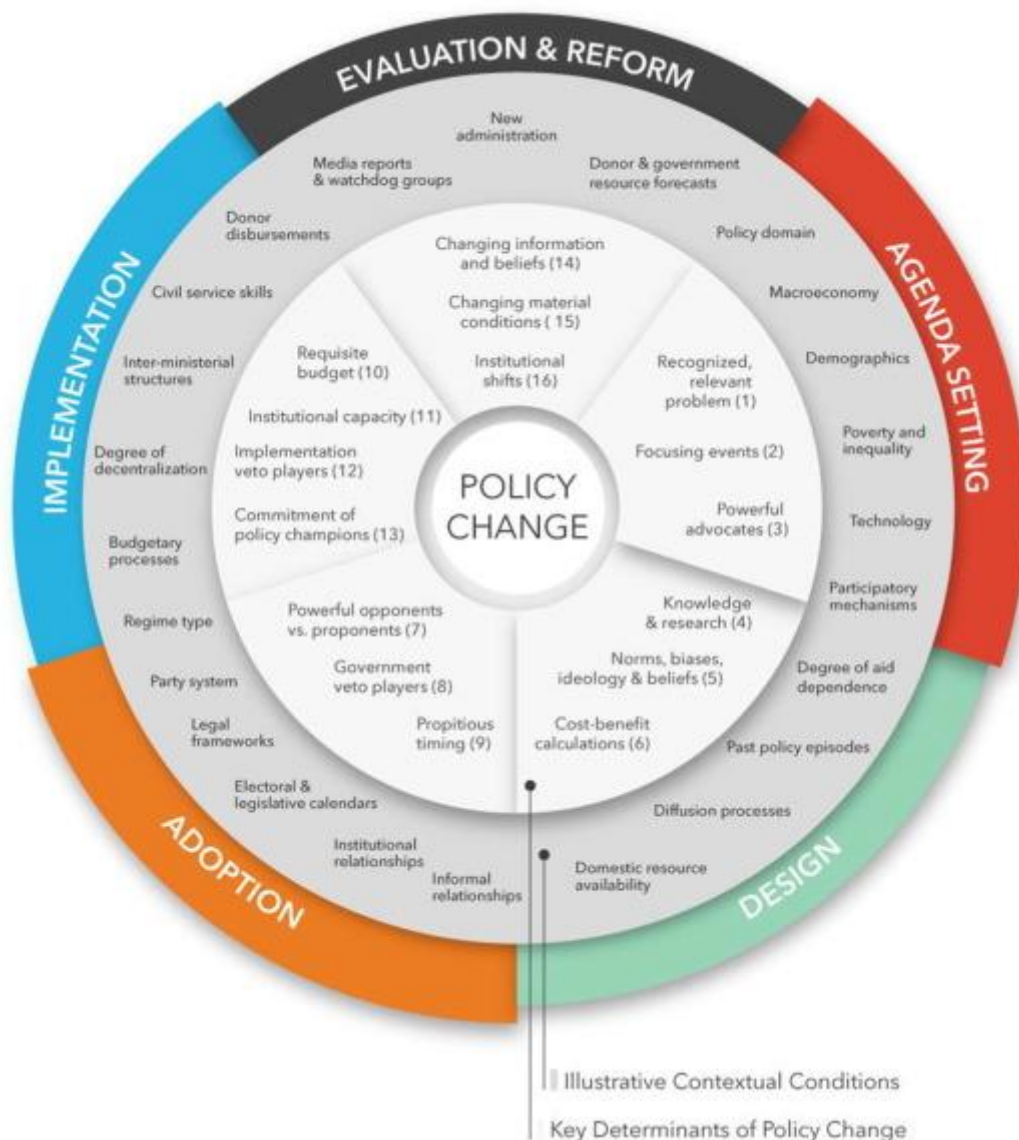
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Appendix A: Kaleidoscope model adapted by Resnick et al., (2018)



Demystifying Circular Supply Chain of End-of-Life Smartphones in a Developing Country

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ABSTRACT

The increasing use of electronic devices in Indonesia, particularly mobile phones, has led to a surge in electronic waste (e-waste), leading to negative environmental impact if not well-managed. Due to inexistence of formal supply chain for end-of-life (EoL) smartphones in Indonesia, the present study aims at mapping the circular supply chain of EoL smartphones and revealing challenges of its operations. Special Region of Yogyakarta Province, Indonesia, was used as a studied case. Empirical research involving field study (i.e., interviews to key stakeholders in the circular supply chain) and a survey to smartphone consumers involving 400 respondents were conducted in 2024. The findings indicate that the circular supply chain of EoL smartphones is market driven due to economic value of the EoL smartphones and hence dominated by informal sector. Furthermore, after-sale service centers do not accept used smartphones and existing regulation fails to enforce producer responsibility for end-of-life smartphones. The findings of empirical survey designate that majority of consumers still store their EoL smartphones or dispose of them through informal channels, only 7.75% of consumers choose to recycle their devices, while more than 50% keep them without a clear management plan. Furthermore, lack of recycling infrastructure, consumer incentives, and regulation on Extended Producer Responsibility (EPR) are the challenges encountered. Future research is also discussed.

Keywords

circular supply chain, developing country, empirical research, end-of-life smartphones

INTRODUCTION

In recent decades, the use of electronic devices in Indonesia has increased rapidly, particularly mobile phones. According to data from [1], the proportion of individuals who own or use a smartphone is 67.29%. Given Indonesia's population of 281,603,800 [2], the number of smartphone users in the country is estimated to exceed 189 million. According to [3], the total volume of e-waste in Indonesia is projected to reach 49,627,917 units ($\pm$ 487,416 tons) by 2028, with smartphones being the largest contributor. However, this growth not only creates economic opportunities but also poses serious environmental threats due to improper electronic waste (e-waste) management [4]. E-waste often contains hazardous materials such as mercury, lead, and cadmium [5]. If not properly managed, e-waste can contaminate the environment and endanger human health through exposure to toxic chemicals [6].

Unlike in the developed countries which have directives to regulate and formal waste management to facilitate their electronic disposal, the e-waste management in the developing countries remains unregulated and ambiguous. Most e-waste is not handled through formal channels [7] but instead is processed by the informal sector, which operates without clear standards or regulations [7], [8]. These practices exacerbate environmental pollution risks and limit opportunities to recover recyclable materials from e-waste. This study aims to analysing the circular supply chain of end-of-life smartphones and identifying operational challenges, with a specific focus on the Special Region of Yogyakarta as a studied case. Empirical studies conducted in 2024 involved field studies toward key stakeholders in the supply chain and empirical survey for smartphone consumers.

Although extensive research has examined e-waste management systems, most studies focused on developed countries. Research in developing countries remains limited. Hence, the present study adds body of knowledge to the understanding on the current practices and stakeholders of circular supply chain of EoL smartphones in a developing country of

Indonesia. Furthermore, the present study also demonstrates the role of regulations in shaping e-waste management systems and provides a comprehensive analysis of e-waste regulation, with e-waste supply chain, and consumer behaviour.

E-WASTE REGULATION AND IMPLEMENTATION GAPS

The section briefly reviews current e-waste regulation in Indonesia to provide the context underlying the current waste management system of e-waste. Waste management in Indonesia is regulated under Law No. 18 of 2008 on Waste Management, which classifies waste into household waste, household-like waste, and specific waste. Electronic waste (e-waste) has been categorised as hazardous and toxic waste (B3) since 2020, as stipulated in Government Regulation No. 27/2020, meaning that its management must comply with the provisions set forth in Law No. 18/2008 and Government Regulation No. 27/2020.

Regulations for e-waste management in Indonesia are currently under development and have not yet been successfully applied. The government has enacted Government Regulation No. 27 of 2020, which regulates the management of hazardous and toxic waste (B3), encompassing electronic trash. The government is primarily responsible for guaranteeing sustainable waste management, enhancing public awareness, and supplying the necessary infrastructure and technology for trash processing under these standards. The public contributes to the reduction and responsible management of trash, while producers are obligated to oversee the disposal of their end-of-life products through the Extended Producer Responsibility (EPR) plan, which requires companies to retrieve and recycle used electronic items from customers. Numerous affluent nations have instituted the Extended Producer Responsibility (EPR) system to hold producers liable for the whole life cycle of the electronic items they make [9]. The Waste Electrical and Electronic Equipment (WEEE) Directive in the European Union requires manufacturers to oversee the recycling and processing of electronic equipment at the end of their lifecycle. Japan has implemented restrictions for the disposal of end-of-life cellphones via the Act on Promotion of Recycling of Small Waste Electrical and Electronic Equipment (Small Home Appliance Recycling Law) enacted in 2014. Regrettably, Indonesia has not established a comparable structure, resulting in e-waste management being mostly reliant on private initiatives [11].

E-waste management encompasses two key components: 1) Waste reduction, accomplished by minimising waste generation, reusing materials, and recycling; and 2) Waste processing, which includes sorting, collecting, transportation, treatment, and final disposal. The government is responsible for offering incentives to entities that engage in trash reduction and for securing financing for waste management. Furthermore, Government Regulation No. 5/2021 on Risk-Based Business Licensing governs technical permits for the management of hazardous and toxic waste (B3), encompassing permits for landfills, garbage collection, recycling, and the reuse of electronic waste. Additional technical regulations are specified in various Ministry of Environment and Forestry (KLH) Regulations, including KLH Regulation No. 3/2021, which establishes standards for business activities; KLH Regulation No. 4/2021, which delineates the businesses mandated to secure environmental permits; and KLH Regulation No. 6/2021, which elaborates on the standard procedures and requirements for the processing of B3 waste. Nonetheless, these policies encounter constraints on enforcement and oversight in the domain [12]. Notable deficiencies are recognized, including inadequate infrastructure—despite regulatory mandates for e-waste management, there are severely restricted formal recycling facilities, particularly outside urban centers; insufficient enforcement—numerous informal sector participants operate unlicensed and employ hazardous recycling practices that threaten environmental and public health; and limited producer responsibility—manufacturers of electrical and electronic equipment (EEE) are not yet fully obligated to reclaim their end-of-life products, despite the stipulations of Government Regulation No. 27/2020.

METHODOLOGY

The research methodology employed in this study consists of two main components: (1) a field study involving a set of interviews with key stakeholders in the supply chain, and (3) a consumer survey to assess their behaviour toward e-waste.

Field studies aiming at mapping the supply chain operations of EoL smartphones were conducted through direct observation and a set of interviews with e-waste collectors/recyclers in the Special Region of Yogyakarta, Indonesia. Snowball sampling was deployed to identify relevant stakeholders. Field studies were conducted at both formal and informal collection centres of EoL smartphones. Field studies on the formal sector were conducted at six after-sale service centres in each regency of the province (i.e., Bantul, Gunungkidul, Kulon Progo, Sleman, and Yogyakarta), whereas the field studies of informal sectors were conducted at six informal collection centres in Bantul regency, five at Gunungkidul regency, four at Kulon progo regency, nine at Sleman regency, and three at Yogyakarta city.

The empirical survey was designed to collect data on consumer behaviour in managing their EoL smartphones. A total of 400 respondents residing in the Special Region of Yogyakarta province participated in the survey. The questionnaire consisted of three main sections: 1) Demographic information, including age, gender, education level, and income; 2) Questions related to e-waste behaviour (i.e., whether EoL smartphones were stored, recycled, donated, or discarded. The survey supplements the supply chain analysis in a way to estimate the scale of the return rate of the potential EoL smartphones. The survey was conducted with a total of 400 respondents across the Special Region of Yogyakarta province, distributed as follows: 106 consumers from Bantul regency, 76 consumers from Gunungkidul regency, 45 consumers from Kulon Progo regency, 128 consumers from Sleman regency, 45 consumers from Yogyakarta city.

RESULTS AND DISCUSSION

The section is divided into two parts, i.e., circular supply chain analysis, and managerial implications.

Analysis of Circular Supply Chain of EoL Smartphones

Based on the field studies, the circular supply chain of e-waste involves two main stakeholders, i.e. formal and informal sectors, in addition to consumers of smartphones. The formal sector generally adheres to clear standards and regulations but often lacks flexibility in reaching the broader population. In contrast, the informal sector is more adaptive but lacks proper regulation, leading to potential environmental and social risks. Based on the observational findings, e-waste circular supply chain in the province is dominated by informal sectors. The findings are in line with the studies of [12], [13] which demonstrated that the e-waste supply chain is market-driven, hence predominantly controlled by the informal sector, with collection centres serving as key intermediaries between consumers and recycling factories. The finding is supported by [11] explaining that the informal sector plays a significant role in the collection and processing of electronic waste but often employs unsafe and environmentally harmful methods. In India, for instance, more than 90% of e-waste is processed through the informal sector, as reported by [14]. A similar situation is observed in China, where [15] notes that the informal sector significantly contributes to e-waste management but remains poorly integrated with the formal system. In Indonesia, most informal collection centres and recycling factories operate without clear regulatory oversight. Lack of modern technology and weak economic incentives are major barriers to improving the efficiency of the informal e-waste system, which is in line with [16].

It is also interesting to note that only informal collection centres accept EoL smartphones for recycling, whereas formal collection facilities do not. The main reason after-sales service centres of smartphones refuse EoL smartphones is the absence of a take-back

program from manufacturers. Additionally, manufacturers which operate after-sales service centres do also not accept EoL smartphones from consumers, regardless of whether they are the same or different brands. In contrast, informal collection centres accept all brands of discarded mobile phones. This explains the dominance of informal sectors and non-existence of formal sectors in e-waste circular supply chain, despite the new Government Regulation No. 27/2020.

The process of handling EoL smartphones through informal channel follows this operations: 1) Consumers deliver their used phones to a collection center; 2) The collection center dismantles the phones and sorts the components, as illustrated in Figure 1; 3) The collection center performs activities such as collection, dismantling, and sorting; 4) After sorting the components by weight (in kilograms), the informal collection centers send the components to a recycling factory for further processing; 5) Components including casings, screens/liquid crystal display (LCDs), printed circuit boards (PCBs), and batteries are purchased by the recycling factory. The recycling factory purchases these components at a price range of IDR 10,000 to IDR 15,000 per kilogram; 6) The recycling factory performs shredding and milling & sieving; 7) The processed components from the milling & sieving stage are then either sold to domestic parties or exported.

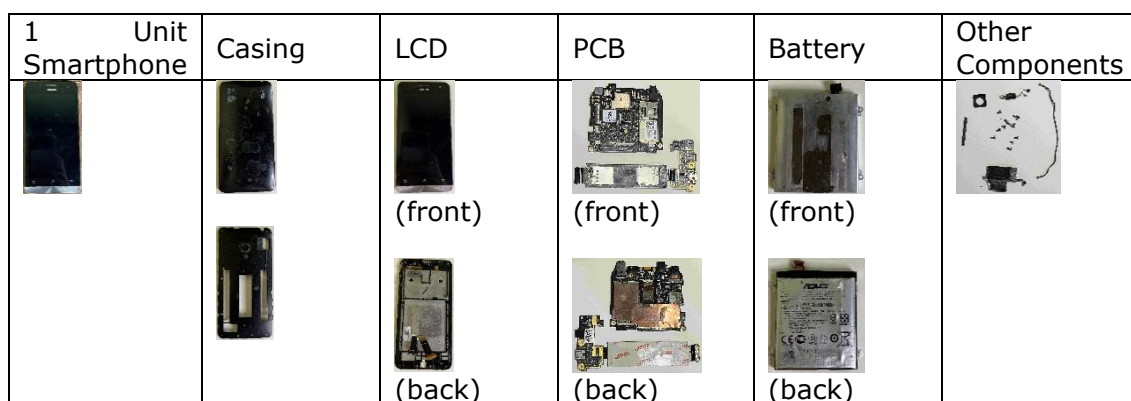


Figure 1. Disassembly Process of Used Mobile Phones

Hereafter, formal collection centres include drop boxes placed at several locations. The drop boxes are managed by the local government of Yogyakarta City and private entities. Table 1 lists the institutions providing the drop boxes in the province. However, the drop boxes are only available in one district (Yogyakarta city). The other four regencies have no drop boxes for consumers to dispose of or collect their e-waste.

Table 1. Formal Collection Centres in the Special Region of Yogyakarta Province

No	Provider	Drop boxes	References
1.	Yogyakarta City Government	Located at six designated areas in Yogyakarta city and collaborates with third parties for e-waste processing.	https://jogja.jpnn.com/malioboro/47/catat-ini-tujuh-titip-drop-box-sampah-b3-di-kota-yogyakarta
2.	EwasteRJ	Located at Greenhost Boutique Hotel and collaborates with PT Teknotama Lingkungan Internusa for e-waste processing.	https://zerowaste.id/peta-minim-sampah/dropbox-ewasterj-di-greenhost-boutique-hotel/

Figure 2 illustrates the circular supply chain for the e-waste management of EoL smartphones. The material flow from consumers, represented by a single end-of-life smartphone, travels two main routes: it is either transferred to an informal collection centre or deposited in dropboxes established by governmental or commercial organisations at

specified sites. There are separate treatment protocols for end-of-life smartphones received at informal collection centres and those deposited in dropboxes. End-of-life smartphones submitted to informal collection centres are subjected to component separation, as depicted in Fig. 1. Post-separation, the retrieved components are gathered by a recycling facility situated in Surabaya, East Java. The recycling facility is situated in another province, necessitating transportation, which lacks a definite supply schedule as it is contingent upon the duration required to gather an adequate number of end-of-life smartphones from consumers. On average, the recycling facility gathers components from informal collection centres monthly, with each batch including 100–200 kg of components (casings, LCDs, PCBs, and batteries) sourced from all informal collection locations in the Special Region of Yogyakarta province. The recycling facility necessitates a minimum of 1 ton of end-of-life smartphone components for processing each month, with a maximum processing capability of 20 tons per month, yielding an average revenue of IDR 732,814,811.04 per ton. The institution overseeing the dropboxes for EoL smartphones in Yogyakarta City is tasked with dispatching the collected devices to a third-party recycling facility for processing.

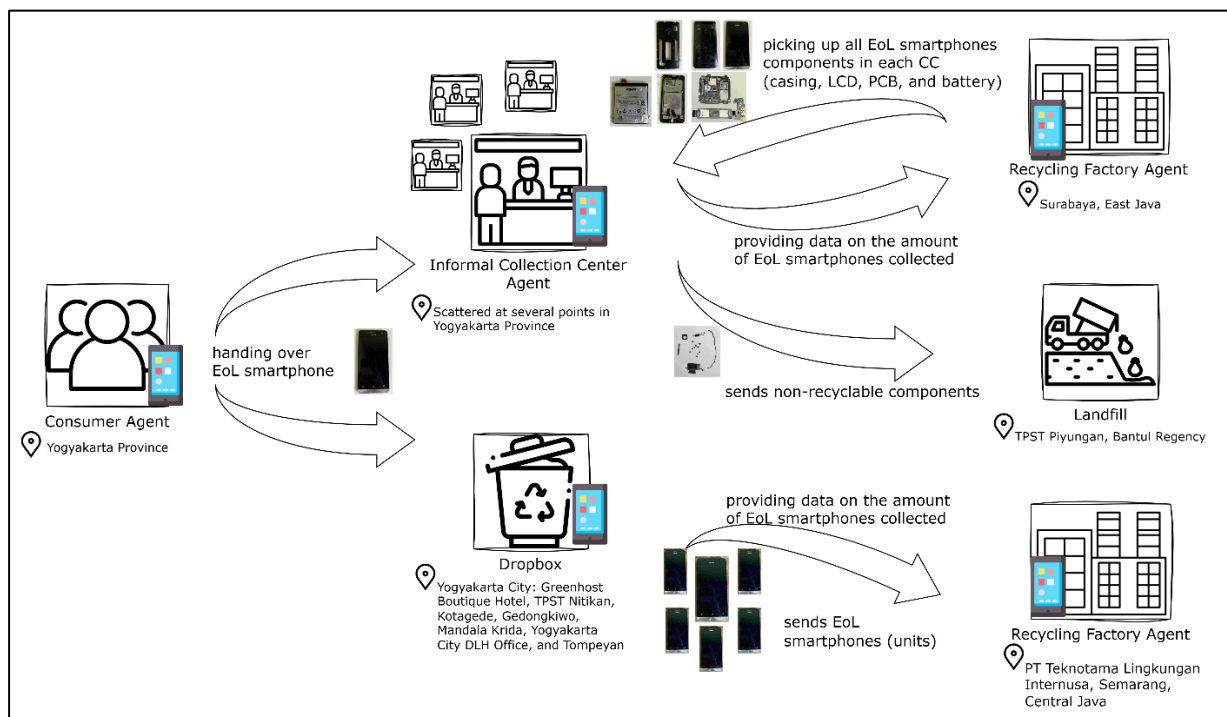


Figure 2. The circular supply chain of EoL smartphones

Because the operation of recycling processes is highly dependent on the collected EoL smartphones, further investigation was conducted to explore consumer behaviour toward EoL smartphones. Consumer behaviour in e-waste management plays a crucial role in determining the success of recycling systems. Consumers' decisions on how to handle their used electronic devices are influenced by several factors, including their level of knowledge about electronic waste [17], [18], environmental awareness [17], [19], the functionality of the previous device [20], the resale value of used devices [21], social motivation [22], information security concerns [23], the availability of recycling facilities [24], subjective norms [22], [24], [25], and regulations governing e-waste management [5], [24]. One study highlights the importance of sentimental value as a key barrier to recycling e-waste. In Indonesia, consumer behaviour regarding e-waste remains a challenge. A study by [17] revealed that low public awareness of the environmental impacts of e-waste is a major barrier to proper waste management. The majority of consumers choose to store their used devices, indicating a lack of access to formal recycling facilities.

The survey results indicate that the predominant consumer behaviour regarding e-waste management is storage, with more than 50% of respondents opting to keep their used electronic devices. A more detailed breakdown of consumer behaviour in managing e-waste is presented in Table 2. [26] found that many consumers prefer to keep their old electronic devices due to emotional attachment, even if the devices are no longer in use.

Table 2. Consumer Behaviour toward EoL Smartphones

After-Use Behavior	Total	Percentage (%)
Throw	4	1.00
Sell	56	14.00
Recycle	31	7.75
Donate	90	22.50
Keep	219	54.75
Grand Total	400	100

The survey results presented in Table 2 are consistent with previous research conducted by [17] in Jakarta, which found that 39% of consumers store their ICT e-waste, such as smartphones, laptops, and PCs, while only 2% of consumers recycle their e-waste. The findings of the present study indicates that 7.75% of consumers choosing to recycle their phones, with the majority handing them over to informal collection centres. One of the main barriers preventing consumers from recycling is their lack of awareness regarding the existence of collection centres in their communities. As a result, consumers prefer to store their e-waste rather than recycle it. This study also found that incentives and government regulations significantly influence consumers' willingness to recycle. The survey results indicate the need for more recycling facilities and greater awareness campaigns regarding collection centres to increase consumer participation in e-waste recycling, public awareness of the importance of e-waste recycling remains low. Many consumers opt to store their used electronic devices or dispose of them with household waste [19], increasing the volume of unmanaged waste. Additionally, economic incentives also play a role in influencing consumers' decisions to recycle, as discussed by [23].

Managerial Implications

E-waste management in Indonesia faces several key challenges. First, consumer behaviour plays a crucial role in determining the success of e-waste management systems [18], [25]. Studies indicate that consumers' decisions regarding used electronic devices are influenced by environmental awareness [17], [19], the economic value of the device [21], and the availability of recycling facilities [24]. Without understanding consumer behaviour in managing e-waste, it is difficult to estimate the amount of e-waste generated and determine the necessary system capacity. Second, Indonesia's e-waste supply chain is largely controlled by the informal sector. Limited formal collecting/recycling infrastructure plays a crucial role in influencing consumer decisions regarding the management of their discarded mobile phones. Small collection centres and recycling factories often play a central role in e-waste collection and processing [12]. However, this sector faces numerous challenges, including limited access to modern technology, minimal economic incentives, and unsupportive regulations [27]. By contrast, in developed countries, formal systems enable more efficient recycling processes, supported by government policies and collaboration with the private sector [9]. Third, existing regulations are not yet fully effective in supporting e-waste management systems [12]. Although Indonesia has introduced some relevant policies, such as Government Regulation No. 27 of 2020 on the management of specific waste, their implementation remains inadequate. Oversight of the informal sector remains weak, leading to numerous e-waste processing centres operating without adequate standards. As a result, unsafe processing practices are common, such as

open burning and the use of hazardous chemicals in the extraction of valuable metals from discarded devices [17].

To bridge these gaps, several measures are recommended: 1) accelerate the development of e-waste processing facilities, particularly in underserved areas; 2) strengthen monitoring systems to prevent illegal recycling practices and provide incentives for the formal industry; 3) enhance regulatory enforcement by adopting an Extended Producer Responsibility (EPR) approach, requiring manufacturers to take responsibility for managing their products at the end of their life cycle; 4) increase public education efforts to raise awareness of proper e-waste management and mitigate its environmental impact.

The findings of this study have several important implications for the development of Indonesia's e-waste supply chain system: 1) The importance of integrating the informal and formal sectors. Currently, the system is still dominated by the informal sector, which lacks clear sustainability standards. Therefore, policies should encourage collaboration between small businesses and formal industries; 2) Expansion of collection centres to improve public accessibility to recycling facilities. A concrete step that can be taken is establishing partnerships with the private sector to develop more e-waste collection centres; 3) Enhancing consumer awareness through educational campaigns and incentive programs to increase participation in the recycling system; 4) Utilisation of modern technology to improve the efficiency and sustainability of the recycling process. Countries such as Germany and Japan have successfully reduced the environmental impact of e-waste by adopting more advanced recycling technologies [10]. By implementing these measures, Indonesia's e-waste management system is expected to become more efficient and sustainable, thereby reducing environmental impacts and improving the welfare of those involved in this sector.

CONCLUSION

This study reveals that the circular supply chain of EoL smartphones, particularly in the Special Region of Yogyakarta province, continues to face significant challenges. The majority of consumers prefer to keep their used mobile phones devices rather than recycle them. Low awareness of the importance of e-waste management, limited recycling facilities, and a lack of incentives are the primary factors contributing to low participation in the recycling system. The circular supply chain of EoL smartphones is still dominated by the informal sector, which operates without clear regulations. After-sales service centres do not accept used mobile phones due to the absence of a take-back scheme from manufacturers. As a result, discarded electronic devices are mostly processed through informal channels that lack environmentally responsible management standards. This poses a risk of exacerbating environmental pollution and limits the reuse of valuable components from these devices. Although regulations for e-waste management exist, their implementation remains weak. The lack of recycling infrastructure, inadequate oversight of the informal sector, and the ineffective execution of the Extended Producer Responsibility (EPR) policy are the main challenges. Compared to developed countries, Indonesia still requires regulatory reinforcement to ensure that manufacturers take responsibility for their products after the end of their lifecycle. To enhance the effectiveness of e-waste management, expanding recycling facilities, providing incentives for consumers to recycle their devices, and integrating the informal sector with the formal system are essential. Additionally, public education plays a crucial role in raising awareness about the environmental impacts of e-waste and the importance of responsible management.

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Adoption of Circular Supply Chain Practices in Agricultural Processing Small- and Medium-Sized Enterprises in Developing Countries

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1. Introduction

The traditional linear agricultural supply chain, characterised by resource extraction and waste disposal, has accelerated environmental damage and threatened agricultural sustainability (Farooque *et al.*, 2019). Alarmingly, nearly one-third of food (1.3 billion tons) is lost within the agri-food supply chain, while 820 million people suffer from food deprivation worldwide (Sundgren, 2022). Addressing these challenges requires a shift in supply chain management, with circular supply chain management (CSCM) emerging as a transformative solution that transitions from the linear "take-make-dispose" model to systems prioritising circularity (Agyabeng-Mensah *et al.*, 2023). CSCM is the integration of the circular economy (CE) into supply chain management to circulate materials at their highest value while minimising waste (Farooque *et al.*, 2019). The principles of circular supply chains (CSCs) are to reduce material usage, prolong product life and create new values of materials across the supply chain (Bocken *et al.*, 2016), aiming for a zero-waste vision while generating competitive advantages (Farooque *et al.*, 2019).

Achieving agricultural sustainability through CSCs is unfeasible without including small- and medium-sized enterprises (SMEs), which drive economic growth but also significantly impact the environment. SMEs account for about 90% of businesses, 50% of the global workforce (Dey *et al.*, 2022), and 50%-60% of global pollution (Agyabeng-Mensah *et al.*, 2023). Given SMEs' substantial presence and influence, their adoption of CSCs is essential for achieving global agricultural sustainability. However, despite the recognised benefits of circular supply chain practices (CSCPs), SMEs remain hesitant to adopt them, perceiving them as burdensome (Suchek and Franco, 2023). This hesitation is compounded by the fact that CSCPs remain a relatively new area of research (Kühl *et al.*, 2022), with limited studies focusing on SMEs in developing countries (Dey *et al.*, 2022, Zhang *et al.*, 2023). The unique characteristics of SMEs in these regions underscore the need for empirical evidence on adoption factors, prompting this study to address calls for further research on CSCPs in developing countries by Zhang *et al.* (2023). Specifically, this study focuses on the post-harvest stage, the primary contributor to 20%-30% of food loss and waste in developing countries (Krishnan *et al.*, 2020, Papargyropoulou *et al.*, 2014), targeting processors as key intermediaries between producers and customers. Enhancing CSCP adoption at the processing stage can encourage similar practices among upstream and downstream supply chain partners through knowledge sharing and risk management (Cole and Aitken, 2020), contributing to greater supply chain sustainability. Moreover, research on CSCPs primarily focuses on technical materials in manufacturing (Kühl *et al.*, 2022), highlighting the need for studies on biological materials in agriculture, given their perishability and ecological ties.

Thus, this research aims to gain a comprehensive understanding of the key factors influencing CSCP adoption among agricultural processing SMEs in developing countries. To achieve this research objective, the study uses the Technology-Organisation-Environment (TOE) framework, which has been widely used to explain firms' adoption of innovation. Accordingly, it addresses the following research question: *What are the key factors within the technological, organisational, and environmental contexts that influence the adoption of CSCPs by agricultural processing SMEs in developing countries?* To address the research question, agricultural processing SMEs in Vietnam are selected as subjects of investigation. Vietnam has emerged as one of the world's leading exporters of agricultural products, ranking among the top five global suppliers of various items (The World Bank, 2020). This

highlights the urgent need for effective management of the significant by-products and waste generated by its agricultural sector, which contributes 24% to GDP, 20% to exports, and over 70% to employment (Maitah *et al.*, 2020).

2. Theoretical background and literature review

2.1. Theoretical background

The TOE framework by Depietro *et al.* (1990), supported by strong theoretical and empirical evidence, is widely applicable across contexts, making it well-suited for studying CSCP adoption in agricultural SMEs in developing countries. This study builds on the TOE framework by integrating key factors from relevant theories: the technological context from Diffusion of Innovation (DOI) theory (Rogers, 1995), the organisational context from the Organisational Readiness for Change (ORC) theory (Weiner, 2009), and the environmental context from Institutional theory (DiMaggio and Powell, 1983). As managers often navigate pressures to balance economic efficiency with meeting institutional pressures for symbolic compliance (Kauppi, 2013), this study integrates DOI and ORC to address efficiency motivations and Institutional theory to capture legitimacy-driven responses, forming a comprehensive framework to understand CSCP adoption.

2.2. Factors influencing CSCP adoption in SMEs in developing countries

The current literature identifies four main sustainability supply chain narratives, namely reverse logistics, green supply chains, closed-loop supply chains, and, more recently, CSCs (Batista *et al.*, 2018, González-Sánchez *et al.*, 2020). While reverse logistics focuses on backward flows, closed-loop supply chains integrate forward and reverse flows within a firm, and green supply chains emphasise environmental performance. CSCs broaden beyond these models by incorporating both closed- and open-loop flows across industries and addressing the holistic triple bottom line of organisations. As a result, they are considered more effective in enhancing supply chain operations' ability to restore and regenerate materials.

CSCs are a relatively new concept with limited research, primarily focused on technical materials in manufacturing (Kühl *et al.*, 2022). Batista *et al.* (2018) attribute this trend to the suitability of restoration processes like repair, refurbishing, and remanufacturing for durable, non-perishable materials (e.g., steel, plastics) rather than biological materials (e.g., food). Biological materials undergo irreversible changes during use, making repair or refurbishment impractical for extending their lifespan. Consequently, few studies explore CSCPs in agriculture, leaving a gap in understanding the factors influencing their tailored application to biological materials, a defining characteristic of the sector. Furthermore, existing CE research predominantly examines large organisations (Dey *et al.*, 2022) and developed countries (Zhang *et al.*, 2023), with only 5% focusing on emerging economies (Mhatre *et al.*, 2023), and just 6 of the top 50 CSC studies addressing developing countries (Zhang *et al.*, 2023). Given the critical role of SMEs in agricultural value chains in developing countries, understanding CSCP adoption in this context is crucial. SMEs in developing countries often prioritise short-term economic gains over sustainability due to resource constraints (Dey *et al.*, 2022). Moreover, sustainability principles from developed nations often misalign with the contexts of developing countries, where lower income levels reduce demand for sustainable products, leaving businesses with little incentive to prioritise sustainability (Hoang *et al.*, 2023). Additionally, insufficient regulations further hinder CSCP adoption (Zhang *et al.*, 2023). Food loss and waste patterns also differ: in developing countries, most occur post-harvest (20–30%) due to inadequate infrastructure, while in developed nations, the consumption stage dominates (40%) due to consumer behaviour (Krishnan *et al.*, 2020, Papargyropoulou *et al.*, 2014). As key intermediaries in supply chains and major contributors to food loss and waste, agricultural processing SMEs in developing countries are a focus of this study. Using the TOE framework, it analyses key factors influencing CSCP adoption, helping to promote sustainability across supply chains.

Technological factors influencing CSCP adoption

Underpinned by DOI theory by Rogers (1995), technological factors represent perceived characteristics of CSCPs that affect their adoption: perceived relative advantage, perceived compatibility, perceived simplicity and perceived observability. *Perceived relative advantage* refers to the degree to which an innovation is perceived to be superior to what it replaces (Rogers, 1995). It is argued that SMEs are more likely to adopt CSCPs when benefits like cost savings, eco-efficiency, value creation, and enhanced reputation directly address their operational and financial challenges (Suchek and Franco, 2023). *Perceived compatibility* is the degree to which an innovation is perceived to be compatible with the requirements, experiences, and current values of potential adopters. SMEs in developing countries are more likely to adopt CSCPs if these practices fit seamlessly with their limited resources and existing operations, reducing resistance to change. *Perceived simplicity* reflects the effort required to implement an innovation. Simple, accessible solutions lower adoption barriers, particularly for resource-constrained SMEs. *Perceived observability*, defined as the extent to which the outcomes of CSCPs are visible to others, enhances adoption likelihood by demonstrating successful implementation examples.

Organisational factors influencing CSCP adoption

According to ORC theory (Weiner, 2009), organisational readiness is a collective state where members exhibit both commitment to change (change commitment) and confidence in their ability to achieve it (change efficacy). Key organisational factors influencing CSCP adoption align with these dimensions: top management commitment reflects change commitment, while cognitive readiness, resource readiness, and supply chain collaboration collectively represent change efficacy. *Top management commitment* reflects an organisation's willingness to adopt CSCPs (Kitsis and Chen, 2021) and is especially crucial for SMEs, where sustainability awareness is often limited and efforts often focus on survival rather than growth (Centobelli *et al.*, 2021). *Cognitive readiness*, representing an organisation's knowledge and skills base, is vital for enabling CSCPs (Lokuge *et al.*, 2019), but is often insufficient in SMEs in developing countries. *Resource readiness* reflects the ability to reconfigure resources to support CSCP adoption (Lokuge *et al.*, 2019). *Supply chain collaboration*, which involves sharing information, knowledge, and resources (Berardi and de Brito, 2021), is critical for advancing CSCPs. It enables the transformation of waste into higher-value resources across supply chains and helps SMEs access external resources to overcome financial and expertise limitations.

Environmental factors influencing CSCP adoption

Institutional theory suggests that corporate actions are influenced by regulations, customer expectations, community norms, and competitor behaviour, with non-compliance risking boycotts, reputational damage, and legal disputes (Kitsis and Chen, 2021). *Government influences*, including regulations and support, significantly impacts circular innovation adoption (Centobelli *et al.*, 2021). While weak enforcement in developing countries often slows progress, incentives can help resource-limited SMEs adopt CSCPs. *Customer pressures* arise from customers' requirements and expectations regarding CSCPs. Consumers increasingly expect firms to meet environmental standards and collaborate with suppliers that adopt sustainable practices (Ana *et al.*, 2018). *Social community influences*, including NGOs and local communities, promote sustainability through advocacy and resources, especially in regions with weak institutional support (Centobelli *et al.*, 2021). Finally, *competitive pressures* drive firms to adopt CSCPs to stay competitive when their competitors have already implemented them (Calzolari *et al.*, 2023).

3. Research methodology

3.1. Data collection

CSCs remain a nascent concept with limited research. Thus, this study employs a qualitative approach using semi-structured interviews with academics, industry experts, and practitioners from agricultural processing SMEs in Vietnam. SMEs are defined by the

OECD (2024) as small (10–49 employees) or medium (50–249 employees). Semi-structured interviews with open-ended questions enable flexibility to uncover diverse insights into emergent and multifaceted phenomena like CSCPs (Creswell and Creswell, 2018). Purposive sampling was employed to ensure diversity in organisational size and geographic location, targeting respondents across Vietnam’s North, Central, and South regions through LinkedIn, industry news, and professional networks. Data saturation determines the sample size when no new insights emerge. The inclusion criteria are: (1) academics or industry experts with relevant CSCPs knowledge and experience, and (2) agricultural processing SME practitioners in Vietnam (e.g., owners, chief executive officers (CEOs)) with at least five years of experience and a strong understanding of CSCPs. Nineteen interviews (45 to 86 minutes each) were conducted face-to-face or online, comprising four with academics and experts (Code B1-B4) and fifteen with CEOs of agricultural processing SMEs in Vietnam (Code A1-A15). SMEs range from 12 to 249 employees, with all firms operating for at least five years.

3.2. Data analysis

The interview responses are transcribed, coded and analysed using both predetermined and emerging codes (Creswell and Creswell, 2018) in NVivo 12. In open coding, data from interview transcripts is collected, and key concepts are grouped into broad initial categories (first-order concepts). Next, axial coding is conducted by identifying relationships among the first-order concepts and aggregating them into higher-order themes (second-order themes). Finally, axial code themes are integrated into overarching dimensions that shape the framework. Figure 1 provides a coding example of the organisational factors.

To enhance the rigour of this study, four trustworthiness criteria were applied: credibility, transferability, dependability, and confirmability (Korstjens and Moser, 2018). Credibility was supported through data triangulation, and validation of findings with interviewees. Transferability was addressed by providing detailed descriptions of the interview context. Dependability was ensured through purposive sampling and maintaining confidentiality. Confirmability was reinforced by transcribing and archiving interviews, documenting the analysis process, and using a literature-based interview protocol (Appendix). These methods help ensure that the findings are free from researcher bias, remain stable over time, and allow for assessment of their transferability to other contexts.

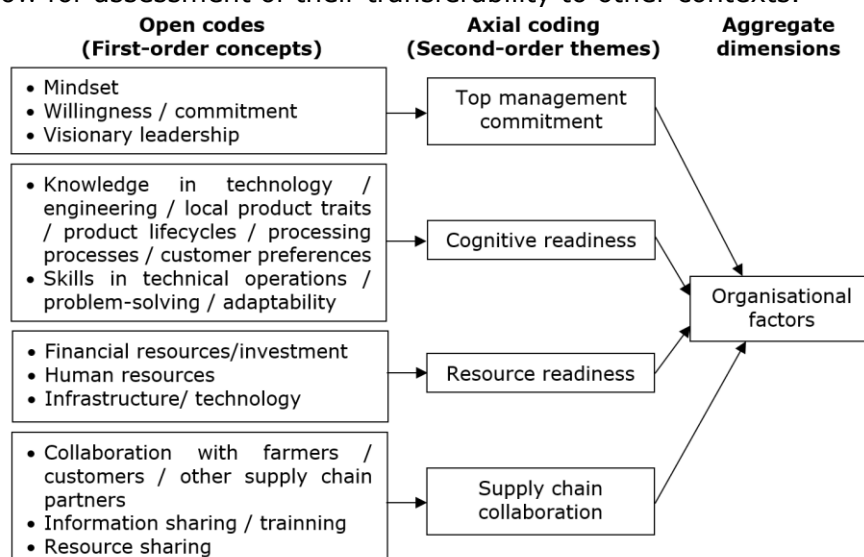


Figure 1. Coding example of the organisational factors

4. Findings and discussion

While the findings align with the broader literature on major factors influencing CSCP adoption, notable differences emerge in how these factors manifest and their relative

importance for SMEs in developing countries like Vietnam. The findings also underscore the dual primary motivations behind CSCP adoption: economic efficiency and legitimacy, offering a comprehensive understanding of CSCP adoption (Figure 2). Technological and organisational factors primarily address SMEs' economic efficiency needs, focusing particularly on cost savings and new revenue streams. Meanwhile, environmental factors reflect legitimacy-driven responses, as SMEs respond to external influences to maintain their reputation, comply with regulations, and meet stakeholder expectations. As technological and organisational factors are managed within the firm, they demonstrate firms' internal readiness, while environmental factors, being beyond the firm's direct control (Depietro *et al.*, 1990), represent external influences.

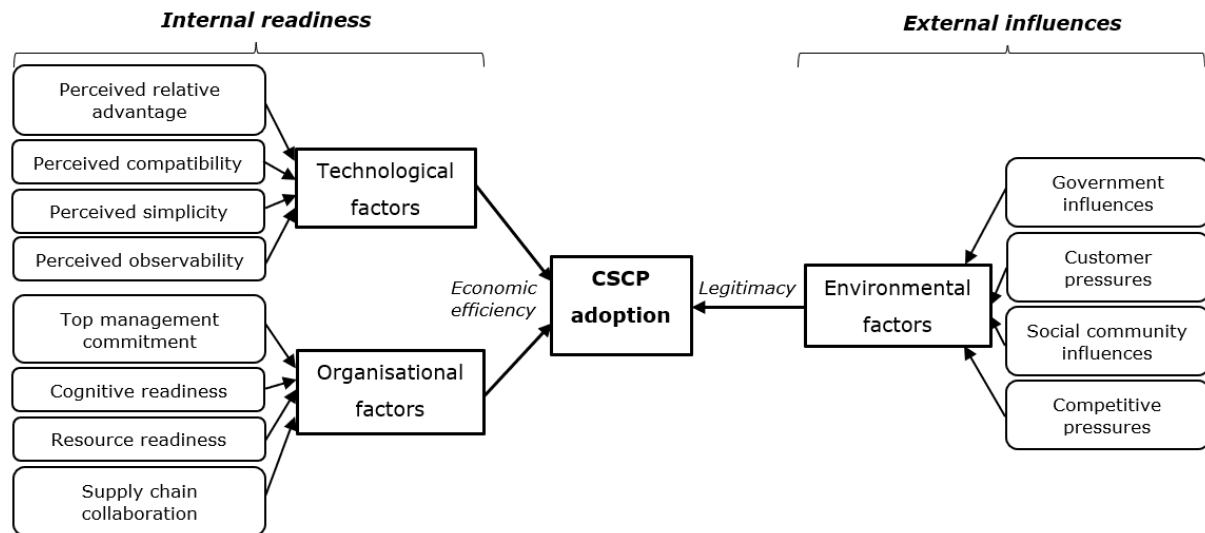


Figure 2. Framework of factors influencing CSCP adoption

4.1. Technological factors

Technological factors capture SMEs' perceptions of the benefits and feasibility of adopting CSCPs, focusing on how effectively these practices address economic efficiency needs while accommodating resource constraints. Participants emphasised a reactive approach, prioritising practical, seamlessly integrated solutions that deliver immediate benefits.

Perceived relative advantage, cited by 19/19 participants, emerges as the most significant driver of CSCP adoption. While the literature underscores the simultaneous economic, environmental, and social benefits of CSCPs (Batista *et al.*, 2018), SMEs tend to take a reactive approach, prioritising immediate economic gains. For instance, agricultural by-products and waste, often treated as disposable, are instead transformed into higher-value products, helping reduce material costs and generate additional income. A4 noted: "Adopting a CSC helps us generate revenue by creating new products, instead of releasing waste into the environment."

Perceived compatibility, identified by 15/19 participants as a key driver, reflects SMEs' preference for solutions that integrate seamlessly into existing operations, minimising disruption and avoiding costly restructuring. This aligns with their resource constraints and focus on economic efficiency. As A5 noted, "The principles of CSCs are compatible with our ginseng products, including ginseng plants, roots, and flowers, which can be part of a circular system. I plan to develop a product from ginseng flowers to use as incense to extend the product lifecycle of ginseng flowers."

Perceived simplicity, noted by 13/19 participants, drives SMEs to prefer CSCPs that are easy to understand, learn, and implement, favouring low-cost, incremental changes over major upgrades. However, the perishability of biological materials adds complexity, requiring specialised knowledge and quick processing to prevent spoilage and retain value.

As a result, many SMEs adopt CSCPs selectively, prioritising practices suited to their limited resources and capacity. B1 stated: *"SMEs may avoid circular practices if they perceive them as overly complex or requiring significant technical expertise."*

Perceived observability, cited by 17/19 participants, strongly supports adoption by demonstrating tangible outcomes like cost savings and product innovation from peers. Observing CSCPs applied to biological materials, such as transforming agricultural by-products into safe, value-added food products, builds confidence and lowers perceived risks for SMEs constrained by resources and technical expertise. A10 noted: *"I learned about the CE from attending a session shared by another coffee company that applies a CSC. I believe if they can do it, then I can do it too."*

4.2. Organisational factors

Organisational factors influence CSCP adoption by ensuring SMEs possess the necessary commitment and resources to implement these practices, particularly addressing economic efficiency needs. For Vietnamese agricultural SMEs, this often involves adopting reactive strategies to tackle immediate challenges rather than proactive, long-term planning. A key example is managing agricultural by-products and waste, which, if left unutilised, not only contribute to environmental pollution but also represent lost economic value.

Top management commitment is highlighted as a decisive factor in the adoption of CSCPs by all participants. In SMEs, business owners often double as CEOs, making them central to CSCP adoption. They directly drive these initiatives by aligning business models and allocating limited resources for CSCPs implementation. A4 stated: *"We always think about CSCPs. We aim to find solutions to fully utilise the entire coconut tree effectively. Previously, coconut trees without fruit (due to salinity intrusion) were simply cut down."*

Cognitive readiness, reported by 16/19 participants, is crucial for SMEs to adopt CSCPs effectively, requiring context-specific knowledge. Unlike the broad knowledge base discussed in the literature, agricultural SMEs prioritise understanding local product traits and product lifecycles to manage biological by-products and waste effectively through timely recovery and repurposing before degradation. Knowledge of customer preferences for circular products also supports adoption. A8 noted: *"It is essential to understand anaerobic technology to treat wastewater. If the water is not sufficiently clear and pure when used in the factory to process cassava starch, it will spoil immediately."*

Resource readiness is also crucial for SMEs (highlighted by 17/19 participants) to invest in circular solutions suitable for biological materials. Unlike large organisations that can reconfigure extensive resources, SMEs focus on incremental solutions rather than large-scale infrastructure. A4 commented: *"Human resources are the most important factor. Additionally, we need funding for technology to implement a CSC. For example, without vacuum concentration technology, we would not be able to recover distilled water."*

Supply chain collaboration, cited by 15/19 participants, is vital for CSCP adoption among agricultural SMEs, enabling resource sharing and knowledge exchange. In a CSC, where one process's output becomes another's input, collaboration with partners like farmers, cooperatives, and companies that utilise by-products and waste is crucial for efficient resource recovery and reducing environmental impact. A6 commented: *"We participate in a cooperative as an ecosystem to connect with other businesses to process passion fruit peels on the same day to prevent environmental pollution and avoid penalties."*

4.3. Environmental factors

Environmental factors reflect legitimacy-driven responses, as SMEs strive to meet external demands for symbolic compliance while managing limited resources. SMEs often adopt reactive strategies to address environmental pressures, focusing on compliance with regulations and market demands rather than proactively pursuing innovation.

Government influence, cited by 17/19 participants, is a key driver of CSCP adoption. In Vietnam, while regulations promote CE principles, implementation is hindered by unclear policies and limited financial and technical support. As a result, SMEs often adopt reactive strategies, focusing on compliance to avoid penalties rather than pursuing innovation beyond legal requirements. A8 mentioned: *"Implementing a CSC ensures stable production by consistently adhering to environmental protection regulations, preventing government-imposed penalties or suspensions."*

Customer pressures, cited by 16/19 participants, influence CSCP adoption differently in domestic and international markets. Domestic consumers increasingly prefer sustainable products but rarely demand CSCPs explicitly and are price-sensitive. In contrast, international customers, especially in the EU, US, and Japan, enforce strict standards (e.g., Global GAP, JAS, USDA) that, while not explicitly mandating CE principles, include criteria related to CSCPs, such as by-product and waste management, driving SMEs to adopt CSCPs to remain competitive in export markets. A12 shared: *"Foreign customers following organic certification standards encourage avoiding the use of fossil fuels in processing."*

Social community influences, reported by 11/19 participants, while recognised in the literature as important drivers for sustainability, are notably weaker in Vietnam. While younger generations are increasingly supportive of environmental sustainability, limited public awareness of CSCPs reduce their influence. However, some NGOs fill this gap by providing knowledge and financial support, helping resource-constrained SMEs adopt CSCPs more effectively. A5 stated: *"Last month, with the funding from Worldwide Fund for Nature, we reduced a total of 4,883 single-use plastic bottles, equivalent to 73.3 kg of plastic no longer released into the environment."*

Competitive pressures, cited by 12/19 participants, drive SMEs to adopt CSCPs, with peer success as a motivator. SMEs adopt CSCPs to demonstrate symbolic compliance, enhancing their market reputation and gaining a competitive edge. A1 mentioned: *"Seeing other businesses embrace CE principles encourages me to take similar steps."*

5. Conclusions

This study is among the first to holistically examine factors influencing CSCP adoption in agricultural processing SMEs in developing countries like Vietnam. Resource constraints often drive SMEs to adopt reactive strategies that address immediate challenges. Awareness of CSCP characteristics plays a pivotal role in building organisational capabilities and fostering commitment, while external influences compel SMEs to prioritise these efforts. These findings highlight the need for tailored strategies that address the unique limitations and priorities of SMEs in developing countries.

5.1. Theoretical implications

This study enhances the TOE framework by integrating complementary theories, namely DOI, ORC and Institutional Theory to address the complexities of CSCP adoption in agricultural processing SMEs in developing countries. The framework incorporates both economic efficiency-driven factors (underpinned by DOI and ORC) and legitimacy-driven factors (underpinned by Institutional Theory), offering a holistic understanding of the dual motivations driving SMEs to balance efficiency needs with external influences. By focusing on biological materials, the study addresses sector-specific challenges such as managing perishable by-products and waste promptly to retain value and prevent environmental pollution. It also reveals the reactive strategies of SMEs in resource-constrained contexts, thus filling a critical gap in understanding CSCP adoption in SMEs in developing countries.

5.2. Practical implications

This study offers practical insights to promote CSCP adoption among agricultural processing SMEs in developing countries, addressing resource constraints and market challenges. By analysing TOE factors, it introduces a strategy matrix (Figure 3) inspired by a mountain-climbing metaphor. The matrix categorises firms based on internal readiness (measured as the average of technological and organisational factors) managed within the firm, and external influences arising from environmental factors beyond the firm's direct control. Firms are classified into 16 quadrants based on the number of external influences experienced and internal readiness achieved. Each quadrant represents a unique combination of capabilities and pressures. Precisely identifying a firm's position in the matrix enables the development of tailored strategies to facilitate smoother progression through the adoption stages. The most advantageous position for CSCP adoption is the Trailblazers quadrant, where firms combine high internal readiness with proactive engagement in external support mechanisms, while also being responsive to increasing external pressures, providing both the capacity and motivation for effective implementation.

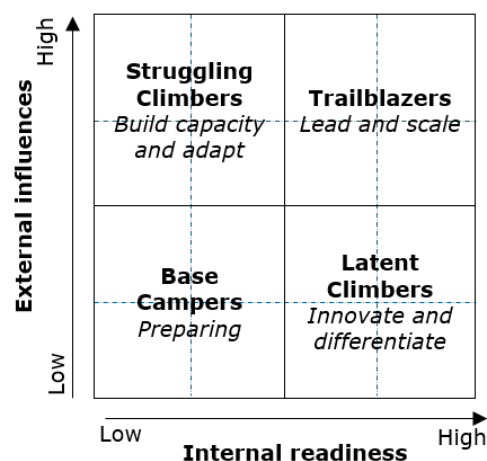


Figure 3. Strategic matrix of CSCP adoption

Trailblazers, with high readiness and strong external influences, should lead and scale by integrating CSCPs across all operations, ensuring global compliance and strengthening collaboration for large-scale adoption. *Base Campers*, with limited readiness and weak external influences, should focus on preparation by building awareness, training staff, and adopting low-cost CSCPs with minimal disruption, while monitoring trends to anticipate future pressures to gradually progress toward Latent Climbers and eventually Trailblazers. *Struggling Climbers*, experiencing high external influences but lacking capacity, should prioritise building their capabilities by leveraging government support and actively collaborating with supply chain partners to adopt incremental solutions to progress toward the Trailblazers quadrant. *Latent Climbers*, with strong internal readiness but weak external influences, should innovate by adopting voluntary CSCPs, aligning with global standards, and highlighting achievements to differentiate themselves in the market.

5.3. Limitations and future research

This study has certain limitations that open opportunities for future research. First, it is based on semi-structured interviews with a small sample size, aiming to refine theory rather than testing. It provides a foundation for future research to develop testable hypotheses and validate them through larger-scale quantitative methods, such as surveys. Second, the study focuses exclusively on agricultural processing SMEs in a developing country. While the proposed framework is likely applicable to similar settings, cross-country studies are necessary to identify contextual differences.

Appendix. Interview protocol

Part	Interview questions
Introduction	Can you share your current role, and your experience with CSCPs in Vietnam's agricultural industry?
Influencing factors	What dimensions of the technological, organisational, and environmental factors affect CSCP adoption in agricultural processing SMEs in Vietnam or within your firm? How do they influence adoption?

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Procurement Logistics in the Circular Economy: Pilot Study on Plastic Packaging Take-Back in German Viticulture

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INTRODUCTION

In recent years, the circular economy has gained considerable importance, particularly with regard to the recycling of plastics. At a time when sustainability and the efficient use of resources are increasingly taking centre stage, the return of plastics for recycling is becoming essential (Hopewell *et al.*, 2009; WEF, EMF, McKinsey&Co, 2016). While the focus is often on urban areas and household waste, the agricultural sector is also contributing to the plastic waste issue. Plastics are mainly used in agriculture for the packaging, storage and transport of agricultural products, as well as for components and materials used, such as fertilisers and pesticides. According to Naturschutzbund Deutschland e. V. (NABU), over 13,000 tonnes of plastics are released annually in Germany as a result of agricultural activities (NABU, 2021). Resulting plastic waste poses a significant environmental problem due to the challenges of disposal and recycling.

A key obstacle in the endeavour to recycle plastic waste from agriculture lies in inadequate take-back systems. This lack makes it difficult for farmers to dispose of their plastic waste efficiently. Increased participation of agricultural businesses in take-back systems could significantly increase a controlled and managed return of plastic packaging. Despite commercial actors offering take back solutions in the agricultural domain, participation remains a challenge for many farmers and agricultural businesses.

Based on the practical experience of one of the authors in the domain and against the outlined background, this study asks the question: What logistical challenges hinder the take-back of plastic packaging in agriculture and how can these be overcome in order to increase the return rate? This study examines this question through a qualitative research design based on expert interviews with (representatives of) winegrowers in the Deidesheim region in Germany (state of Rhineland-Palatinate). This region was selected due to its typical challenges and conditions for take-back schemes.

The objective of the study is to identify specific obstacles and opportunities for improvement in the take-back processes in order to contribute to the development of a more effective circular economy in agriculture. The study aims to provide take-back solution providers and other stakeholders with insights on the logistics- and supply chain-related barriers in establishing efficient and effective return flows of agricultural plastic waste and potential measures to overcome those barriers.

The following section therefore outlines the theoretical background of supplier relationships and transaction costs in circular value chains as a foundation to analyse take-back systems for commercial plastics. After describing the qualitative research approach, the results section presents findings on plastic waste in viticulture and respective challenges for commercial take-back systems. The discussion connects drivers for returns with recommendations for take-back systems to increase return rates. Eventually the study suggests future research directions in the domain of circular supply chains for plastics in agriculture.

LITERATURE REVIEW

Circular Value Chains, Procurement and Supplier Relations

Within the framework of the Circular Economy (CE), supplier relationships entail transactions that diverge from those observed in traditional, linear supply chains (SCs).

The formation of circular SCs often requires relationships with previously unfamiliar market participants, characterised by uncertainty and transaction specificity. Ideally, such transactions would be governed by hierarchical structures (Williamson, 1975). Any strategy designed to mitigate uncertainty—and to increase return volumes—must entail a comprehensive understanding of supplier and exchange relationships, as well as the transaction costs involved.

Circular business models necessitate the integration of new, often autonomous market participants (Östlin *et al.*, 2008). Circular processes are predominantly reliant on, and frequently associated with, reverse logistics (O'Reilly and Kumar, 2016; Guide *et al.*, 2003). Within this framework, the procurement of used products is often identified as a critical bottleneck, as companies encounter difficulties in managing supplier relationships. Enterprises aiming to 'close the loop' encounter procurement challenges when attempting to identify and acquire end-of-life products for their operations (Östlin *et al.*, 2008). Such challenges are typically addressed through integration to enhance product returns, with one such approach being the avoidance of ownership transfer. Nonetheless, the introduction of reverse flows introduces additional complexity to supply chains. Although many studies focus on the return of products or components for reuse and remanufacturing, the challenge of managing suppliers in recycling is equally significant for packaging materials including plastic packaging from agri- and viticulture.

In Supply Chain Management (SCM), relationship management and relationship marketing are pivotal concepts aimed at mitigating the costs and risks inherent in market transactions (Christopher *et al.*, 2002). Procurement relations are guided by strategies and frameworks, such as incentives, designed to achieve these objectives (Biergans, 1984). The involvement of numerous independent actors in CE activities highlights the necessity to reassess and cultivate new supplier relationships. Key theoretical frameworks addressing these organisational dimensions include transaction cost economics and property rights. These theories provide insight into the level of organisational integration within circular supply channels. Factors such as uncertainty in quality or timing, resource dependence, and transaction costs drive the inclination towards vertical integration to mitigate associated risks (Williamson, 1975; Carter and Rogers, 2008).

Commercial Plastic and Take-Back Systems

Plastic is one of the most important resources in the modern economy. The production of plastic has increased continuously in recent decades, which exacerbates the disposal problem. Until 2015, some 6300 million metric tons have been produced globally whereof only about 9% have been recycled, 12% have been incinerated for energy recovery; 79% are estimated to be landfilled (Geyer *et al.*, 2017).

For the context of this study in Germany, commercial municipal waste includes waste from sources other than private households, such as commercial and industrial waste, as well as waste from public institutions (Bundesregierung, 2017). Plastic packaging is crucial for protecting products during transport, but its environmental impact necessitates mitigation measures. Take-back systems for plastic packaging are gaining traction, yet the degree of actions taken seem less than necessary to mitigate resulting issues (Phelan *et al.*, 2022).

In Germany, private households manage plastic waste through the so-called dual system, despite concerns about transparency and efficiency of waste management companies. The growing demand for plastic complicates disposal efforts; however, only a small fraction of plastic waste ends up in landfills (Deutscher Bundestag, 2013). Legislation aims to minimise packaging waste and to promote a circular economy. The EU encourages the use of reusable plastics, and international organisations are collaborating to address plastic waste globally (Hughes, 2017).

In the commercial sector, collection of plastic waste is handled differently. According to regulation, commercial actors must organise waste management via commercial take-back systems or municipal recycling programmes that cater for commercial needs (Bundestag,

2023; German Circular Economy Act). Commercial entities, including agricultural businesses, must adhere to regulations set forth in the Commercial Waste Ordinance (Bundestag, 2002), which mandates the proper separation and disposal of commercial waste, including plastics. Non-compliance can result in legal penalties.

National regulation will be further influenced by the European regulation on Packaging and Packaging Waste Regulation (PPWR) effective since February 2025. This regulation focusses on recycling, use and tracking possibilities of (secondary) materials in packaging and effects end users of any kind, business or consumer (EC, 2025).

Plastic Waste in Agri- and Viticulture

The packaging materials used in viticulture include plastic containers for fertilisers and pesticides, stretch films for pallet wrapping, and protective nets for vines, hence serving various purposes such as protection, storage and (safe) transportation. To contextualise numbers and to emphasise the need to increase circularity in this sector, this section briefly compares Germany and France, one of the largest agricultural producers in the European Union and Germany's neighbouring country.

France has a significantly larger agricultural area, covering approx. 26.7 million hectares in 2020 (agreste, 2022), compared to 16.6 million hectares in Germany (Statistisches Bundesamt, 2025). This difference influences the volume of agricultural plastic waste produced per country: France produces approx. 85,000 tons annually (Euronews, 2021), while Germany generates a total of up to 22,000 tons annually (NABU, 2021). Yet it is not clear why numbers differ by more than 100% despite France having only 60% more agricultural land. France relies on ADIVALOR, a centralised take-back system with a recycling rate of 70–77% (Euronews, 2021), whereas Germany uses multiple systems such as PAMIRA, ERDE, and RIGK, achieving a recycling rate of 75–80%.

Plastics released in agriculture are also entering the soil, often through farming practices (Sa'adu and Farsang, 2023). Therefore, reducing plastic use in agriculture is essential to prevent environmental contamination. Studies have shown that even vineyard soils contain microplastics due to intensive plastic use (Klaus *et al.*, 2024). In Germany, agriculture generates approx. 1.1 kilograms of plastic emissions on average per hectare annually. However, pollution levels vary significantly among farms, influenced by the type of agricultural practices. For instance, using soil conditioners can lead to about 400 kilograms of plastic per hectare each year, while seeds and pesticides contribute less than 0.1 kilograms. Additionally, plastic packaging may contaminate the soil if damaged. This highlights the sector's need to adopt more responsible practices regarding plastic use (NABU, 2021).

METHODOLOGY

The research methodology follows a qualitative approach. The authors reviewed circular supply chains and supplier relation characteristics as well as commercial take-back systems for plastics waste. They further conducted selected expert interviews (*purposive sampling*) with farmers from the Deidesheim region to gain insights into waste-plastic management strategies. Due to the exploratory nature of the research at this stage, the study has a pilot character to provide initial insights and inform future in-depth investigations.

Deidesheim is a small town of approx. 11,000 inhabitants in the Palatinate wine region of Germany, situated along the German Wine Route. The area is predominantly known for viticulture. The region benefits from a mild climate and fertile loess and sandstone soils, making it ideal for wine production. Sustainable farming practices are increasingly adopted, reflecting the global trend toward environmentally conscious viticulture (Krieger, n.d.).

Purposive and extreme case sampling were used for the targeted selection of both farmers participating in take-back schemes and those that do not in order to highlight differences between the groups, to shed light on contrasts between 'typical' and 'deviant' cases and to collect valuable information about possible influencing factors (Meyer and Reutterer, 2007).

Expert interviews were selected as the method due to the necessity of acquiring both process and interpretive knowledge to address the research question. Process knowledge encompasses experiential insights, including organisational structures and procedural actions, derived from lived experiences. Conversely, interpretive knowledge not only involves factual information but also includes subjective evaluations that are crucial for future predictions (Bogner *et al.*, 2014).

Basic information about the surveyed winegrowers was collected (see

Table 3), revealing that their length of engagement ranged from 10 to 49 years. A total of six winegrowers were interviewed, including one oenologist and five farm managers. Out of twelve initially contacted farmers, eight agreed to participate, while four declined or did not respond. Another two interviews were excluded due to a lack of relevance. Interviews were held from August 20 to 26, 2024, lasting 7 to 15 minutes each (pilot character, see above).

A primary objective was the involvement in agricultural plastic recycling programs. Three winegrowers were already engaged in such systems, while the remaining three were not involved. The reasons for (non-)participation were discussed in detail. Additionally, farm size (16–54 hectares) and waste volumes (6–30 tons) were recorded.

Intervie	Position	Duration	Interview Date	Particip. in Take-Back-System	Farm Size (Ha)	Annual Waste Quantity (T)	Waste per Hectare (T/Ha)
A	Oenologist	9 Min	20.08.2024	Yes	54	30	0.56
B	Management	7 Min	20.08.2024	Yes	50	28	0.56
C	Self-employed Winemaker	15 Min	21.08.2024	Yes	16	6	0.38
D	Management (family business)	10 Min	22.08.2024	No	34	20	0.59
E	Management	9 Min	26.08.2024	No	20	7	0.35
F	Management	11 Min	26.08.2024	No	30	15	0.50

Table 3: Study Group

Two different guiding questionnaires were used, one for participants of take-back systems and one for those that do not participate. This differentiation allows for a detailed analysis of the different experiences, motivations and challenges associated with participating in a take-back system. The questionnaire used was based on the standard questionnaire from a company that offers a commercial take-back solution, adapted to the needs of the study.

The interviews were recorded, translated and coded using maxQDA. A total of eight categories were identified during the coding and categorisation process, namely:

- for (potential) **incentives**: logistical relief; provision of collection containers; sustainability and environmental awareness; economic benefits
- for **challenges** and obstacles: reliability and flexibility of collection cycles; costs; (additional) sorting and storage efforts; and regional availability of take-back systems.

The following section outlines the interview results based on these categories. These preliminary findings are analysed against the current take-back systems eventually leading to implications on drivers and challenges for return rates of commercial plastic packaging.

RESULTS: Drivers and Challenges for Take-Back Systems

The data indicate that larger farms tend to generate more waste, yet smaller farms that do not participate in take-back schemes seem to generate similar waste quantities per hectare as bigger farms that do participate. Although a limited data set, this indicates that efficient waste management solutions are relevant in the region's viticultural practices.

Drivers and potential incentives

The interviews make it clear that several wine-growing businesses are keen to participate in take-back schemes, although the reasons for doing so vary. A key incentive is the possibility of reducing the logistical burden (*'logistical relief'*). For winegrowers that are regularly confronted with large quantities of waste, the collection of waste by third parties is a considerable relief. Some of the interviewees emphasised that the free collection of waste, which can be guaranteed by a take-back system, is a particularly important motivation. This relief enables winegrowers to concentrate more on their main tasks and minimise the time spent on waste disposal. As one interviewee (A) commented: "We have little work and don't have to worry about disposal."

Another aspect interviewees indicated as a potential benefit is the *provision of collection containers* that would allow winegrowers to sort and store their waste on site better. This would not only facilitate the disposal process but would also provide a better overview of the waste volumes produced. Interviewee A explains: "It would be practical as we could then collect the materials easily and in an organised way". Some winegrowers (e.g. interviewee F), stated that collection containers could make the disposal process easier and reduce the burden on the farm. However, it was also pointed out that a lack of space on site could make it difficult to use additionally provided containers (interviewee E).

Sustainability and the possibility of recycling plastic waste also played a crucial role in the winegrowers' decision to participate in a take-back scheme. Several interviewees mentioned that the environmental friendliness of their work processes was important to them. For certified-organic winegrowers, participation in a take-back scheme is part of their commitment to sustainable production methods. In this context, Interviewee A stated: "We are certified organic and prioritise sustainable solutions. So, it is natural for us to recycle our waste". Another interviewee emphasised that environmental thinking plays a central role, and that recycling is encouraged by returning materials to the cycle (interviewee C). The opportunity to contribute to the circular economy by participating in a take-back scheme is a key incentive for many, as it not only reduces the burden on their business but also raises environmental awareness.

In addition, potential *economic benefits* were also mentioned as an incentive to participate in take-back schemes. Some, especially smaller winegrowers mentioned that potential savings and the avoidance of additional costs could motivate them to participate. Yet this seemed to be a secondary objective rather than the main driver.

Challenges and Obstacles

Although many winegrowers are motivated to participate in take-back schemes, the interviews also revealed logistical challenges that make participation difficult. One of the main hurdles that represent logistical efforts is the *reliability and flexibility of collection cycles*. Several interviewees emphasised that irregular or poorly coordinated collection times are particularly problematic. According to interviewee A, staff shortages often interrupt collection schedules. As a result, waste must be stored for longer periods of time, which leads to capacity issues, especially for smaller businesses with less storage space.

Related to the collection schedules, mentioned by several interviewees, is the lack of *flexibility* regarding *collection times*. Winegrowers are reliant on fixed schedules that cannot always be easily coordinated with their operational processes. As a result they often transport their waste themselves if it is not collected on time. In this context, interviewee C

commented: "With fixed cycles, there is a risk that containers are either not full enough or that waste such as glass standing around for too long is a problem for us."

Another logistical obstacle is the need to *sort and store* the waste before collection. This requires additional labour and time, which complicates the disposal process. Some interviewees stated that although they would be willing to separate and store their waste in principle, this would not be practical without appropriate support. Interviewee D explained: "It's just too much effort to sort everything manually and wait for it to be collected." This represents a considerable additional burden, particularly for farms that already operate with limited staff.

In addition to the logistical hurdles, the cost issue was mentioned in several interviews as a major factor that makes participation in take-back schemes difficult. Especially smaller winegrowers see the high disposal costs as an obstacle. Participation in take-back schemes is associated with costs that are more affordable for larger winegrowers. Interviewee A emphasised: "The costs for disposal are far too high, especially for smaller farms. That simply makes it unattractive." Even if take-back systems could offer economic benefits in the long term, the initial financial burden acts as a deterrent.

In addition, the lack of *regional availability of take-back systems* was mentioned as an obstacle, forcing the winegrowers to longer disposal trips. Interviewee F said: "There are hardly any collection centres in our region. This makes it very difficult to participate regularly." This highlights the challenge for more remote farms where take back solutions are not profitable and hence winegrowers have no other choice than delivering their plastic waste to collection centres themselves with respective resource needs.

DISCUSSION: IMPLICATIONS AND DRIVERS FOR INCREASED RETURNS

Overall, take back systems, like reverse logistics solutions in other domains, such as remanufacturing, are necessary for return flows due to the transfer of ownership; in this case, of the plastic containers that are sold to winegrowers with fertilisers, pesticides and other components. While close vertical integration does not seem feasible in the context of agri-/viticulture, the role of ownership and more likely still the producer's responsibility in the form of regulation could change the situation. The new European regulation on Packaging and Packaging Waste Regulation (PPWR) increases extended producer responsibility (EPR) yet does not specifically address the collection and reverse process for plastic waste. Although the regulation may also increase certain costs, likely for administration, monitoring and compliance, the need to increase secondary materials in packaging will increase the pressure on producers to acquire more recycled plastic; the latter may reduce costs in take back systems overall, e.g., due to economies of scale but also due to standardisation of packaging materials. Eventually, regulation may also increase investments into take back systems. Hence, the regulatory framework helps take back systems to generate volume, yet collection rates could still improve further.

The results from the interviews conducted with winegrowing businesses in the Deidesheim region reveal a nuanced landscape regarding participation in take-back schemes for agricultural plastic waste. At first glance, the findings may appear contradictory, especially with respect to the economic incentives associated with these systems. While some winegrowers express their concerns over the high transaction costs associated with participation in take-back schemes, others highlight potential economic benefits; particularly smaller winegrowers see both the avoidance of additional costs as a motivating factor and the initially increasing costs as an obstacle for participation. Yet this duality raises some questions about the overarching importance of economic considerations in the decision-making process of winegrowers regarding waste disposal.

A deeper analysis of the responses indicates that economic incentives are not the primary driving force behind winegrowers' willingness to engage in take-back systems. Instead, logistical facilitation and sustainability emerge as more significant factors influencing their participation. The results suggest that the logistical relief provided by take-back schemes—

such as the collection of waste by third parties and a potential provision of collection containers—plays a role in motivating winegrowers. This reflects transaction costs principles. Many interviewees emphasised the value of reducing the logistical burden associated with waste disposal, allowing them to focus more on their core agricultural activities. This sentiment is echoed by those who expressed a desire for better organisation and efficiency in the disposal process, highlighting that logistical support can significantly alleviate the pressures they face in terms of coordination and administration costs.

Logistical hurdles can deter participation, especially for smaller winegrowers with limited resources and storage capabilities, which to a certain degree can become specific investments when the space cannot be used otherwise. The emphasis on logistical facilitation underscores the need for take-back systems to be designed with the realities of agricultural operations in mind. Flexible collection schedules that accommodate the variable nature of farming activities, as well as support for waste sorting and storage, are critical to enhancing participation rates. Eventually, minimising the transaction costs due to sorting, storing and in some cases delivering can attract winegrowers to take back schemes. This highlights the importance of fostering effective supplier relations that not only address explicit economic incentives but also streamline operational processes, enabling winegrowers to concentrate on their core agricultural activities while contributing to sustainability efforts within the circular economy.

Take back solutions providers that want to make their offering more attractive may investigate solutions that facilitate more flexibility. One example can be solutions that reduce sorting efforts, e.g., with specific collection containers or technological solutions to sort waste after collection, subject to the business needs and capabilities. They may further improve the collection options by making them more flexible or even predictive, e.g., by using machine learning, other artificial intelligence solutions and 'intelligent containers' to better plan for collections runs avoiding both empty and too-full containers.

Moreover, the commitment to sustainability and environmental stewardship appears to resonate with winegrowers. For those who are certified organic, participating in a take-back scheme aligns with their values of sustainable production and environmental responsibility. The opportunity to contribute to the circular economy and enhance their environmental practices is a compelling incentive that transcends mere economic calculations. This suggests that, for those winegrowers, the value of sustainability and the desire to minimise their environmental footprint due to their focus being on 'organic' outweigh the financial considerations associated with participation in take-back systems.

CONCLUSION

This study investigated take back systems for plastic packaging in agriculture, more specifically in viticulture in the German region of Deidesheim. Asking the question, what logistical challenges hinder the take back of packaging in this context and how to overcome obstacles to increase return rates, this study reviewed the theoretical background from a circular supply chain and transaction cost perspective as well as the current take back environment. With an explorative approach conducting initial interviews, the authors shed some light on the challenges as well as drivers for winegrower's participation in take back schemes. This preliminary results revealed that a nuanced landscape exists regarding participation, yet that explicit financial incentives are not necessarily the dominating driver for participation. Rather important where indirect economic incentives in the form of facilitation of the collection process complemented by sustainability considerations; the logistical facilitation translates into potential savings on transaction costs. Nevertheless, participation in take back schemes can carry additional costs, e.g. for sorting and storing, whereas collection handled by third parties may not compensate for those costs.

The analysis in this study is limited. Firstly, it is preliminary as only six winegrowing business were interviewed. In addition, it only covers selected elements of transaction costs. For example, the search and information costs of winegrowers to find a suitable take back solution provider, and monitoring and enforcement costs have not been analysed.

Furthermore, during the interview process in 2024 it became clear that the new EU regulation will take effect in 2025; this regulation can accelerate the adoption of take back schemes and recycling. Future research should therefore investigate whether and how regulation and legislation such as PPWR serves increased return flows. Transaction costs and further theories such as the principal-agent theory should be looked at in this context to better understand the motivation of actors regarding municipal and commercial systems.

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SMART/DIGITAL CONNECTIVITY IN LOGISTICS AND SUPPLY CHAINS

Applying Industry 4.0 Technologies in Remanufacturing Systems: A Systematic Literature Review

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1. INTRODUCTION

Today sustainability has become a top priority, prompting significant shifts in manufacturing practices. Scaling up remanufacturing can help achieve the EU's goal to realise a fully circular economy by 2050. To drive these shifts, companies must move from the pioneering phase, which focuses on economic and technical feasibility, to the differentiation phase, emphasising standardisation, coordination, and automation. Industry 4.0 (I4.0) technologies play a critical role in supporting this transition by introducing advanced information systems that streamline processes, improve efficiency, and enable real-time decision-making (Kerin & Pham, 2019). Central to these technologies are Cyber Physical Systems (CPS), which, integrate Information and Communication Technology (ICT) with the Internet of Things (IoT) (Blömeke et al., 2020). This integration enables smart machines, devices, and warehouses to communicate and collaborate.

We conducted a systematic literature review to guide technology selection for scaling operations and setting priorities in remanufacturing. Building on the foundational studies of Blömeke et al. (2020) and Kerin and Pham (2020), this research contributes to further development of smart remanufacturing frameworks by estimating the impacts of I4.0 integration into remanufacturing activities. This study is highly relevant as it directly supports circular economy objectives by identifying which I4.0 technologies can address the unique challenges of remanufacturing, such as uncertainty in end-of-life product condition, complex disassembly, and the need for integrated lifecycle data. The review is novel in its approach, introducing three technology clusters, data-driven, automation-driven, and identification-driven remanufacturing, each specifically tailored to remanufacturing's operational demands. Furthermore, the research maps these technology clusters to eight remanufacturing phases, demonstrating how innovations like machine vision with AI, human-robot collaboration, and extended reality (XR) can enhance processes from collection and inspection to disassembly and reassembly. The study also identifies significant research gaps, such as the limited empirical application of I4.0 in industrial remanufacturing and the need for better integration of real-time data into decision-making frameworks. The research question we formulated is:

Which I4.0 technologies can contribute to upscaling of the remanufacturing process?

The next chapter discusses research design with an explanation of the developed technology clusters. Chapter 3 provides a quantitative and qualitative analysis of the results. The final chapter answers the research question and describes the limitations, implications and directions for further research that follow from it.

2 METHODOLOGY

We conducted the research by selecting literature based on keywords and selection criteria. We then defined technology clusters and carried out a content analysis.

2.1 Research design

We followed a five steps approach (Tranfield et al., 2003) consisting of (1) defining the research question; (2) locating and downloading relevant studies; (3) article selection and evaluation; (4) analysis and synthesis; and (5) reporting and using the results. To identify relevant literature, we sourced studies from the Web of Science and EBSCO databases as these provide extensive and high-quality coverage of management research. We focused

our search on literature published in English from 2011 to June 2024 to reflect developments since the term "Industry 4.0" emerged in Germany . Moreover, because the terms "Refurbish" and "Remanufacture" have been used interchangeably in the literature (Sundin, 2004), we included both keywords in our search strategy. Accordingly, we conducted eight search routines in each consulted database using the keywords shown in Table 1.

Industry 4.0 related keywords	Remanufacturing related keyword
Industry 4.0	Refurbish
I 4.0	Remanufactur*
Smart Industry	
Smart Technolog*	

Table 1 Used keywords

Initially, we first assessed how well each article aligned with the research question based on its abstract. For descriptive analysis, we recorded several details of each study in Excel. These included the title, authors, year of publication, DOI or link, research type, findings, methodology, and abstract. This approach provided an overview of the material. Following this, we allocated the selected studies to technology clusters and mapped them to specific remanufacturing phases based on content analysis. These phases include: (1) collection/acquisition, (2) inspection/sorting, (3) disassembly, (4) cleaning, (5) re-inspection, (6) reprocessing, (7) reassembly, and (8) testing (Sundin, 2004).

2.2 Identification of technology clusters

Identifying and defining technology clusters in remanufacturing systems serves several strategic and practical purposes. Remanufacturing processes are inherently complex and require a wide range of technologies, each with distinct roles and capabilities. By categorising these technologies into clusters, researchers and practitioners can systematically organise the technological landscape, clarifying which technologies are best suited to address specific challenges at various stages of the remanufacturing process. This approach aligns technology selection with the unique needs of remanufacturing, such as uncertainty in end-of-life product condition and complex disassembly requirements, and supports strategic planning, investment, and process integration. Additionally, defining technology clusters provides a common language for collaboration, facilitates standardisation, and helps identify research gaps and opportunities for innovation, enabling scalable and efficient remanufacturing operations.

Various frameworks have classified I4.0 technologies into clusters to better understand their roles in manufacturing. For example, the European Patent Office (EPO) framework, groups them into core technologies, enabling technologies, and application domains (de Medina et al., 2023). Similarly, Wee (2014) classifies them by capabilities and functional roles, while Suleiman et al. (2022) identifies five distinct clusters: smart manufacturing, cyber-physical systems, IoT, big data analytics, and cloud computing. Despite these differing classifications, a common structure emerges around three central clusters: data-driven manufacturing, automation-driven manufacturing, and connectivity-driven manufacturing, illustrating I4.0's multifaceted role in advancing manufacturing systems.

Building on this foundation, we adapted I4.0 technology clusters to remanufacturing and introduced an identification-driven cluster. This study merges data-driven and connectivity-driven clusters, reflecting their interdependence (de Medina et al., 2023; Wee, 2014). Cyber-physical systems, as identified by Suleiman et al. (2022) further illustrate this connection by linking physical operations with digital intelligence. In remanufacturing, smart identification technologies are essential for assessing the uncertain condition of end-of-life (EoL) products and guiding decisions to remanufacture, recycle, or discard (Ragampeta, 2022). Moreover, AI and machine vision support efficient disassembly while lifecycle data integration, from beginning of life (BoL) to EoL, enhances sustainability and product lifespan (Teixeira et al., 2022). Additionally, smart identification ensures quality

compliance and facilitates reverse logistics by tracking and sorting used products efficiently (Alqahtani et al., 2019; Sasikumar & Kannan, 2008).

2.3 Definition of technology clusters for remanufacturing

The data-driven remanufacturing cluster encompasses technologies focused on the collection, analysis, and utilisation of large volumes of data to optimise remanufacturing processes, improve decision-making, predict failures, and enhance resource use in remanufacturing. This includes advanced analytics of big data, Internet of Things, artificial intelligence, Blockchain, cloud computing, digital twins and machine learning, which enable better decision-making within various stages of the remanufacturing process (Zhu et al., 2023). Automation-driven remanufacturing integrates robotics, cobotics, sensors supported by data-driven and identification driven systems to improve efficiency, reduce human intervention, and ensure consistency. It integrates automation technologies into autonomous systems to optimise tasks such as disassembly, inspection, and testing, addressing challenges in product variability and volume fluctuations (Okorie et al., 2024). The identification-driven remanufacturing cluster focuses on technologies like RFID, 3D scanning, and vision systems for tracking products, assessing quality, and improving process transparency. Extended reality (XR) technologies, including AR and VR, enhance operator training, task guidance, and remote collaboration, boosting efficiency and accuracy (Yang et al., 2023).

3 ANALYSES

3.1 Quantitative analysis

In total 184 journal papers were found. After removal of duplicates and non-matching papers and after addition of fifteen hand searched papers, finally 75 relevant journal papers remained for analysis. Given that most of the research has been published in recent years (Figure 1), it is evident that this topic is gaining increasing attention from the academic community. The 75 selected articles appeared in 39 journals, with 52 articles published in just 16 journals, highlighting the interdisciplinary nature of smart remanufacturing. Notably, 32 studies were literature reviews, while empirical research was limited. This suggests that Industry 4.0 technologies are still in the early stages of application within industrial remanufacturing (Figure 2).

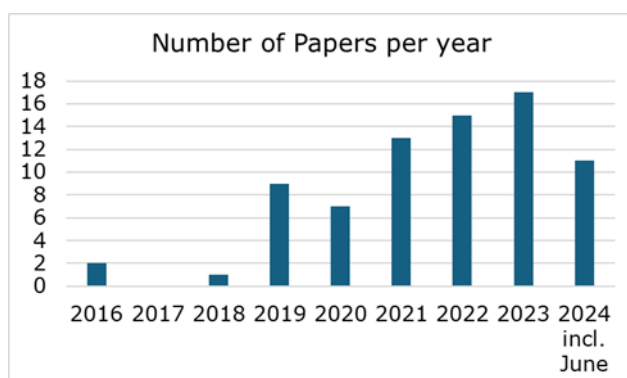


Figure 1 Selected articles per year

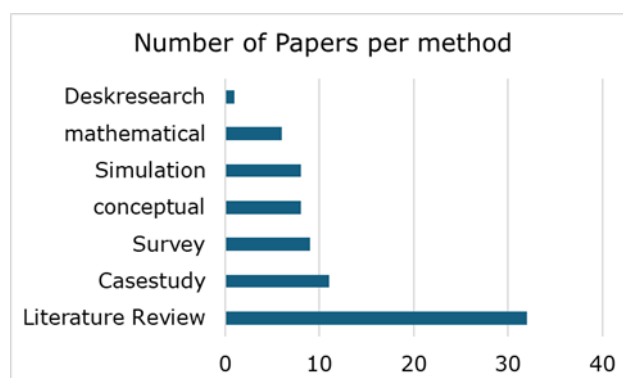


Figure 2 Used methodologies in studies

This review synthesises insights from 35 key studies, selected for their relevance and representativeness using Cooper's taxonomy (Cooper, 1988). These works exemplify Industry 4.0's transformative role in remanufacturing and provide a conceptually and empirically grounded foundation for conclusions on trends and challenges.

3.2 Findings

Data-driven remanufacturing

The integration of I4.0 technologies has revolutionised remanufacturing systems, emphasising data-driven approaches to enhance efficiency and sustainability. At the core of this transformation lies the IoT and connectivity, which enable real-time tracking and streamlined component inspection (Liu et al., 2023; Sharpe et al., 2019). These technologies are complemented by Blockchain, which enhances traceability and lifecycle optimisation (Tozanli et al., 2020). Building upon this foundation, Artificial Intelligence (AI) and Machine Learning (ML) drive significant advancements by enabling smart decision-making and process optimisation across various aspects of remanufacturing, including disassembly planning, quality assurance, and predictive maintenance (Guo et al., 2021). Furthermore, Digital Twins and cloud computing enhance the data-driven approach by offering virtual replicas of physical systems and centralised data management (Caterino et al., 2022). To integrate these technologies, frameworks like the Reference Architecture Model for Industry 4.0 (RAMI4.0) and ontology-based approaches are crucial for standardisation (Sharpe et al., 2019). These interconnected architectures guide remanufacturing from initial collection to final distribution, enhancing resource efficiency and adaptability (Mejía-Moncayo et al., 2023).

Automation-driven remanufacturing

Automation-driven remanufacturing introduces key advancements that enhance efficiency, precision, and flexibility. Robotic disassembly systems using deep learning and haptic feedback reduce the need for human oversight (Zhou et al., 2024), while human-robot collaboration improves adaptability in disassembly tasks (Huang et al., 2019; Siew et al., 2020). Modular automation setups enable the handling of diverse end-of-life products (Wang et al., 2023) and advanced monitoring systems provides insights into component conditions (Daneshmand et al., 2023; Yang et al., 2018). Additionally, IoT integration boosts traceability and facilitates a shift towards automated, data-rich environments (Oztemel & Gursev, 2020). Techniques such as Wire Arc Additive Manufacturing offer energy-efficient and high-precision solutions for component restoration (Priarone et al., 2021), with intelligent systems enabling precise part rebuilding (Yusoh et al., 2021). Finally, AI-driven optimisation streamlines decision-making, enhancing defect detection and repair quality (Guo et al., 2021).

Identification-driven remanufacturing

Identification-driven technologies are significantly advancing remanufacturing by improving efficiency, precision, and adaptability. Machine vision combined with AI enables accurate, non-destructive quality assessments by detecting wear and material degradation (Schlüter et al., 2021). Simultaneously, robotic systems like the LPAS framework support autonomous inspection of complex geometries without relying on digital twins (Poole et al., 2022). In addition, videogrammetry-based 3D modelling allows automated disassembly even without original technical drawings (Siddiqi et al., 2019). Moreover, extended reality offers real-time worker support for component identification, condition checks, and reassembly (Kerin & Pham, 2019). Crucially, human-robot collaboration merges human flexibility with robotic accuracy, improving task allocation, recognition, and safety, while also reducing setup time and handling product variability (Huang et al., 2019; Roda-Sanchez et al., 2023). Collectively, these technologies enable more intelligent and adaptable remanufacturing systems.

4 LIMITATIONS, CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

This section answers the question: Which smart technologies can contribute to upscaling the remanufacturing process?

4.1 Limitations

This research highlights two key limitations. First, the remanufacturing phases of cleaning and testing receive limited attention in the analysed literature, despite their importance for quality. Few studies explore how Industry 4.0 technologies can enhance these stages, indicating a gap in current research. Second, of the 75 studies reviewed, 32 are literature reviews, revealing a lack of empirical research and real-world case studies. This limits

practical insights into the implementation of smart technologies in remanufacturing. Addressing these gaps will be essential for developing a more comprehensive understanding of I4.0's impact on remanufacturing processes.

4.2 Conclusions

Industry 4.0 technologies significantly enhance remanufacturing by improving efficiency and adaptability across all process phases (Table 2). In the collection phase, technologies such as the Internet of Things and Digital Twins enable real-time tracking and detailed product data capture, while AI and big data analytics optimise collection strategies. Cloud computing supports coordination across supply chains. (Liu et al., 2023). During inspection, machine vision, AI, and machine learning improve product condition assessments. IoT and RFID facilitate real-time analysis and predictive insights, and augmented reality assists manual classification (Schlüter et al., 2021). In the disassembly phase, human-robot collaboration boosts flexibility and safety, enabling hazardous tasks and reducing manual labour risks. Vision systems and augmented reality help with product identification and optimal disassembly paths, supported by data-driven technologies. Especially for high-value parts, data-driven identification enables extraction of precious materials and parts (Saenz et al., 2024). In the reprocessing phase, additive manufacturing allows precise repair of high-value components. AI and machine learning support adaptive decision-making, while Digital Twins provide lifecycle data to enhance repair strategies (Yusoh et al., 2021). Finally, in the testing phase, robotised non-destructive testing increases speed and access, while IoT supports real-time monitoring for immediate quality control. Machine learning further improves predictive quality analysis. Overall, I4.0 technologies enhance responsiveness and scalability in remanufacturing, supporting broader industrial adoption. (Poole et al., 2022).

Technology Cluster	Key Technologies	Phases	Current Applications
Data-Driven	- IoT, - AI/ML, - Blockchain, - Digital Twins, - Cloud Computing	- Collection, - Inspection, - Disassembly, - Reassembly, - Testing	- Real-time tracking of cores - Predictive maintenance - Blockchain for lifecycle traceability
Automation-Driven	- Robotics, Cobotics, - Additive Manufacturing, - Sensors	- Disassembly, - Reprocessing, - Reassembly	- Robotic disassembly - Wire Arc Additive Manufacturing
Identification-Driven	- Machine Vision, - 3D Scanning, - RFID, - XR (AR/VR)	- Inspection, - Sorting, - Re-inspection, - Testing	- AI-enhanced machine vision for wear detection - XR for operator training

Table 2: Concept matrix: Industry 4.0 in Remanufacturing

4.3 Implications for industry

The integration of data, automation, and identification-driven technologies is revolutionising the remanufacturing industry with significant industrial implications. Data-driven tools such as AI and big data analytics enable the collection and analysis of product information throughout the lifecycle, facilitating faster and more accurate decisions regarding sorting, disassembly, and process optimisation (Siddiqi et al., 2019; Teixeira et al., 2022). AI, machine vision, and sensors enhance inspection and identification by providing real-time insights into wear and usability (Kerin & Pham, 2019; Yang et al., 2018). Automation technologies, particularly human-robot collaboration, improve precision and efficiency, mitigate labour shortages, and standardise complex tasks (Huang et al., 2019). Identification technologies also address variability in remanufactured products, enabling more consistent sorting and condition assessment (Blömeke et al., 2020).

Collectively, these technologies increase the scalability, flexibility, and sustainability of remanufacturing processes and, at the same time, reduce manual labour and increase reliability.

4.4 Challenges and suggestions for future research

The identified research gap in the cleaning and testing phases of remanufacturing may result from technical complexity, lack of standardisation, reliance on tacit knowledge, and their perception as low-priority tasks (Shukla, 2018). Testing is further challenged by high product variability and limited data infrastructure, reflecting its traditionally supportive role (Liu et al., 2023). Future research should prioritise the development of standardised, knowledge-based, and automated cleaning procedures. Moreover, more industry-specific case studies are needed. For instance, Caterpillar's use of AI for core forecasting in remanufacturing illustrates how digital technologies can optimise inventory and operational efficiency. However, integrating real-time data with decision-making frameworks and developing algorithms to manage variability remain significant challenges. Additional barriers to implementation include financial, technical, organisational, and human factors (Daneshmand et al., 2023). To support the digital transformation, it is essential to create a comprehensive roadmap. This roadmap should serve as a strategic tool to bridge current research gaps and facilitate the effective implementation of I4.0 technologies across remanufacturing systems.

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Challenges and Opportunities in Digital Transformation for Sustainability: Insights from Thailand and Sweden

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INTRODUCTION

In recent years, academic and practitioner interest in the relationship between digitalisation and sustainability performance has grown significantly (Anvari, 2021; Del Río Castro et al., 2021; Kumar et al., 2022; Sahu et al., 2022). The consensus in the literature is that digitalization—encompassing technologies while Internet of Things (IoT), and blockchain long were expected to recolonize the Supply Chain (SC), Artificial intelligence (AI) becomes more attention today—can play a pivotal role in enhancing environmental, social, and economic sustainability (Amjad et al., 2021).

On the positive side, these tools enable real-time monitoring of resource flows, improve energy efficiency, strengthen supply-chain transparency, and support circular economy initiatives through waste reduction and extended product lifecycles. They also spur sustainable innovation by fostering new business models, such as product-as-a-service and digital platforms for shared consumption. Despite these benefits, concerns persist regarding the net impact of digitalisation, such as high initial costs, increased energy consumption, cybersecurity risks, and partial implementations that fail to deliver the full spectrum of improvements. Ultimately, a holistic approach—integrating digital transformation with deliberate sustainability objectives—holds promise for maximising the positive contributions of digitalisation while minimising its adverse effects (Del Río Castro et al., 2021; Tan and Zhao, 2021).

Although the authors primarily draw on academic literature with a particular focus on digitalisation and sustainability, Guandalini (2022) points out that the field remains highly fragmented. As a result, current studies on digitalisation and sustainability often adopt a scope that is too narrow to fully capture the complexity of this phenomenon. To address this gap, research that examines these issues across different sectors and geographic contexts is imperative. Such work would significantly enhance our understanding of the factors, dynamics, and approaches that either facilitate or obstruct the integration of sustainability and digital transformation. This recognised need highlights the importance of further inquiry in this domain and underpins the motivation for the present paper.

In Sweden, digital tools are integral to ambitious sustainability goals—such as achieving carbon neutrality by 2045—by helping optimise energy grids through facilitating circular economy models. Thailand, under its Thailand 4.0 development strategy, is similarly promoting digital transformation in areas like e-commerce, robotics, and smart agriculture to boost economic growth and improve social welfare. Despite the variances in scale and economic context, both countries share an understanding that digital transformation can serve as a catalyst for sustainable progress. Therefore, this study explores the challenges and opportunities in digital transformation for sustainability, drawing on lessons from both Thailand and Sweden.

The rationale for selecting these two countries lies in their contrasting economic and digital development contexts. Thailand, as an emerging economy in Southeast Asia, is actively pursuing digital transformation, yet faces infrastructure gaps, limited SME capacity, and regional disparities. In contrast, Sweden represents a highly developed and digitally advanced economy with strong policy support for sustainability and innovation, including its national digital strategy and alignment with the European Green Deal. Studying Thailand

provides insight into the adaptive strategies of middle-income nations in navigating digital and environmental transitions, while Sweden offers a benchmark for best practices in integrating digital technologies into sustainable development.

Additionally, this study is supported by existing academic and institutional collaborations between researchers in Thailand and Sweden. The research team includes scholars with extensive experience in digital innovation and sustainable development. The long-standing engagement in regional development projects, digital policy analysis, and SME support initiatives in both countries enhances the study's depth and contextual relevance. These collaborative links not only facilitate data access and stakeholder engagement but also ensure a balanced and informed interpretation of findings across both contexts.

METHODOLOGY AND APPROACH

This study employs a mixed-method approach that combines a systematic literature review (SLR) with a targeted context-specific literature analysis from Sweden and Thailand. The SLR serves to identify global trends and insights on digitalisation in supply chains, while the additional literature sources capture unique local perspectives, regulations, and practices relevant to the Swedish and Thai contexts. By integrating these two streams, the methodology aims to provide both a broad theoretical foundation and in-depth, context-bound findings.

Systematic literature review (SLR)

The study started with a systematic literature review (SLR). It used to capture the intersection of digital transformation and sustainability. The initial search was performed through Scopus® database include only the articles, reviews, editorials which written in English. However, to ensure a complete coverage, results were compared and integrated with Web of Science, and EBSCO search engines without any specific field restriction. Guandalini (2022) reviewed that in 2020, the number of articles on digitalisation and sustainability reached peak levels (a total of 48). This demonstrates that the academic environment has drastically worked in picking up on the relationship between digitalisation and sustainability and continuing to rise (Allam and Jones, 2021; Hanelt et al., 2020). Therefore, this study time restrictions the timeframe of 2020-2024 were imposed with the purpose of collecting all relevant literature available on the examined databases.

The query included use keywords such as "digital transformation," "sustainability," "Industry 4.0," and "digital economy." The query included use keywords such as "digital transformation*", "sustainability*", "digital sustainab*", "Industry 4.0*", and "digital economy*". Combining these terms in various configurations ensures that potentially relevant literature—ranging from case studies and empirical articles to theoretical debates—is captured in the initial search. The search resulted in an initial list of 96 papers. By skimming through the abstract, 32 articles met the criteria and were fully reviewed. Backward snowballing of articles which integrate the digital transformation and sustainability were performed, and 14 more articles are reviewed.

Country-Specific Literature Review: Sweden and Thailand

While the SLR focused on global research, specific regional dynamics in Sweden and Thailand may not be fully captured by international journals or might be published in local databases, government reports, or industry white papers. Therefore, to gain deeper insight into country-specific policies, economic contexts, and cultural factors, additional Swedish and Thai literature was included in a supplementary review. Only English-language sources was included for consistency in analysis. Databases such as ThaiLIS (Thailand Library Integrated System) and local university repositories were explored. Each Swedish and Thai source was checked against the study's focus on digitalisation for sustainability, specifically looking for discussions on challenges and opportunities. Themes emerging from Swedish

and Thai contexts were compared against the global SLR results to identify unique local conditions such as cultural attitudes, specific regulatory frameworks or infrastructural constraints. Where relevant, Swedish and Thai examples were added to illustrate how general digitalisation challenges manifest in these two regions.

FINDINGS

Recent research on digital technology adoption for sustainability in Thailand shows that the automotive, food manufacturing, and agricultural sectors increasingly rely on IoT, remote sensing, robotics, and real-time data analytics to optimise processes, reduce energy consumption, and minimise waste (Bounnoy, Thammaporn, and Chinakul, 2022; Kuntanapong and Boonvut, 2022; Rerkpiboon and Gamarra, 2021). In contrast, while Sweden known for its advanced technological ecosystem and strong environmental regulations, has set ambitious goals for sustainable innovation. The findings explain how these challenges might differ and highlight the emerging strategies discussed below.

Category	Thailand	Sweden	Reference
Human Capital	Aging farmer population, tech resistance among older generations; youth engagement needed	Lean is a cultural norm in SMEs; workforce adapts easily to digital tools	Jaee & Melati (2024) Tan & Zhao (2021) Chen et al. (2023)
Technological Infrastructure	Infrastructure gaps in rural areas limit adoption of IoT and smart farming	Well-developed digital infrastructure supports ERP/IoT integration	Kamienski et al. (2019) Tan & Zhao (2021) Chen et al. (2023)
Technical Expertise	Low digital literacy; lack of blockchain expertise in agriculture; need modular training	SMEs access innovation through collaborations (e.g., RISE) offering applied tech training	Jaee & Melati (2024) Medvedev & Molodyakov (2019) Chen et al. (2023)
Cybersecurity	Weak cybersecurity in AI/Big Data use; privacy and hacking concerns in smart farming	Security emphasised in digital systems (e.g., end-to-end encryption); public trust supported by strong policy	Jaee & Melati (2024) Kleinschmidt et al. (2019) Jerhamre et al. (2022) Chen et al. (2023)
Cost Concern	High upfront costs for automation; SMEs lag behind large companies	State-supported testbeds and partnerships lower tech entry cost for SMEs	Kuntanapong & Boonvut, (2022) Chen et al. (2023)
SME Context	SMEs face high transaction costs, limited access to data/markets; tech use based on intuition, not systems	DISEL framework shows how digital + lean improves SME sustainability with minimal resources	Sakthivel & Udayakumar (2019) Chen et al. (2023)

1. Human capital

Thailand's agricultural sector is confronting two significant and interlinked challenges. First, an aging population of farmers is leading to labour shortages, as many older farmers retire without being replaced by younger workers. Second, there is a growing global demand for food, which puts additional pressure on agricultural producers to increase efficiency and productivity. Encouraging youth involvement in agriculture is widely seen as a key strategy

for sustaining the agri-food and agricultural sector, particularly because of the growing adoption of advanced technologies (Jaee and Melati, 2024; Tan and Zhao, 2021). As digital technologies reshape jobs, these changes can drive the creation of more flexible employment opportunities but also underscore the urgent need for widespread upskilling and reskilling. At the same time, there is a well-documented generational communication gap in agriculture: older farmers may find it challenging to grasp the technical aspects of new tools and digital innovations. Likewise, Kernecker et al. (2020) observed that many European farmers do not recognise a clear benefit or relative advantage in adopting new technologies. They also find these systems overly complex and often unsuitable for the scale of their farms.

2. Technological infrastructure

The Thai government has made digital transformation a priority through the Thailand 4.0 policy; however, a major obstacle remains the gap in technological infrastructure. While urban centres like Bangkok benefit from cutting-edge digital tools, rural agricultural areas face challenges such as unreliable internet access, limited mobile coverage, and insufficient smart technologies. Kamienski et al. (2019) emphasise that a dependable internet connection and robust technological infrastructure—supported by adequate human and financial resources—are essential to overcome these barriers. Such disparities ultimately hinder the widespread adoption of digital solutions across industries (Tan and Zhao, 2021).

3. Technical expertise

The existing literature recognised the potential of blockchain in supply chain management, particularly in the agriculture and food export industries for example, develop digital traceability systems for agriculture and food exports to ensuring compliance with international food safety standards. However, blockchain adoption in Thailand is still in its early stages, and technical expertise hinder its widespread implementation (Jaee and Melati, 2024). Furthermore, digital transformation requires substantial in technology training.

Many agriculture and food exporters lack the expertise to implement advanced digital solutions to expand their market, primarily due to insufficient digital skills or limited availability for lengthy training (Sakthivel and Udayakumar, 2019). To address this gap, Medvedev and Molodyakov (2019) propose shorter, model-based courses that integrate technical, economic, and managerial components of smart farming. Importantly, these courses are offered on-demand, allowing busy farmers to participate at their convenience.

4. Cybersecurity

Thailand is gradually integrating AI-driven supply chain solutions, particularly in the agriculture and food processing industries. Companies are using AI-powered demand forecasting tools to predict crop yields, optimise food distribution, and reduce supply chain waste. The government is also encouraging the use of big data analytics in trade and customs clearance processes to enhance supply chain transparency and efficiency. This involves the collection, analysis, and use of large datasets, raising concerns regarding data privacy and cybersecurity. However, businesses and consumers remain cautious about how their data is managed and protected. Weak cybersecurity infrastructure, poses risks not only to sustainability but also to public trust in digital solutions (Jaee and Melati, 2024). Addressing these concerns is vital for the successful integration of digital technologies for sustainability purposes.

Security is a critical aspect of IoT in smart farming. Given that farming data is highly valuable and often treated as a trade secret, Kleinschmidt et al. (2019) stress the importance of end-to-end encryption from the sensor to the application. In practice, this involves synchronising the security strategy of the IoT sensor network with both the cloud

database and any fog computing infrastructure. Moreover, Jerhamre et al. (2022) highlight how hacking risks associated with implementing smart farming technologies can compromise not only individual farmers but also society at large, underscoring the broader vulnerability of online IT systems.

5. Cost concern

Thai companies are increasingly focusing on waste reduction, biodegradable packaging, and energy-efficient manufacturing to align with global sustainability standards. However, cost concerns remain challenges in achieving large-scale green supply chain transformation. Thailand is gradually adopting warehouse automation, particularly in large-scale distribution centres owned by Top 50 listed companies. The demand for automated storage and retrieval systems (AS/RS) and robot-assisted picking is rising due to the rapid growth of e-commerce and cross-border trade. However, the high initial investment required for automation limits widespread adoption, particularly among small and medium-sized enterprises (SMEs).

Sweden's government has actively promoted digitalisation through the "Digital Strategy for Sweden". Collaborative networks between academia, industry, and government are a hallmark of Sweden's innovation ecosystem. Research institutes like RISE (Research Institutes of Sweden) work closely with businesses on digital sustainability pilots, providing testbeds for emerging technologies and business models. These partnerships help drive the adoption of sustainable digital practices while fostering real-world applications of theoretical research.

6. SME

SME farmers generally lack access to technologies, information, and markets, making food production risky due to limited access to information about weather patterns, soil characteristics, future market demand, and other variables essential for adopting innovative solutions. In Thailand, agri-food systems are frequently dominated by intermediaries, resulting in high transaction costs for SMEs due to the substantial financial investment required for technology and training. Although SMEs form a large part of the Thai economy, they often lack both the financial resources and expertise to implement advanced digital solutions (Kuntanapong and Boonvut, 2022). Given these limitations, SMEs often rely on experience and intuition, leading to less efficient and more risk-averse decision-making (Sakthivel and Udayakumar, 2019).

Chen et al. (2023) explore how Swedish manufacturing SMEs can achieve environmental sustainability by integrating digital technologies with lean principles. In a country where sustainability is both a regulatory and cultural priority, the study finds that lean practices are already embedded as daily routines rather than formal programs. Through case studies of three SMEs, the authors show that digital tools—particularly IoT and ERP systems like Sweden's MONITOR—support lean by enhancing real-time visualisation, communication, and standardisation. These integrations help reduce energy use, material waste, and emissions, aligning with both customer expectations and national green targets. The proposed DIESEL framework (Digitalisation Supports Environmental Sustainability through Lean principles) offers a practical roadmap for SMEs to begin digital transformation with minimal resources, emphasising that lean culture provides a strong foundation for environmentally sustainable innovation in the Swedish SME sector.

VALUE

The literature draw highlights key factors affecting digital sustainability efforts. These include availability of skilled labour, access to financing, and intersectoral collaboration between government. By leveraging lessons from each other's experiences—such as

Thailand's flexible approach to scale-up digital adoption in high-growth industries and Sweden's robust regulatory frameworks—stakeholders can pave the way for more resilient, inclusive, and sustainable digital ecosystems.

PRACTICAL IMPLICATIONS

Cost is often the biggest stumbling block for SMEs on their digitalisation and sustainability journey. However, careful planning, phased investments, and strategic use of available government and private-sector support can mitigate these financial barriers. By managing costs effectively, SMEs can unlock the long-term benefits of digital solutions—improved resource efficiency and enhanced competitiveness—thus contributing to both their own financial resilience and broader sustainability goals.

LIMITATION

The study is limited by its methodological scope. Incorporating both qualitative and quantitative methodologies would strengthen the depth of analysis. While qualitative studies such as interviews or case studies can offer valuable insights into stakeholder perspectives, quantitative approaches such as big data analysis can enhance the objectivity and reliability of the conclusions.

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Optimising Air Cargo Capacity Planning for Forwarder: Point Vs Distributional Forecasts

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Abstract

Consider an air freight forwarder who secures cargo space through long-term block space agreements and short-term ad-hoc bookings. This study compares point and distributional forecasts for medium-term allotment decisions under uncertain weekly demand. Two criteria are analysed: cost minimisation and service level assurance. The distributional forecast policy minimises the expected cost, while the service-level policy ensures a target probability of meeting demand with long-term capacity. Numerical experiments based on historical demand records from one of the largest freight forwarders in Thailand reveal that distributional forecasts outperform point forecasts, particularly in achieving desired service levels under fluctuating demand.

Keywords: air cargo, capacity management, forecasting, applied operations research

1. INTRODUCTION

Air cargo, a crucial component of the global supply chain network, is projected for significant growth, with an annual expansion rate of 4.1% through 2041 (Boeing, 2024). This positive outlook is largely driven by the continuous expansion of global GDP and trade.

The air cargo service chain includes shippers (consignors), air freight forwarders, carriers, integrators, and consignees. Integrators provide end-to-end logistics services, including transportation, warehousing, and delivery, often using their own fleet of aircraft. Forwarders generally do not own aircraft; instead, they purchase cargo space in bulk from carriers through long-term contracts known as *Block Space Agreements (BSAs)*. The amount of space, often measured in the number of pallets, is called the *allotment*. They collect individual shipments from shippers and consolidate them for transport by carriers. If weekly demand surpasses the allotted space, forwarders may purchase additional space on an ad-hoc or free-sale basis in the spot market. While BSAs offer forwarders lower freight rates, they also impose a minimum chargeable weight on the allotted space, meaning that if the actual usage falls below this threshold, the forwarder must pay for the unused portion. Non-BSA space on the spot market usually comes from indirect flights, whereas BSA space comes mostly from direct flights. Since air shipment is time sensitive, direct flights are preferred to indirect flights.

This study aims to address the following research question: How does the use of point forecasts versus distributional forecasts affect air cargo capacity planning decisions for freight forwarders? Specifically, we examine their performance in determining weekly allotments under demand uncertainty. Point forecasts are easier to interpret and implement, whereas distributional forecasts provide the probability distribution but involve greater computational complexity. This comparison enables us to quantify the potential gains from adopting distributional forecasts in terms of cost efficiency and service level attainment.

2. LITERATURE REVIEW

The air cargo industry's landscape is thoroughly examined in the works of Debbage and Debbage (2021) and Sales and Scholte (2023). A detailed review of the air cargo literature

is provided by Feng et al. (2015). Our research emphasises medium-term decision-making from the forwarder's viewpoint. The short-term capacity planning involves the air cargo capacity control problem, in which booking requests arrive sequentially and an accept-or-reject decision needs to be made for a fixed capacity. The medium-term capacity planning involves the contract problem between air cargo carriers and freight forwarders. A freight forwarder signs the BSA contract with a carrier to secure a medium-term space, and may purchase additional short-term/ad-hoc space if its demand exceeds the medium-term allotment.

From the forwarder's perspective, Bing and Bhatnagar (2012) formulates an MDP that minimises the total expected freight cost from both medium- and short-term capacities. In both He et al. (2018) and Leung et al. (2017), a forwarder has the option to secure capacities from three distinct sources: allotments provided by carriers, bookings made within alliances, and subcontracting. Unlike our approach, these papers do not explicitly consider the value of time. In Bertazzi et al. (2021), both tactical and short-term decisions of the forwarder are integrated into a model covering production, inventory, and transportation, explicitly considering transportation lead time.

Air cargo forecasting is crucial to making decisions at all three levels, namely long-term, medium-term, and short-term. The long-term planning level involves investment for airport infrastructure, expansion and modernisation of airports. For the long-term forecasts, Singh et al. (2016) uses the econometric model to forecast the yearly air cargo demand in India. Gerardo and Díaz Olariaga (2023) use the convolutional neural network (NN) to forecast the yearly air cargo demand in Columbia based on various socioeconomic variables such as Gross Domestic Product, population, consumer price index, foreign direct investment, imports and exports. For the medium-term level, Magaña et al. (2016) forecasts monthly tonnes to handle at London Heathrow Airport cargo terminal. Short-term decisions include daily scheduling on each route (Totamane et al., 2014), overbooking on each flight (Popescu et al., 2006) and shipment loading on aircraft (Tseremoglou et al., 2022). Finally, comparative analyses of different forecasting models are conducted in Madhavan et al. (2020), Liu et al. (2020) and Li et al. (2020). Except Popescu et al. (2006) and Tseremoglou et al. (2022), the output is a point forecast, a single number for each time period. Ours compare performances of both point and distribution forecasts.

3 METHODOLOGY

3.1 Air cargo capacity planning problem

Consider an air freight forwarder not endowed with any cargo space. The forwarder has two sources of capacity, namely 1) the BSA, and 2) the ad hoc space from the spot market, referred to as the non-BSA space. The BSA flight is a direct flight, whereas the non-BSA flight is an indirect flight. The BSA cost, denoted as r , is cheaper than the non-BSA cost, denoted as s . The non-BSA cost s includes both the spot freight rate and the time penalty cost associated with an indirect flight. Assume $s > r > 0$. The forwarder has to determine the *allotment* (the number of pallets under the BSA contract), denoted as x , before knowing the demand. The BSA imposes the minimum chargeable weight requirement: If the actual allotment usage is less than the requirement, the forwarder has to pay the minimum charge. Each allotted pallet has the capacity of κ and requires a minimum chargeable weight of $\rho \leq \kappa$. The maximum number of allotments available to the forwarder is x^u .

3.2 Data set

The dataset, obtained from one of Thailand's largest air freight forwarders, spans from January 1, 2022, to December 31, 2023, covering a total of $n_T = 104$ weeks. It focuses on the export of general cargo originating from BKK airport. When ranking by the total demand over the above period, the top four destinations are NRT, HKG, PVG and CGK, respectively. The weekly demand exhibit significant variation as shown in *Figure 3*.

The forwarder needs to determine the weekly allotment before knowing the actual demand. The parameters for the weekly capacity supply are provided in *Table 4*. The non-BSA flight

is indirect, whereas the BSA flight is direct. From Binsuwadan et al. (2022), for Thai air carrier, the value of time is 32.56 USD/(tonne-hour) or equivalently 0.02 THB/kg/minute. The non-BSA unit cost is the sum of the unit freight cost and the unit time cost. For example, the non-BSA unit cost for PVG is $35 + 0.02(90) = 35 + 1.80 = 36.80$ THB/kg.

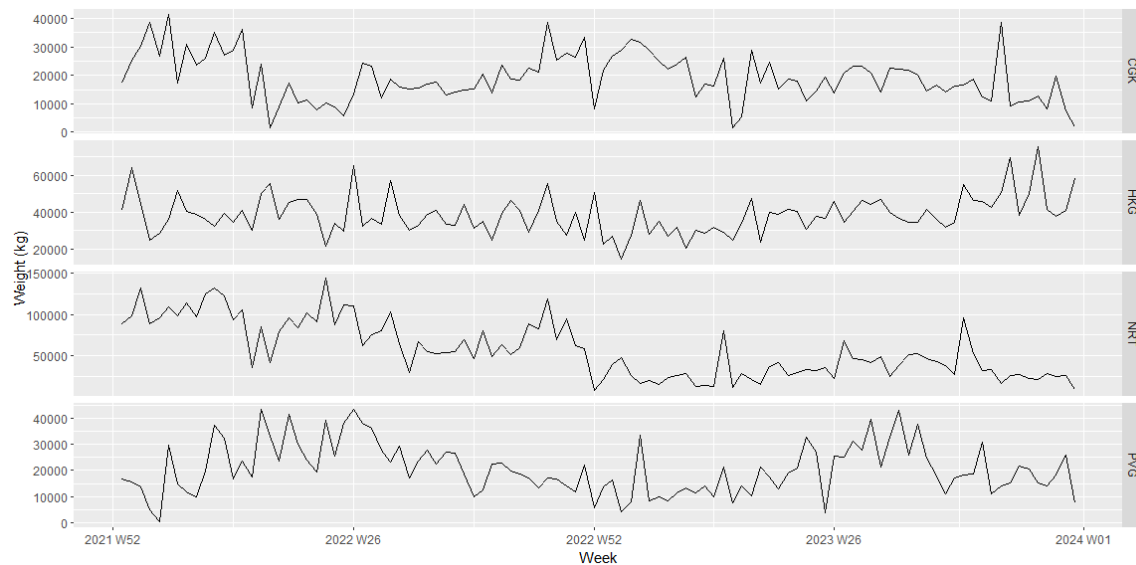


Figure 3 Weekly demand

Table 4 Parameters for weekly capacity supply

Destination	CGK	HKG	NRT	PVG
BSA Unit Cost (THB/kg)	98.00	25.00	100.33	18.50
Non-BSA Unit Cost (THB/kg)	111.84	41.11	132.42	36.80
Pallet Capacity (kg)	7500	2500	2500	4500
Minimum Weight Requirement (kg)	1500	1650	1500	2200
Maximum Allotment (pallet)	9	19	64	14

3.3 Forecasting

Forecasting methods are used to predict the uncertain nature of business trends in an effort to help managers make better decisions and plans. Such efforts often involve the study of historical data and the manipulation of these data in the search for patterns that can be effectively extrapolated to produce forecasts (Hank and Wichern, 2014). Two primary approaches to forecasting are point forecasting and distributional forecasting, each with distinct characteristics, advantages and limitations. Herein, three point forecasting methods; mean method, exponential smoothing and Box-Jenkins methods are involved. The lognormal distribution is engaged in distributional forecasting.

3.3.1 Mean method

Mean method forecasting is one of the simplest and most intuitive techniques for predicting future values based on historical data. This approach assumes that the future values will be similar to the average of past observations. It is particularly useful when there is no clear trend or seasonality in the data (Hyndman and Athanasopoulos, 2018).

3.3.2 State space models for exponential smoothing

Exponential smoothing provides an exponentially weighted moving average of all previously observed values to make predictions. The weight decreases exponentially as observations get older, meaning more recent observations have more influence on the forecast than older ones. This method is particularly useful for data with no clear trend or seasonal patterns, although there are variations that handle trends and seasonality. State space models for exponential smoothing are so-called ETS models which stand for Error,

Trend, and Seasonality (Hyndman and Athanasopoulos, 2018). The flexibility of ETS models allows them to handle a variety of time series patterns, making them a popular choice in many forecasting applications.

3.3.3 Box-Jenkins

The Box-Jenkins method is a widely used statistical approach for time series forecasting, particularly effective for modeling and predicting data that exhibit patterns over time. The Box-Jenkins method, through the ARIMA model, provides a structured approach to time series forecasting by combining autoregressive, differencing, and moving average components. One requirement assumption is that the time series is stationary. The ARIMA model is generally expressed as $ARIMA(p, d, q)$, where p is the order of the autoregressive term, d is the degree of differencing, and q is the order of the moving average term and the model is written with backshift notation (Box, Jenkins, and Reinsel, 2015, Hyndman and Athanasopoulos, 2018).

3.3.4 Probabilistic forecasting

Probabilistic Forecasting involves predicting the entire probability distribution of future outcomes rather than a single value. It is a key to optimising business processes. This approach provides a comprehensive view of uncertainty by estimating the likelihood of different possible outcomes. In this work, the lognormal distribution is used to produce confidence intervals for future values instead of single-point estimates. One way of analysing such data is to log-transform the original variable X and to base the inference on the transformed variable $Y = \log(X)$ (Olsson, 2005).

3.4 Allotment decision from the distributional forecast

From a point forecast $\hat{d}$, the allotment decision is trivial: The allotted weight is exactly equal to the point forecast $\hat{d}$, and the allotment is obtained as $\hat{d}/\kappa$.

From a distributional forecast, the forwarder assume that the random weekly demand D follows the probability distribution G . In this case study, the log normal distribution is employed. Our analysis holds for any continuous distribution. Two decision criteria for the forwarder are as follows:

3.4.1. Cost criterion

The random cost, for the random demand D and the allotment x , is given as:

$$\Pi(x, D) = r \max(\min(D, \kappa x), \rho x) + s (D - \kappa x)^+$$

The first and second terms represent the BSA and non-BSA costs, respectively. The allotment usage is the minimum between the demand and the BSA capacity. If the allotment usage is smaller than the minimum chargeable weight required ρx , then the forwarder pays the minimum charge. The last term $(D - \kappa x)^+$ represents the excess demand that cannot be accommodated by the BSA space and is handled in the spot market. The forwarder maximises the expected profit with respect to the demand distribution G : $\pi(x; G) = E_G[\Pi(x, D)]$. It can be shown that the expected profit is convex and is minimised at $x^{(0)}$ such that

$$r\rho G(\rho x^{(0)}) - (s - r)\kappa (1 - G(\kappa x^{(0)})) = 0.$$

Note that this formulation is closely related to the expected profit in the classical newsvendor model: there is a single decision period, and the forwarder selects an allotment before demand is realised. In the special case where $\rho = \kappa$, the forwarder pays for the entire allotment regardless of the actual usage, the problem reduces to the classical newsvendor model. Hence, the newsvendor model is a special case of our more general framework.

3.4.2. Service criterion

The air cargo shipment is time sensitive. A direct flight is preferred to an indirect flight. The probability that entire demand can be accommodated by the BSA space (direct) flights

is $P(D \leq \kappa x) = G(\kappa x)$. This is referred to as the *service level (SL)*. To ensure the SL of at least α , the allotment is $x^{(\alpha)} = G^{-1}(\alpha)/\kappa$.

Recall that the maximum number of allotment is x^u . The allotment is $\min\{x^{(c)}, x^u\}$ where $c = 0$ for the cost criterion and $c = \alpha$ for the service criterion. This may be fractional, and a simple rounding method may be used.

4. RESULTS FROM CASE STUDY

Let $A = \{\text{CGK, HKG, NRT, PVG}\}$ denote the set of destinations. As shown in Figure 4, demand fluctuations are relatively severe across all destinations. To address this, a log transformation is applied to all observations during the data preprocessing step to stabilise the variances, since most statistical forecasting model assumes constant variance (i.e., homoskedasticity). A log transformation also helps reduce skewness and lessens the impact of outliers; see Sakia (1992), Feng et al. (2015) and West (2021).

After data cleaning and transformation, three forecasting methods are considered in the model selection phase: 1) Mean method; 2) ETS; 3) ARIMA. Let $M = \{1, 2, 3\}$.

4.1 Evaluation scheme and performance measures

The forward-chaining cross-validation for time series is chosen as our evaluation scheme. We initiate with a training set of thirty weeks ($n_0 = 30$) and incrementally extend the size of successive training sets by a set size of one week as shown in Figure 5. Let $d_a(w)$ be the demand at destination $a \in A$ in week w . For the w th resample where $w = 1, \dots, n_T - n_0$, the training demand is $S_a(w) = \{d_a(w), d_a(w+1), \dots, d_a(w+n_0-1)\}$ and the testing demand is $d_a(w+n_0)$. In this scheme, there are $n_T - n_0 = 104 - 30 = 74$ folds (test demands).

Resample#\Week	001	002	003	...	029	030	031	032	...	103	104	Note
1	N	N	N	N	N	N	T					N T
2	N	N	N	N	N	N	N	T				N: Train T: Test
...												
73	N	N	N	N	N	N	N	N	N	T		
74	N	N	N	N	N	N	N	N	N	N	T	

Figure 5 Time series cross validation scheme

Policy F_{am} from point forecast using forecasting method $m \in M$ at destination $a \in A$ for the w th resample uses a point forecast $\hat{d}_{am}(w+n_0)$ to make the allotment decision, given in Table 5. Note the allotments for both cost and service criteria are identical.

Table 5 Policy from point forecast F_{am} with forecasting method m at destination a

Train data	$S_a(w) = \{d_a(w), \dots, d_a(w+n_0-1)\}$
Output from training data	Point forecast: $\hat{d}_{am}(w+n_0)$
Unconstrained allotment for cost and SL criteria	$x_a(w; F_{am}) = \hat{d}_{am}(w+n_0)/\kappa_a$
Allotment for both cost and SL criteria	$\min\{x_a(w; F_{am}), x_a^u\}$

Policy G_{am} from distribution forecast using forecasting method m at destination a for the w th resample uses the probability distribution $G_{am}(\cdot; w)$ to make an allotment decision in Table 6. For the cost criterion, the optimality equation in §3.4.1 is solved. For the service criterion, the percentile of the distribution is used.

Table 6 Policy from distributional forecast G_{am} with forecasting method m at destination a

Train data	$S_a(w) = \{d_a(w), \dots, d_a(w+n_0-1)\}$
Output from training data	Probability distribution function: $G_{am}(\cdot; w)$

Unconstrained allotment for cost criterion	$x_a^{(0)}(w; G_{am}) = \operatorname{argmin}\{\pi(x; G_{am}(\cdot; w))\}$ in §3.4.1
Unconstrained allotment for SL of $100\alpha\%$	$x_a^{(\alpha)}(w; G_{am}) = G_{am}^{-1}(\alpha; w)/\kappa_a$ in §3.4.2
Allotment for cost minimization criterion ($c = 0$) and service level ($c = \alpha$)	$\min\{x_a^{(c)}(w; G_{am}), x_a^u\}$

As a benchmark, we consider the perfect (P) policy and the current policy (C). For the perfect hindsight P assumes the knowledge of actual demand $d_a(w + n_0)$. For the current policy, the maximum allotment is used. All policies at destination a for the w th resample are summarized in Table 7.

Table 7 All policies

Policy \ Allotment	Cost criterion	Service criterion
Point forecast F_{am}	$\min\{x_a(w; F_{am}), x_a^u\}$	
Distribution forecast G_{am}	$\min\{x_a^{(0)}(w; G_{am}), x_a^u\}$	$\min\{x_a^{(\alpha)}(w; G_{am}), x_a^u\}$
Perfect P_a	$\min\{x_a(w; P), x_a^u\}$ where $x_a(w; P) = d_a(w + n_0)/\kappa_a$	
Current C_a	$x_a(w; C) = x_a^u$	

4.2 Results

Recall that there are $n = n_T - n_0 = 74$ folds. For fold $w = 1, \dots, n$, forecasting method $m \in M$ at destination $a \in A$, let $e_{am}(w + n_0) = d_a(w + n_0) - \hat{d}_{am}(w + n_0)$ denote the error, the actual demand minus the forecast demand. We compute the following error metrics:

- Mean absolute error (MAE) $\frac{1}{n} \sum_{w=1}^n |e_{am}(w + n_0)|$
- Root mean squared error (RMSE) $\sqrt{\frac{1}{n} \sum_{w=1}^n e_{am}^2(w + n_0)}$
- Mean absolute percentage error (MAPE) $\frac{1}{n} \sum_{w=1}^n |100e_{am}(w + n_0)/d_a(w + n_0)|$

Table 8 Performance of all models for all destinations

Metric	Model	CGK	HKG	NRT	PVG
MAE	Mean	18692.65	10408.11	32290.2	15460.96
	ETS	20316.93	9580.88	15520.59	16460.59
	ARIMA	19624.3	9124.06	17478.6	15147.74
RMSE	Mean	20061.95	12683.17	37033.78	17194.83
	ETS	21928.23	11782.63	22555.56	19748.14
	ARIMA	20829.26	11271.46	24564.46	17647.14
MAPE	Mean	180.78	33.46	128	127.44
	ETS	176.24	30.34	54.66	119.37
	ARIMA	176.47	28.87	56.72	118.74

For each error metric and destination, the best-performing model (i.e., the one with the lowest error metric) is given in boldface in Table 8. Overall, the ETS model frequently outperforms others. In particular, its MAPE is the lowest for three out of five destinations. The ARIMA model offers modest improvements in specific routes, such as HKG, but are generally less dominant. These results suggest that ETS is a strong candidate for accurate forecasting.

Figure 6 shows the performance of all policies for the NRT destination, where the ETS forecasting method is applied for policies F and G. Similar patterns were observed for other destinations and forecasting methods, so they are omitted here.

The top panel shows the allotted weights from all policies. Policy F uses the point forecast as the allotted weight. Policy C, the current policy, uses the maximum allotment. For distributional forecasts, policy G0 applies the cost minimisation criterion, whereas policy

G90 targets a service level of $\alpha = 0.90$. Under the perfect policy P, the allotted weight is identical to the actual demand. For all policies except the current policy, the allotted weights are positively correlated with the actual demand. The allotments from the distributional forecast policies (G0 and G90) show smoother adjustments compared to policies F and C.

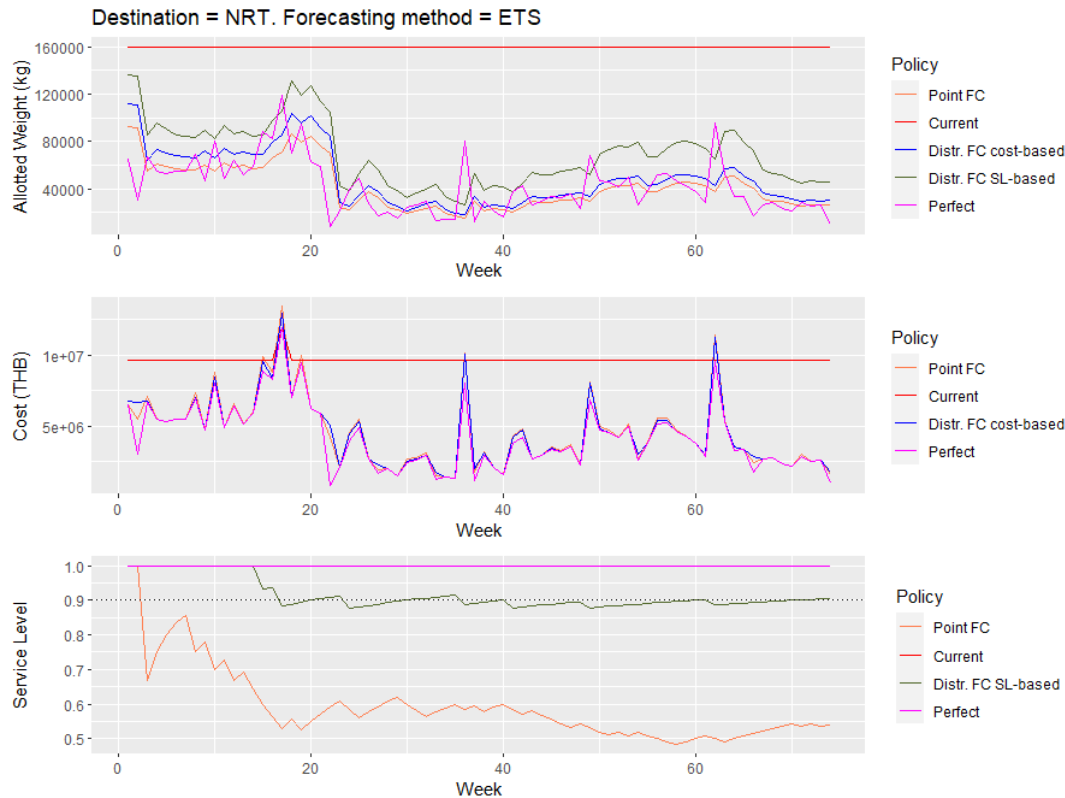


Figure 6 Allotments from all policies and their performances

The middle and bottom panels display the cost and service level achieved using the allotments from each policy. Costs fluctuate dynamically with weekly demand (as seen in the top panel, purple line): higher demand corresponds to higher costs and vice versa. The perfect policy P achieves the lowest cost while maintaining a 100% service level. Under the current policy C, the maximum allotted weight is much larger than the actual demand for all test weeks, so the service level of 100% is maintained; however, it incurs high cost due to the minimum chargeable weight imposed by the contract.

For the cost-minimisation criterion, the allotments from the distributional forecast policy G0 and the point forecast policy F perform similarly in terms of cost. However, under the service level criterion, the point forecast policy F performs poorly, with service levels falling well below 90% in many weeks. As weekly demand variability increases (starting around week 15), the service level under the point forecast policy F drops significantly. In contrast, the distributional forecast policy G90 shows a much smaller decrease in service level, maintaining at least a 90% service level for most weeks.

This highlights the importance of distributional forecasts in achieving service level targets. Maintaining a 90% service level means that in 9 out of 10 weeks, shipments are fulfilled entirely via direct (BSA) flights. Since air cargo is time-sensitive, this is a critical operational advantage. Overall, distributional forecast policies—particularly G90—demonstrate greater robustness than the point forecast policy, especially when service reliability is prioritised.

4. CONCLUSIONS

This study considers a forwarder's capacity planning problem using point and distributional forecasts. Under the distributional forecast policy, two decision criteria are considered: (1) cost minimisation and (2) service level attainment. The expected total cost includes both BSA and non-BSA costs, with non-BSA space incurring higher costs due to more expensive freight rates and indirect routing. The service level represents the probability that the entire demand is shipped via a BSA flight, which provides direct service. Our empirical results show that while both policies perform similarly in terms of cost, distributional forecasts—particularly the service-level-based policy—consistently achieve higher reliability. In particular, the ability to maintain a 90% service level, even under fluctuating demand, demonstrates the robustness of the distributional approach over traditional point forecasts, which are commonly used in practice.

The current study focuses on a single-leg, weekly planning context. Future research could extend this framework along spatial and temporal dimensions—for example, by considering multi-leg networks, multi-modal logistics, or daily dynamic capacity adjustments. Another possible direction is the integration of advanced machine learning techniques to enhance forecasting accuracy. Finally, as noted in Section 3.4.1, a heuristic solution can be derived from the classical newsvendor model. An interesting direction for future work is to compare the performance of this newsvendor-based heuristic with the solution approach proposed in this study.

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Crowd-Delivery Parcel Allocation with a W-Score Framework and Unsupervised Machine Learning

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Introduction

Postal service, specifically in Estonia, is in a rapid evolution, thus needing to reposition itself in the parcel transport market, achieving this by consolidating various services, from parcel machines to courier deliveries (Tulev *et al.*, 2024). This evolution has led the postal service to introduce crowd deliverers to its business model to streamline the high seasonality and volume spikes in courier services, with the most significant peaks occurring in the winter holiday season. Postal service providers typically plan their fleet resources in terms of number and vehicle size based on peak demand periods, leaving resources underutilised in low and off-peak seasons. Here, the crowd deliverers are introduced as the enablers for balancing the fluctuations and keeping the business net positive.

The estimated improvement on parcel pricing is to lower the cost per stop on the outsourced deliveries by 20%, possibly also improving the number of stops per hour.

Crowd courier delivery is seen as a feasible method in the city environment, since there is a limited number of couriers available in rural areas.

The objectives of the postal service are to incorporate the crowd-deliverers in a balanced way so that the in-house fleet is not left with time-constrained stops or couriers idling. At the same time, the objective is not to rely too heavily on crowd delivery but to find an equilibrium in the balancing.

Since the introduction of crowd deliverers, a new business need has emerged: identifying suitable parcels for them. To organise outsourced parcel delivery effectively, a planning system must be developed to allocate and manage the stable workload. Since the deliveries are made by individuals not employed by the entity responsible for deliveries, the use of couriers introduces uncertainty – availability of couriers, behaviour, whether they will accept the delivery task, and how they will execute it (Savelsbergh and Ulmer, 2022). Our contribution to this process is to identify the possible parcel parameters by applying the most appropriate methods to allocate them for crowd deliverers, considering the aforementioned aspects.

Related work

The evolution of the postal services, with the main gaps in the automation process, as well as the crowd package delivery as an emerging sub-domain in parcel delivery, was described by Tulev *et al.*, 2024, highlighting amongst others the need for improvements in data management and analysis, for example, customer behaviours. At the same time, the postal companies' human factor is an issue with the new needed skills as well as the current workforce's inapplicability to the new roles (Tulev *et al.*, 2024).

Kafle et al have introduced the concept of partial crowdsourced delivery, with the aim of segregating the parcels for the crowd deliverers. The concept supports our study of identifying the outsourceable workload.

Crowd deliverers or Crowdsourced Logistics (CSL) (crowd+outsourced), as described by Howe, (Howe, 2006) is a group of outsourced workers that are carrying out tasks, in this context delivering postal and parcels.

The aim of crowd logistics (CSL) is to achieve economic benefits for all stakeholders and shareholders (Kersten *et al.*, 2015), with the goal of CSL to complete last mile delivery (LMD) by speeding up delivery times and reducing the access gap to sparsely populated regions. In other fields, such as Amazon e-commerce (Alnaggar *et al.*, 2021), Walmart grocery delivery (Alnaggar *et al.*, 2021; Bose, 2018), DHL delivery concept in Sweden (*LogisticsMatter*, n.d.), or PiggyBaggy in Finland (*CORDIS - EU research*, n.d.), crowdsourcing has been tested or introduced to the business models in the last-mile delivery operations.

Savelsbergh and Ulmer described the main features that distinguish crowdsourced delivery from traditional delivery: uncertain delivery capacity, both in availability and behaviour. They see it as an opportunity to research how to integrate behavioural aspects into optimisation-based decision making, for example, a discrete choice model or a machine learning model. In their study, they also point out opportunities and challenges in the service area, having a trade-off between the additional demand on a larger area, which may generate additional costs by servicing the demand.

Gevaers et al defined the five core efficiency factors: the level of consumer service, security and delivery type, the geographical area, the degree of market penetration and density, the environmental impact, vehicle fleet and technology employed, which we incorporated into our research to develop a scoring model, including the incentive or behaviour of the courier, for the parcel allocation process.

From the managerial side (Figure 1), research on user feedback via comments on the services (Çelik *et al.*, 2025), has revealed implications on crowdsourced vs traditional couriers. For example, areas where crowdsourced couriers excelled were user satisfaction over traditional services, as well as assurance and tracking.

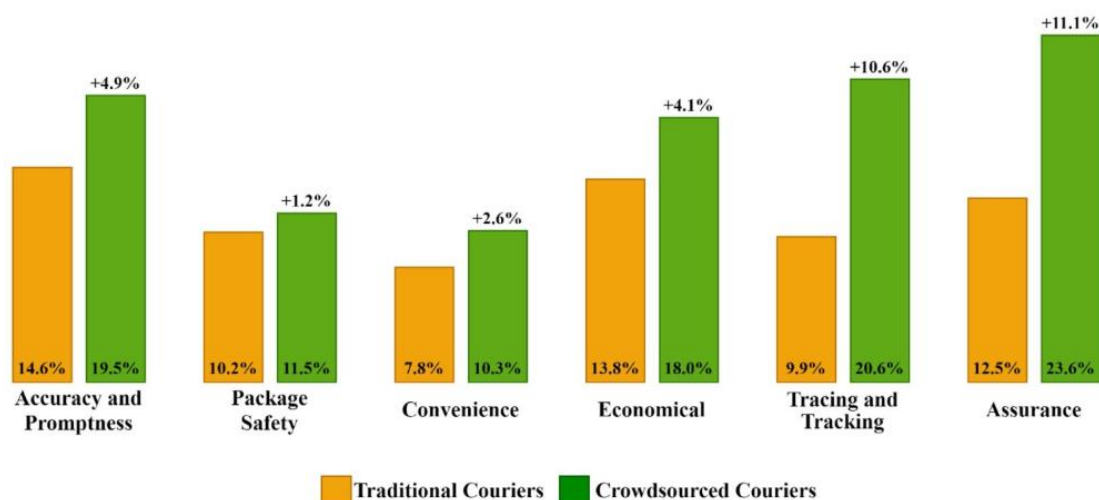


Figure 1: Positive sentiment rates.(Çelik *et al.*, 2025)

The study also points out that the satisfaction of crowdsourced services is highly volatile, possibly reflecting the variability in service quality, which might be derived from the services provided by not yet standardised corporate structures and operational processes. The described volatility is in a decreasing trend due to the standardisation of the crowd delivery processes. Still, the customer satisfaction with traditional couriers is lower but stable; standardised processes and control over employees have led to smaller fluctuations.

To proceed with our study on optimisation of the decision-making via machine learning models, we give a brief overview of the options.

In ML, there are three types of learning problems: Supervised, Unsupervised,

and Semi-Supervised Learning (Naeem *et al.*, 2023). To describe the cases: in the case of Supervised Learning, we use labelled data as input (known input, unknown mapping to known output, for classification, regression); Unsupervised Learning we only have the input data (known input, unknown mapping to unknown output (clustering, dimensionality reduction (PCA), association; and Semi-Supervised Learning (known input, unknown mapping to known and unknown output as a prediction).

The reasons to use unsupervised learning include the input data being unlabeled – (in our case, we have the parcel data with no knowledge, if the parcel is suitable or not for the crowd), data tagging is time consuming operation, ML may be used to drive the process, it can be used to investigate unknown or unprocessed data, and it comes in handy when dealing with large datasets and pattern detection (Naeem *et al.*, 2023). Types of Unsupervised Learning include Autoencoders, Anomaly Detection, Clustering, and Association. (Naeem *et al.*, 2023).

Xu and Tian's comprehensive work on the application of clustering algorithms gives a broad overview of the possible options (Xu & Tian, 2015). We chose K-Means, as a partition-based model, and DBSCAN, as a density-based model, as the most viable algorithms for the study (Xu & Tian, 2015), as the parcels' data is multi-dimensional, having spatial coordinates for pick-up and drop-off points, weight, dimensions, fragility properties, and operational metrics such as distance or courier incentive, both selected methods allow the grouping of parcels from the unlabelled data source. To further elaborate on this kind of algorithms, refer to (Naeem *et al.*, 2023; Xu & Tian, 2015).

Research methodology

We used mixed research methods, combining expert interviews, literature review, synthetic data generation, and unsupervised learning, following routing optimisation.

3.1 Expert input, managing peak volumes

We began with expert interviews with representatives from the business side of the national postal service Omniva to gain an overview of the problem and gather input on relevant constraints. Since the postal service had planned on introducing the crowd deliverer, a method was needed to help balance in-house fleet operations with outsourced crowd deliverers.

With the postal service's main goals in this issue of managing peak volumes and reducing the fleet costs, we clarified and set the suitability rules for the parcels and operational constraints details.

3.2 Parcel attributes and composite W-Score

Since the optimisation needs to incorporate both regular couriers and crowd deliverers, and the latter is compatible with only selected parcels, due to vehicle size, courier skill, and trip length, we present a function to align the parcels' suitability. For each parcel, we assigned drop-off coordinates, weight, volume, fragility factor, fleet cost per km, distance, and the incentive of the courier. Composite W-score (1) represents a compound value derived from parcel attributes to evaluate the parcels' compatibility for crowd delivery:

$$W = \alpha D + \beta H + \gamma G + \delta C - \theta \text{Inc} \quad (1)$$

Where:

- D - level of service to the consumer as the distance between pick-up and drop-off points;
- H - compound value of parcel weight, volume, and fragility as a function;
- G - geographical demand density, with low density equivalent to higher cost;

- C - cost factor per km;
- Inc - incentive of the courier, offer attractiveness;
- $\alpha, \beta, \gamma, \delta, \theta$ for adjusting weights to control the relative importance of each factor in the simulation model.

Component D (2) is the distance between the PUDO points.
Function H (3) is a compound of parcel weight, volume and fragility.

$$H = \lambda_1 \cdot ParcelWeight + \lambda_2 \cdot ParcelVolume + \lambda_3 \cdot ParcelFragility$$

(3)

Function G (4) is the density ratio of deliveries per square kilometre, to allow the generation of higher demand areas.

$$G = \frac{1}{Deliveries\_per\_km^2}$$

(4)

Function C (5) is determined by the costs associated with the fleet and the type of vehicle. These are weighted according to the impact of each constant. Where $\frac{FleetCost}{km}$ is a given constant of the combination of the Total Cost of Ownership and η_1 is the weighting factor, *FleetTypeScore* represents parametric values of different modes of transport.

$$C = \eta_1 \frac{FleetCost}{km} + FleetTypeScore$$

(5)

Function Inc is defined by the adjustable coefficients ρ_i , which are based on importance ranking, multiplied by both the Volume and Distance that the Courier must cover to deliver the parcel. The incentive should not be considered a cost; rather, it represents a variable benefit for the Courier, reflecting the perceived effort. As such, it is deducted from W.

$$Inc = \rho_1 \cdot ParcelVolume + \rho_2 \cdot DeliveryDistance$$

(6)

This modelling approach enables us to generate various types of W, resulting in a series of combinations to assess the conditions under which parcels could be assigned to a crowd deliverer. Incorporating W-score for parcel segregation into clustering algorithms allows the model to consider both spatial proximity and delivery complexity.

3.3 Data creation

The input data for our study consists of the following components:

- Real-world pickup points – 29 real lockers, post offices, and depot were geocoded;
- Synthetic parcel data (n=495) – physical attributes with operational factors;
- Authors simulated courier movement on the following scenarios: Parcel machine to Customer; Postal Office to Customer; Depot to Parcel machine, Postal Office, and Customer.

Around each pick-up point, we generated 4 to 30 drop-off points. Simulated weight ranges between 0.2 to 20 kg, volume ranges from 0.01 to 0.2 m³. Factors like distance to the drop-off and incentive score for the courier are also considered. To get the composite score W for each parcel, we defined a weight to control the relative importance of each factor (see 3.2 Parcel attributes and composite W-Score). The data with drop_off_lat, dropoff_lon, and W values were normalised to a common scale before applying the clustering process.

3.4 Scenario definitions

To standardize the models, we will not define specific time windows for collections and deliveries, nor will we consider parcels being returned or rejected. The experiment location takes place in Tartu County, Estonia, which meets the criteria for all three scenarios, having routes from the departure depot (DD), parcel machines (PM), and a Post Office (PO). The simulation will use a random sample of twenty-nine Pick-up and Drop-off (PUDO) locations, representing 50% of the total PUDO locations in Tartu. Deliveries are assumed to be B2C, with each parcel considered a single unit. No seasonal demand, weather, or traffic factors will be included, and specific assumptions regarding vehicle types will be clarified in each scenario.

Table 1: Scenario setting overview

ID	Description
Scenario 1	Allocating parcels from the PM to a Courier that will deliver within a small radius range of ~ 6 km; cargo bicycle vehicle.
Scenario 2	Allocating parcels from the PO to a Courier that will deliver within a radius of ~ 6 km; cargo bike vehicle.
Scenario 3	Allocating parcels from the DD to a Courier that will deliver within a radius range higher between ~ 6 km to 12 km; 4WD vehicle.

3.5 Clustering

Before applying the algorithms, we carried out a parameter tuning process.

3.5.1 K-Means

The K-Means requires a predefined number of clusters to be set. We used the Elbow method (optimal density) ("Balancing Risks and Monetary Savings When the Crowd is Involved in Pickups and Deliveries", 2023; Haonan *et al.*, 2019) with resulting $K = 4$, and also the Davies-Bouldin index (lower value = low internal dispersion), resulting in 4 clusters with the lowest Davies-Bouldin index, which confirmed the $K = 4$ optimum.

Outcome of the clustering: 4 clusters, 260 out of 495 parcels assigned to the cluster (Figure 2).

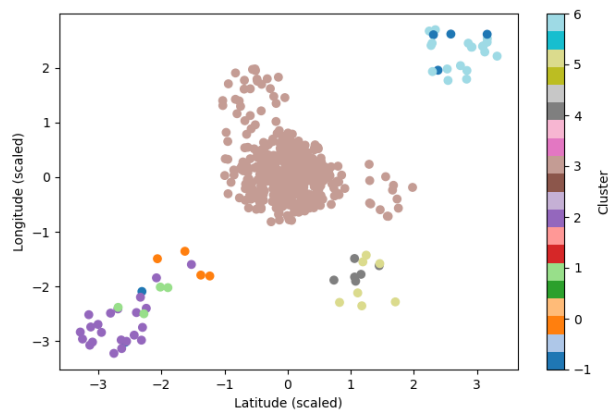
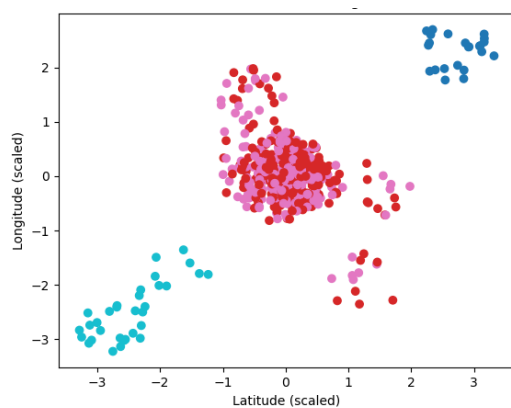


Figure 2. Drop off points K-Means clusters. Figure 3. Drop off points DBSCAN clusters.

3.5.2 DBSCAN

The DBSCAN does not need a predefined number of clusters, although the data needs to be scaled (as done in the preprocessing step). Clusters are created by combining the points where the neighbourhood radius ϵ overlaps, with the left-out being noise.

By applying the Silhouette Score (Xu & Tian, 2015) we found the most suitable values as $\epsilon=0.8$, $\text{minPts}=4$, $\text{Silhouette}=0.37$ (higher score = optimal ϵ fitting, well segregated groups). Clustering on DBSCAN resulted in 443 grouped out of 495, and 6 drop-off points classified as noise (Figure 3).

3.5.3 Comparative results

Table 2. Comparative clustering results

	Model	Total Clusters	Noise Points (Percentile 15)	Avg W (crowd candidates)	Std W (crowd candidates)	Crowdsourcing Candidates	Avg W (All parcels)	Dropoff Total parcels
0	KMeans	4	0	6.761762	2.598208	260	9.21889	495
1	DBSCAN	7	6	9.094320	3.486878	443	9.21889	495

3.5.4 Parcel candidate filtering

We set the min threshold of 15% for the parcels for crowdsource deliverers; radius 2-7 km; weight ≤ 10 kg; fragility ≤ 1.5 ; volume ≤ 0.08 m³.

From the total parcels distributed for pick-up points, 53 can be assigned to crowdsource deliverers in the simulation of the shortest delivery route.

Results and discussion

Our evaluation on using unsupervised machine learning models for assigning parcel candidates for crowdsourcing showed positive results with the iterative methods used.

We propose a W-score for identifying possible candidates for crowdsourcing by factors that define delivery efficiency: level of consumer service, security & type of delivery, geographical area & market density, fleet & technology, and environment (Gevaers *et al.*, 2014). The W-score weights the variables of the parcel and allows for its use as a measurement standard for matching parcels to crowdsourcing.

K-Means clustering: 4 clusters, 260 out of 495 of parcels assigned to cluster.

DBSCAN clustering: 7 clusters, 443 grouped out of 495, and 6 drop-off points classified as noise.

Both models are suitable for the purpose, although DBSCAN is the primary choice in the tested scenario, since it does not require the number of clusters to be known for input and is also able to identify noise.

DBSCAN creates a cluster for every centre that has at least minimum points (minPts) neighbours within a radius. Any point that is not reachable from another centre and does not have enough neighbours is labelled as noise. In this context, a distant parcel point would not suit crowd deliverers. Also, this gives the opportunity for possible dynamic pricing in the model.

On the other hand, the K-means model, with a fixed number of centroids, also matches all points to a cluster.

If we look at the noise found by DBSCAN, this opens the possibility for allocating the parcels for specific deliveries, not suitable at first for crowd-sourcing.

We argue that, if both models were to be used in conjunction, for example, each DBSCAN cluster having K-means applied inside, it may balance sub-groups when there is a need for a fixed number of routes for the deliverers.

Managerial implications

The proposed W-score gives the operator the option to have a tunable parcel allocation method for crowdsourcing the packages.

From cost reduction, in the case of Estonia, the cost per stop can be reduced by about 20% per stop for the crowdsourced deliveries. Although the current study does not incorporate additional cost components, such as human resources management, office, etc, the reduced cost per stop is a component contributing to avoiding negative fleet operating margins (net neg).

To illustrate the possible application of the clustering results in operation, each scenario (see 3.4 Scenario definitions) was routed with an OR-Tools solver for the shortest path based on vehicle type and delivery radius. From the total segregated parcel candidates, we randomly selected one pickup point for a scenario, making sure each had at least 2 drop-off points. Each of the scenario simulations matched the feasible routes for the shortest path.

Incorporating the method allows scaling of the delivery capacity during spikes without the need for an excess in-house fleet. The operator may use the process as a tool to measure the crowd deliverers' impact on the in-house fleet, as well as outsourced couriers' efficiency, identify couriers' idling times, and the overall impact on the in-house fleet and process evolution. The W-score, in conjunction with clustering, supports the balancing of in-house and outsourced operations.

The enhanced management of peak volumes is the enabler of improving customer satisfaction or the Net Promoter Score (NPS), as one of the main objectives.

From the clustering methods tested with the W-score, DBSCAN can flag noise, that is, from another perspective, parcels allocatable for in-house couriers.

Further options could include dynamic pricing for the cases. Overall, the method provides operational flexibility, not just cost savings.

From a human workforce perspective, as pointed out in previous research, the current postal workforce is not suitable for reallocation in many cases (Tulev *et al.*, 2024), the introduction of crowd deliverers opens up new job options for the carriers, some of them being former postal deliverers, as they may offer their services as crowd deliverers to multiple courier service providers (Savelsbergh and Ulmer, 2022).

Finally, package allocation process for crowd deliverers AS-IS and TO-BE perspectives.

Currently, the process is manual selection of the routes, driven by SLA (Service level agreement, in this context, the commitment to deliver the parcel within a timeframe and set conditions) or customer redirection, where the in-house courier has failed to deliver. Also, experimental reasons, just outsourcing areas to see if we have enough supply of crowd couriers, and building app stickiness for crowd couriers.

Future allocation, shipments before being scanned/sorted in the sorting centre, would be identified by the algorithms as the most optimal delivery driven by the cost factor (cost per stop) and allocated to the delivery channel/route that can deliver without breaking the customer (Sender) SLA.

Value of the study

We demonstrate how unsupervised machine learning models can be implemented for pre-selecting parcels for their suitability for crowdsourcing on the last-mile courier deliveries. By formalising the composite W-Score, the study provides a tunable metric for the crowd delivery suitability. This metric is adjustable and also extendable, to suit specific business needs, adjust to cost-relevant aspects, etc. The findings give postal operators input and decision support on seasonal demand fluctuation management.

For the research, the study extends the literature on partial crowdsourcing with validation metrics and iterative methods, which can be extended with organic parcel data, travel-time matrices, and also transferred to other geographies.

Limitations and future work

We used synthetic, simulated data for the parcels. Initially, we were looking for the possibility of using organic real-case study data. To avoid legal issues with possible GDPR violations, the coordinates of parcel clients could be subject to, we simulated the data and decided to validate the study results externally with the Postal Service.

To keep the scope clear on exploring ML models for their suitability, the distances for the test were not mapped with actual driving distances and travel times. This was not in our current study scope and can be incorporated by creating a travel-time matrix and supplying the solver tool with the cost or time dimensions. Data for it can be obtained by acquiring driving distances and times between geocoordinates from external routing engines.

Also, we did not use specific time windows for collections, reverse logistics, and parcels that could be rejected; we left out detailed cost estimation, which is a subject of future studies and production implementations.

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Tools and resources

General scripting and analysis: Python 3.8. Libraries: NumPy; scikit-learn for machine learning; OR-Tools (pywrapcp, routing_enums_pb2) for routing; geopy.distance for geospatial distance. Algorithms and methods: K-Means and DBSCAN for unsupervised ML clustering; Elbow method, Davies-Bouldin index, Silhouette coefficient for cluster validation.

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Digital Transformation Empowering Women to Leadership Positions in the Logistics Industry

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Introduction

Logistics is vital as it manages the flow and storage of goods, and services, it requires effective leadership to inspire and motivate employees, directly enhancing company performance (Kolasińska-Morawska et al., 2019). The logistics industry is growing rapidly, and now it is digitalised (Amr et al., 2019). Despite its rapid digitalisation, the logistics industry faces persistent gender inequality due to traditional stereotypes (Yang et al., 2024). These stereotypes link men to leadership and physical tasks while confining women to supportive roles, affecting hiring, promotions, and self-perception (Noh et al., 2023; Akbari et al., 2024; Yusriza, 2023).

On top of that, many articles have independently explored gender inequality and digital transformation in logistics, however, there is limited research examining how digital technologies can address the barriers women face in the industry (Gunawardane et al., 2023). The logistics industry remains male-dominated, and while technology has enhanced efficiency, its potential to promote gender equality remains underexplored (Kern, 2021). This research aims to explore this gap by investigating the barriers women face in their workplace and assessing whether digital tools can help overcome these challenges. By asking two research questions: What barriers do women face in leadership positions in the logistics industry? Can digital transformation help in overcoming these barriers?

Literature review

Barriers Women Faced in Logistics

After reviewing many literatures, it has been found that most of the leadership style are perceived as feminine styles, however they remain underrepresented in leadership positions. As women deal with many barriers that not only makes it harder for them to being promoted but also demotivates them to continue their careers.

The primary source of barriers can often be traced back to societal stereotypes. To this day, the traditional gender roles stated that men are responsible operation tasks such as production and leadership positions, while women will engage more in supportive administrative roles, like customer service (Akbari et al., 2024). Yang et al. (2024) further argue that society accepts this unequal division of labour because women should prioritise domestic chores like family welfare and childbearing. As a consequence of these traditional stereotypes, some individual struggle to adjust to the idea of having a female leader (Kolasińska-Morawska et al., 2019). As they think that women are incapable of lead effectively and do not trust them to engage in important networking events (Yang et al., 2024). These stereotypes may extend that the managers assume that women are not interested or lacking the capabilities to work in technical roles which actually limits the opportunities for women and makes them insecure and demotivated to apply for these jobs (Akbari et al., 2024; Ruel and Jaegler, 2021). Yusriza (2023) added that women are not taken seriously in the air industry and may be passed over for promotions because the managers underestimate their capabilities.

Furthermore, the company's regulations play an important role in creating the barriers as they do not promote gender diversity so women will feel less supported and valued (Reynolds, 2024; Yanikoglu et al., 2023). Edirisinghe (2018) and Yusriza (2023) provided an example for the policies which is maternity leave can be a factor for the underrepresentation. Furthermore, in logistics, women have less experience than male which is called pipeline problem. (Gipson et al., 2017) this may be due to domestic responsibilities or inadequate training practices (Yang et al., 2024). Akbari et al. (2024)

add that the companies may have formal policies to prevent any discrimination and sexual harassment, however, they may not deal with the problem effectively. Many articles have argued that women deal with gender discrimination in the workplace, it can be through mistreatment, hiring, performance evaluation or glass ceiling (Yanikoglu et al., 2023; Yusriza 2023; Ruel and Jaegler, 2021). Subhash et al. (2016) added that discrimination may be difficult to identify especially for young women. Thus, women often feel pressured to be more masculine in order to gain acceptance from their peers (Yanikoglu et al., 2023). Akbari et al. (2024) add that approximately 30% of women working in industrial sectors report experiencing either physical or mental harassment. For instance, Edirisinghe (2018) explains that in the maritime sector, women who face harassment are often transferred to another ship, while the man faces no consequences. Similarly, in air transport, Yanikoglu et al. (2023) report that women tend to avoid reporting harassment to avoid being called problematic.

On top of that, women are being recognised for their gender and not their accomplishments, even though they perform the same or even better than the male workers (Yanikoglu et al., 2023; Vo et al., 2023). This will lead to adding pressure on themselves to prove their worth, which will be stressful and sometimes they will feel insecure about their performance so they will feel demotivated to improve it (Yanikoglu et al., 2023). Ultimately and most crucial is the working conditions, logistics requires long and inflexible working hours, continuous travelling and it has very demanding schedules that can be on weekends and even holidays, which affect women negatively as they have other responsibilities (Yang et al., 2024; Reynolds 2024). Akbari et al. (2024) stated that the inflexibility of work conditions makes it challenging for women to deal with their dual burden "meet their responsibilities in both their home and at work". Vo et al. (2023) studied the maritime sector in several countries and found that women feel more overwhelmed by balancing work and housework compared to men, even though men also expected to be present at home as father figures. Based on their study, they concluded that women will eventually have to choose between being a good mother and pursue their dreams. Yanikoglu et al. (2023) found similar results when they studied the air industry.

Vo et al. (2023) also argued that due to the unconscious bias and the stereotype that women should prioritise being a mother and a wife over their careers, makes it challenging for women to balance their private and professional life, adding that networking, which mainly happens outside of working hours is also considered part of the professional life. These challenges are combined by the fact that the networking events are very important for someone career, however they are often dominated by men (Zin et al., 2018). The connections are important, as promotions are typically decided by senior leaders and usually, they select trustworthy individuals from their networks, usually men (Akbari et al., 2024). Zin et al. (2018) further emphasised that they choose their contacts to ensure that the firms are in good hands. The lack of female role model demotivates other women and it will be hard for them to envision themselves as leaders (Reynolds 2024; Yusriza 2023). Yanikoglu et al. (2023) argued that training is crucial for anyone's career, however female students are not accepted by their male instructors as they think that women do not have abilities to do the job, and they do not provide them with appropriate level of support. This will lead to negative mentoring experience like the mentor can neglect the mentee performance and mentors can use manipulation, consequently, women's self-confidence will decrease (Yanikoglu et al., 2023; Yusriza 2023).

Role of Digital Transformation in Supporting Women

Bulmer et al. (2021) addressed that the traditional stereotypes about the work conditions such as heavy lifting and work in warehouses are not big problems as they used to be due to the digital transformation and the automation of warehouses. Sukri et al. (2023) agreed by adding that it increases the job opportunity for women and reduces the idea of it being dangerous roles. Maurelli and maussimelli (2020) and Mishra (2017) observed that AI and machine learning can increase job opportunities, especially for women, since it combines many traditional jobs and redefine the tasks, also by automating the tasks it became more

appealing for women. Moreover, Noh et al. (2023) believed that women who constantly being trained and have supportive environment, can use the new technologies efficiently to improve their skills and abilities in their jobs which will make them more confident to take new tasks.

Mishra (2017) and Gawel and Mińska-Struzik (2023) believes that leveraging new technologies create more flexible working conditions for women. Gawel and Mińska-Struzik (2023) added that it reduces the entry barriers for women especially if they are motivated to learn new technological skills. Mishra (2017) stated that women entrepreneurs if they can leverage the technology effectively, they will increase their customer base and can reach global customers. Noh et al. (2023) provided an example from the aviation sector, indicating that automation in modern aircraft has made it easier for all genders to operate them, and specifically highlighted how the design of a new ergonomic cockpit suited for female pilots has reduced their fatigues and discomfort, increasing their willingness to perform their jobs.

However, Gawel and Mińska-Struzik (2023) and Mishra (2017) concluded that the digital transformation can have many advantages for women and promote gender equality, but it has many disadvantages that encourages gender gap as not everyone has the same access for the internet, and it is called gender digital divide. Even they have the same access, women may be less skilled to use the new technologies due to the lack of training provided by their firms which can be due to discrimination (Mishra, 2017). Gawel and Mińska-Struzik (2023) observed a new aspect of the problem, which is the finance sector, even with the help of new technologies women still suffer to access financial resources. Lastly, Gawel and Mińska-Struzik (2023) sated that by using new technologies the traditional stereotypes will not disappear. It can be seen in women who tends to learn new technological skills but do not have time due to its responsibility at home.

Research Problem

Gunawardane et al. (2023) had argued that the logistics industry is known as male dominated industry which limit the inclusion of women. Even the women who can cross that bridge and work in logistics companies, they still face many barriers which makes it hard for them to stay in the job like for example the glass ceiling (Gunawardane et al., 2023). This situation continues to exist even with the usage of new technology like blockchain and artificial intelligence (ai) (Gawel and Mińska-Struzik, 2023). Many researches have studied the benefits of digital transformation in logistics and how it improved the efficiency of the processes and automating tasks (Kern, 2021; Maurelli and Mussomeli, 2020), but very few have explored how the digital transformation can affect the barriers that women face.

By focusing on how technology can help women overcome the barriers in logistics, this research aims to promote gender equality within the industry and improving the sector's overall efficiency. This research aims to explore more on the barriers women faces, and whether or not the advanced technology will support women in being leaders in the logistics industry. To achieve these aims. These are the questions that will be answered:

Research question 1: What barriers do women face in leadership positions in the logistics industry?

Research question 2: Can digital transformation help in overcoming these barriers?

Methodology

Given the lack of studies that cover the two main variables together, so not much is known about the topic that is why an exploratory research approach is the most suitable like Cooper and Schindler (2014) had stated, also it allows flexibility in forming a new hypothesis that helps the researchers to understand the concepts more clearly and create priorities. Based on the research questions and the literature review of this research, a qualitative research strategy was selected as it allows for a deep understanding of the experiences of women in the logistics sector (Şenbursa, 2020). The study used interviews

as the primary data collection method due to its effectiveness for gathering in-depth responses and exploring complex personal and social factors, such as workplace experiences and perceived barriers in the logistics field (Şenbursa, 2020). Interviews were designed to be semi-structured interviews with guiding questions and follow up questions if needed. Based on the literature review and the research gap, the interview questions were open-ended questions. The interview was composed of 13 questions. The first three questions were to introduce the participants and their workplace. While the following three questions were to address that barriers that women face in the workplace when they are seeking leadership positions. Then the following three focused on the impact of digital technology in the logistics industry and if it facilitates the work. Finally, the last four questions were to identify if the technology actually helps women to overcome these barriers.

The population includes individuals that work in logistics and supply chain field that implement new technologies in their daily tasks. Specifically targeting managers, supervisors and operational level. As for the sampling techniques, non-probability convenience sampling was used. As Cooper and Schindler (2014) explained convenience sampling as a method that collects information from people within the population that are ready to provide it. The research included a diverse sample starting with including both genders to ensure various perspectives on the problem while also focusing on various levels of management. The expected sample size is seven employees, including four women and three men. However, the researcher will keep interviewing until no new information is reached which is known as theoretical saturation (Sekaran and Bougie, 2016). The data will be collected at a single point in time, which is the cross-sectional technique, by conducting an online interview on platforms such as teams. The data took one month to be collected. At the end, the data was collected from ten interviewees, including six women and four men, and each interview took averagely 10 to 15 minutes. The following table 1 shows details about all of the interviewees who participated in this research.

Findings and Discussion

While all of the respondents have confirmed that it is a male-dominated industry however there are dissimilarity in their workplace's gender dynamics. For instance, two males revealed that their team consists only of males, and three respondents their teams are female dominated, one of the female interviewees added that it is not her first job where the team is female dominated. Also, the other female mentioned that her current job and the previous one were female dominated because it's an office role, however when she worked in a warehouse, she was the only female in a team of seven. This experience has confirmed Akbari et al. (2024) point of view that women stick to the administrative roles. However, five respondents have a balanced dynamic.

When they were asked about opportunities represented for women. It was found a complementary pattern of thought starting with the sudden awareness and acceptance that women can work in this field which increase the inclusivity and of course the introduction of technology which eases the workload like it was mentioned before. As a result of these two we have two other reasons, that due to automation women now can perform operational tasks so easily and due to inclusion more roles are being introduced like the e-commerce and documentation management. And as a result of these opportunities, women may be recognised more for promotion.

Table 1: The classification analysis of the sample

Interviews	Gender	Interview Title	Years of experience
Interviewee 1	Female	Value Chain Manager	27
Interviewee 2	Male	Operations and Logistics Manager	25
Interviewee 3	Female	CEO and Founder of SCS	12

Interviewee 4	Male	Logistics Manager	12
Interviewee 5	Female	PSCM Logistics Manager	10
Interviewee 6	Female	Operation Manager	9
Interviewee 7	Female	Senior Export Logistics	5
Interviewee 8	Male	Customs Clearance Agent	5
Interviewee 9	Female	Order Management treat	4
Interviewee 10	Male	MRP Deputy Manager	3

When they were asked about the barrier's women faces, I've gathered eight barriers. First and the most agreed upon is the work life balance which is exactly like it was mentioned before, however, one respondent added that the difficulty to maintain the balance is also for a newly starter in this field because she will deal so much stress and responsibility that she should learn about in a small time so she should work extra hours and stay at the office as more as possible. The next one is the inflexible working conditions also just like it was mentioned before. They covered the inflexible working hours/ heavy physical tasks/ travel/ communication/ hassle and pressure. Which takes us back to the work-life balance. Third was the traditional stereotypes, when they reached this point most of them talked about their experience for example one of respondents mentioned that she was the only female in a team of six in a warehouse and she wasn't comfortable at all. Another one agreed with her saying that if a woman wants to be respected and taken seriously, she should toughen up and prove herself over and over again and it's very hard because she proves herself for someone who doesn't believe in her which takes us to the fourth barrier which is acting like a man. Her words prove that Noh et al. (2023) is correct when they stated that the stereotypes make the women to crave perfection in these field. Also, their opinion was similar to Yanikoglu et al. (2023) when they mention that women are pressured to be more masculine to gain acceptance. Fifth there is the lack of training especially for leadership & culture. One respondent talked about the willingness to learn is the main barrier regardless the gender. Lastly someone add a new perspective which is the education he mentioned that most of the employees are engineering and a few of them are business and like it is known that most of the engineers' students are males and the business students mainly major in finance and marketing few students that go to other majors. In his opinion that is the main reason why it is a male dominated industry.

Despite all of these barriers most of the respondents didn't face them, only four did. Starting with a female whom ideas were not properly considered by her manager due to her gender, she also has seen during her 10 years of experiences qualified women overlooked for promotions. Another female has observed the family businesses, and the SMEs stick to traditional stereotypes, so they discourage women from taking on operational roles which results in underrepresentation of women in leadership positions. A male also observed that the stereotypes impact career growth for women. Lastly, another male mentioned that his firm provide everything for women to work, like training and inclusive culture but after some time these women are either engaged or pregnant so they leave the firm because they cannot balance their dual responsibilities. However, from what was mentioned previously, there is a male respondent who mentioned that his firm hire males only for his team but when asked if he saw any gender bias decisions taken in his previous experience he said no and he believes it. Which proves that the main barrier is hidden within the culture to the point where individuals cannot point it out.

All of the respondents have agreed that the firm's culture has a great impact on gender barriers, and they believe that it affects both genders equally. A large number of respondents' firms provide their women employees with maternity leave, create cultures that support skills and hard work, have family friendly policies, transportation and equality in salaries. A male respondent even added that his firm always push for having women in the workplace. Provided a personal example that he as a logistics manager have an available vacancy and the main requirements is that a woman will fill this vacancy. Another male gave example of what his firm do to support women like having a female guest

speaker to motivates women workers and provide them a lecture on how to balance their life especially in women's day. While a third male mentioned that his firm lets women work from home during pregnancy or even the first months of childbirth. A female respondent argued that when the manager believes in their employees the opportunities will be provided based on skills and ability regardless the gender which will help the women to prove themselves quickly. Unfortunately, another female believes that even if a firm provides all of these, there may be hidden expectations that women should prioritise family over career. There are two respondents who have the same idea that a supportive culture is helpful, however cultural perceptions will have a great impact on women's career growth.

To know their real thoughts about the implementation of technology, we started by discussing the advantages of it. The first advantage we have received is the streamlining and the optimisation of the tasks, as was reported by three respondents. Another three respondents added that it improves efficiency, and they gave many examples, starting with how it reduces manual labour to how it helps with truck utilisation. Another advantage is that it provides better storage methods by using the 3D modelling for example. If you use technology correctly it will help save times and improve your problem-solving Which builds on Ferreira and Reis (2023) perspective that the firms use image segmentation to improve storage methods skills. Lastly it provides more flexible working conditions. However, everything has its downside, most of the respondents agreed the biggest disadvantage is that technology starts to replace mankind to reduce costs. Two participants focused on the financial side, stating that it will require higher investments to protect the firm from security issues, which aligns with Kern's (2021) thoughts. A male interviewee added on these investments, the costs of the excessive training. According to another male respondents the training is a requirement as the system may be complex, especially for the flow of data, and according to a female participant, due to its complexity, the workers may be resisting the change and unwilling to learn.

On top of that, two participants of both genders think that the utilisation of technology may be backlashed. If a company depends totally on a system and not any human input two things may happen, first the website can lag at any time so the whole processes may be slowed. Secondly the data is not accurate all the time, so the employees need to revise it carefully and be careful while entering any input which also takes a lot of time. Another male participant added another perspective to these ideas, which is the technology is not fully implemented in Egypt. In his point of view, it may be the reason why technology may improve an area and at the same time it may backlash.

When they were asked where they saw equality due to technology, the answers were divided into three categories. The first category is that it provides more flexible working arrangements as it facilitates remote working so women can balance between their dual responsibilities. Which reinforces Mishra (2017) and Gaweł and Mińska-Struzik (2023) arguments. The next category is that it reduces bias in the workplace. By focusing on the skills and qualification instead of the gender, all the candidates will be evaluated fairly whether in the hiring process or performance metrics evaluation. Also, by providing all of the employees with the same technology it would be fairer for both genders to compete for their performance evaluations.

The last category is providing more opportunities for women. As one of the females thinks that women can contribute to the warehouses due to less physical jobs needed, while another thinks that the emerging of E-commerce helps the women to join the workforce easily in general not only in operations. Although another female thinks it gives a chance to learn because when it comes to women, especially in her experience, if you want a task so badly then you have to depend on yourself then it may reflect positively on said person to be more responsible. On the opposite side, two of the males' participants believe that technology helps both gender as it facilitates the tasks in general and it does not affect gender equality. Which moves us to the next group who believes that yes it has its benefits toward gender equality but there are areas where it cannot address it. Starting with two

respondents who think that men will still have the edge to work in operations, while a male interviewee who believes that technology require advanced training which can be inaccessible to women due to their responsibilities which supports Gawel and Mińska-Struzik (2023) idea. Another two respondents presume that technology does not address systematic bias in the workplace culture like decision making, this should be coming from the management to ensure fairness.

Lastly, they were asked if there is any additional measure that impacts gender equality. All of the respondents agreed that culture is the main measure by giving some examples like hiring a specific ratio for each gender and this diversity should be based on experience, skills and talents. A third female also addresses the need to have a culture that challenges gender stereotypes and welcome women for example, launching gender equality programs and leadership development initiatives. All of their opinions explain Reynolds (2024) point of view, which is the inclusive culture improves employee satisfaction, which contributes to the overall success of the firm. The next measure is the firm's policies which three respondents felt that the policies are complementary to the firm's culture and a firm should focus on both simultaneously to enhance gender equality. Furthermore, two respondents mentioned that training is a very important measure. A female accord with them while adding the importance of networking to guide women through their careers and break through glass ceiling in leadership roles. Thus, she complements Reynolds (2024) on his understanding of the importance of networking events in someone's career. A female interviewee has another point of view, she believes that it depends on the manager's ability to assign tasks to employees based on their skills. Also, she focused on the way the managers may want to promote themselves as a gender equaliser and assign any job to women, and they may not have the skills to do it, so it will backfire on both, which will have a negative impact on the organisation and the customer in the end.

Conclusion and Future Recommendations

To conclude, this research aimed to explore the barriers that women face in leadership positions within the logistics industry, along with their contributions to the industry. As well as the role of advanced technology in overcoming these barriers. However, it mainly focused on understanding the challenges, how the logistics industry can be more inclusive in supporting women to leadership positions, and the impact of advanced technology on their career advancement. The research questions helped narrowing the research focus, which are, what barriers do women face in leadership positions in the logistics industry? Can digital transformation help in overcoming these barriers?

This research was an exploratory research approach, utilising qualitative research methodology and conducting semi-structured interviews. A total of ten interviews were conducted with logistics and supply chain professionals, as they provided valuable perspectives on the industry's gender dynamics and the potential of digital transformation. The data collected through one month by a cross-sectional technique, and it was analysed manually using a qualitative analysis method.

The findings revealed that respondents recognise both the challenges faced by women and the opportunities offered to women. These challenges cover many aspects like the working conditions, stereotypes of the logistics industry, and the dual burden of responsibilities which answered the first research question. Technology has proven effective in addressing some of these challenges, by making the operational tasks more accessible and inclusive. However, there are some challenges, like the stereotypes that technology cannot be overcome alone, it needs recognition from the people to shift their way of thinking, which will then affect the organisation's culture. This is linked to the second research question. Moreover, the research highlighted the importance of organisational cultures and policies to promote gender equality.

These findings provided valuable practical implications. As the study offered insights on how to empower women in logistics by implementing inclusive policies and leverage the technology efficiently. It also highlighted the needs for more leadership training sessions tailored to women, while also focusing on providing more flexible working options as allowing remote work for married women to balance dual responsibilities. Moreover, it emphasised to use technology in hiring and performance evaluation processes to reduce gender biases, while also, encourage women to attend networking events. Finally, the research suggested investing more in advanced technologies as it can improve operational efficiency in the long run, while ensuring that technology will not replace the employees.

On top of that, it contributes to the theoretical understanding of gender inequality in the logistics industry by addressing a research gap. Specifically focused on how technology help in overcoming gender-specific barriers. Additionally, the research put forward new ideas for future studies, including the impact of education, type and size of companies, and culture and proposed further studies on how these factors influence gender inequality and create leadership opportunities for women in logistics.

As with most of the research, this research is subject to some limitations. Accordingly, the findings of this study must be seen considering these limitations, hence some recommendations are provided to future researchers. This research focused primarily on the most obvious four barriers that a woman can face and did not fully explore other potential barriers like education or the way women change their whole way of interaction to be respected. Future research should expand the scope to investigate other subtle challenges that could impact women's career. Another limitation is that the study was focused on the MENA region, there are cultural and regional difference that affects the challenges faced by women and the opportunities provided to them. In fact, these two limitations are linked because the common technology adopted in most firms in the MENA is Artificial Intelligence, while Europe for example has more advanced technologies adopted which would change most of the results if this study considered them. Thus, future studies should explore more regions to be able to explore more technological impact and the barriers that women face.

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The Role of Managerial Factors in Digital Transformation Adoption in SMEs: The Case of Vietnam

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INTRODUCTION

Digital transformation (DT) has become an emerging phenomenon and an imperative for all organisations worldwide. Global spending on DT has increased sharply from \$1 trillion in 2018 to \$2.5 trillion in 2024 (Statista, 2024). The widespread adoption of digitalisation has prompted SMEs across diversified sectors to embrace DT to enhance operations and gain a competitive advantage. However, 80% of DT projects failed in 2023 (Dhall & Kanungo, 2023), and despite recognising its importance, 67% of SMEs still struggle to survive (WeForum, 2022). This raises critical questions: *What are the key determinants of a successful DT, and do these determinants remain consistent across companies of different sizes?*

While most DT research focuses on large organisations, studies on SMEs are relatively scarce (Matarazzo et al., 2021). SMEs differ significantly from large enterprises in ways that influence their technology adoption. Due to resource limitations, top managers in SMEs must carefully consider risk and returns when implementing DT. This underscores the critical role of top managers in driving DT within SMEs, where structures are centralised, and decisions significantly impact all aspects of the firm's activities. DT is a complicated and challenging process, raising critical concerns for more managerial issues than technical issues (Walsh et al., 2023). However, research on managerial factors influencing DT adoption in the context of SMEs remains nascent (Bresciani et al., 2021).

The role of managers is particularly pronounced in the Asian context, where hierarchical structures are deeply ingrained. In this setting, leaders often assume an authoritarian role, while followers are expected to respect their decisions (Koo & Park, 2017). The high power distance between leaders and followers in Asia further centralises authority, endowing leaders with substantial control over their organisations. This issue is further reinforced by the influence of Confucian culture, which typically establishes a notable hierarchical distance between leaders and their staff. It is reasonable to posit that the role and authority of owner-managers in shaping innovation decisions within Asian SMEs are of paramount importance. Hence, studying how managerial factors impact DT adoption in Asian SMEs is both timely and necessary.

As a result, this study aims to fulfil two objectives: (1) to understand the level of DT adoption in SMEs in Vietnam and the perspectives of SMEs' managers about DT, and (2) to explore the role of managerial factors as key determinants of the adoption of DT in SMEs in the Asian context, particularly in Vietnam. Theoretically, this study will make a contribution to enriching the body of knowledge on DT studies by exploring the influences of leadership characteristics on the adoption of DT. In addition, to the best of the authors' knowledge, this is perhaps one of the first studies dedicated to exploring managerial factors towards DT adoption in the context of a developing country such as Vietnam in Asia. Practically, this study provides SME owners/managers with practical guidelines for strategies that stimulate firms to embrace the DT journey in today's digital age.

LITERATURE REVIEW

Digital transformation

The origin and development of the term "digital transformation" emerged from Industry 4.0 in the 2000s. DT refers to "the use of new digital technologies to enable major business improvements" (Fitzgerald et al., 2014, p. 1). DT includes three phases: digitisation, digitalisation and digital transformation. Digitisation refers to converting information from

an analogue form into a digital one. Digitalisation is the use of digital technologies to change business processes. Digital transformation – the most pervasive phase- is a company-wide change that leads to developing new business models by creating and seizing value.

DT adoption has been seen in various firms, including SMEs. In this respect, rapid changes in the business environment have pushed SMEs across various sectors towards DT (Eller et al., 2020). However, SMEs seem to lag behind larger enterprises in embracing the DT journey (Eller et al., 2020). This lag in SMEs may lead to limited development and productivity, causing increased inequalities (Malodia et al., 2023). While large enterprises can quickly develop and deploy their own digital platforms, most SMEs have faced various difficulties, thus relying only on third-party digital platforms (Westerlund, 2020). Due to inadequate capabilities and resource constraints, the DT process is significantly different in SMEs compared to large companies; hence, it is crucial to understand the factors affecting the adoption of DT in the context of SMEs (Malodia et al., 2023).

Research on DT has received much attention from scholars over the past two decades (Kraft et al., 2022). However, most DT studies have been mainly examined in the context of large enterprises, while studies focusing on DT in the context of SMEs are relatively scarce (Matarazzo et al., 2021). Extant literature on digitalisation or DT in the context of SMEs has narrowly focused on examining antecedents or drivers and barriers of DT (Eller et al., 2020; Omrani et al., 2024) or dynamic capabilities (Soluk & Kammerlander, 2021). It is argued that managerial issues play a significant role in contributing to the success of DT (Walsh et al., 2023). However, the previous literature has shown that the role of managers in DT seems to be overlooked in SMEs (Soluk & Kammerlander, 2021), where decision-making is centralised, and the owners have a significant influence on the firm's strategic decisions (Eller et al., 2020). Therefore, it is important to consider the managerial aspects of DT in the context of SMEs.

Managerial factors in the DT adoption of SMEs

As firms' key decision-makers, top managers play a crucial role in driving DT. This role is particularly pronounced in SMEs, where the structure of SMEs and decision-making is usually centralised. In those SMEs, both operational and strategic decisions often fall to a single individual, highlighting the concentrated nature of leadership. Consequently, the attitudes, skills, and digital backgrounds of SME managers serve as critical driving forces for the adoption of DT. Despite the growing awareness of DT adoption in practice and the decisive role of SME managers in strategic decision-making, little literature has shed light on the role of managerial factors in DT adoption in SMEs (Malodia et al., 2023). This gap presents an opportunity for this research to explore how the personal attributes, skills, and digital backgrounds of top managers in SMEs shape the DT process specifically. An overview of relevant studies is provided in Table 1.

Table 1. Studies on managerial characteristics in DT adoption

Managerial factors	Definition	References
Digital leadership	Top managers inspire DT plan to staff, provide clear DT vision, commit, motivate and encourage members to achieve DT goals, and consider the DT beliefs of all members	Cichosz et al. (2020); Porfírio et al. (2021); Ko et al. (2021); AlNuaimi et al. (2022)
Digital self-efficacy	The owner-entrepreneur's self-efficacy in efficient adoption and use of digital technologies, and their personal ability in upgrading with the latest updates and versions in hardware and software	Malodia et al. (2023)
Digital awareness	Critical thinking about technology adoption, agile-oriented thinking, crafting a change and entrepreneurial mindset, continuous improvement in business processes, digital knowledge and experience	Leso et al. (2023)
Professional leadership	Qualified and professional manager-owner team, possessing the necessary knowledge, skill, and commitment	Malodia et al. (2023)

Source: Authors, compiled from the literature review

METHODOLOGY

Research approach

The objective of this study was to explore the managerial determinants of DT adoption in SMEs in Vietnam. While studies on DT are prominent, research on the managerial factors of DT adoption in the context of SMEs is still an emerging topic. Therefore, a qualitative approach was deemed appropriate for such an exploratory, in-depth study.

Setting the context: SMEs in Vietnam

In Vietnam, SMEs accounted for 98% of all enterprises and contributed around 40% of GDP (VnEconomy, 2024). Recognising their importance, the Vietnamese government offers various incentives to enhance their competitiveness. However, DT adoption remains in its early stages, with only 10% of SMEs achieving success despite increased investments (Mai et al., 2023). Most Vietnamese SMEs exhibit a low level of technology and innovation, with over 80% of enterprises having just started to understand DT (VCCI, 2020). Moreover, there is a lack of in-depth research on how DT adoption influences operational efficiency and a shortage of clear guidelines for SMEs to adopt DT. Therefore, studying managerial characteristics can offer insights into fostering a proactive digital mindset within SMEs.

Sampling and recruitment

Vietnam is geographically divided into three distinct regions, including the Northern, Central, and Southern areas, and SMEs are dispersed across these regions. Due to this geographical diversity, the study used purposeful sampling to ensure SME size and location diversity across Vietnam's three regions. The sample was drawn from official SME lists, such as the Vietnamese Association of SMEs, the Ministry of Industry and Trade and the Vietnam Chamber of Commerce and Industry, targeting middle and senior managers. In addition, snowball sampling was employed in this study to ask prior participants to introduce others to participate in the interview. As a result, 14 in-depth interviews were conducted online with managers in SMEs in three regions of Vietnam. Table 2 summarises the demographics of the participants and their companies' profiles. Most are individuals in key management positions, such as business owners, directors, and vice directors, with an average of 8 years of work experience. In terms of years of establishment, almost all companies have been in business for more than ten years.

Data collection and data analysis

The interview protocol was designed based on a comprehensive literature review. The instrument was initially developed in English and then translated into Vietnamese following the recommended back-forward translation procedure. The protocol was then pretested with seven academic experts and eight industry professionals in Vietnamese SMEs.

Following a pretest, a pilot test was conducted with two participants. Based on feedback, the protocol was revised, incorporating adjustments to formatting and wording. All interviews were conducted online via Microsoft Teams, with durations ranging from 45 to 108 minutes.

The interview responses were transcribed, coded, and analysed using a combination of predetermined and emerging codes. Following qualitative analysis guidelines, the open, axial, and selective codes were created in NVivo 14. Open coding identified key concepts from transcripts, which were grouped into broad themes. Axial coding created and categorised these themes, while selective coding integrated them into cohesive insights. Table 3 provides the theme of managerial factors.

Table 2. The profiles of participants and their organisation

Participant code	Participant position	Years of experience in the industry	Years of experience in the current company	Sector	Organisation's years of establishment	Location
A1	Director/ Owner	13	6	Architecture & Interior	6	Southern
A2	General Manager	8	6	Manufacturing/ Furniture	12	South Central
A3	IT Manager	20	20	Logistics service	20	Northern
A4	Director/ Owner	25	10	Trading/Sourcing	10	Southern
A5	BOD/ Director	22	14	Logistics service	14	Southern
A6	Director/ Owner	16	16	Manufacturing/ Furniture	22	Southern
A7	General Manager	10	2	Manufacturing/ Food industry	2	Central
A8	BOD/ Director	18	9	Logistics service	9	Central
A9	Director/ Owner	21	21	Manufacturing/ OEM processing	21	Southern
A10	Director/ Owner	18	1	Logistics service	1	Central
A11	Director/ Owner	14	14	Manufacturing/ Energy equipment	14	Central
A12	Vice Director	10	4	Manufacturing/ Handicraft	14	Southern Central
A13	Director/ Owner	12	6	Transportation services	6	Southern
A14	Director/ Owner	20	2	Logistics service	2	Central

Source: Compiled by authors

Table 3. An example of coding

Open codes	Axial codes (Categories)	Selective code (Theme)
Leader awareness of DT benefits Leader vision of the organisation's DT Leader commitment towards DT Leader inspiration towards DT	Digital leadership	Managerial factors
Having digital knowledge Having digital skills	Digital competence	
Having favourable attitude towards DT Dare to do and be willing to change Willing to take risk Openness to explore new things	Risk-taking behavior	

FINDINGS

Lack of full comprehension of DT

Although these three concepts - digitisation, digitalisation, and digital transformation are interconnected, understanding their distinctions is crucial because it helps organisations determine the most appropriate approach for their specific needs. However, most participants had a limited understanding of DT, equating it primarily with adopting software for operational tasks. One manager stated: *"DT means moving away from traditional paper-based processes and instead leveraging information technology to enhance operations and management"* [A1]. Other managers also confirmed this idea: *"DT is the adoption of technology, such as ERP systems, to support interactions on a business's operating system, reducing reliance on human intervention"* [A4].

SMEs at the digitisation and digitalisation stage

Most interviewees indicated that their firms have successfully converted all data and information into digital formats, which are stored in the cloud. One manager noted: *"Almost all information and data have been converted to electronic format. My data and customer records are stored on Dropbox, which is a cloud storage technology"* [A1].

The extent of DT adoption varies based on the firm's size and specific demands due to financial constraints. As A2 shared: *"My company needs to have a roadmap to implement DT. We are developing an ERP system for the factory while combining it with existing customer systems"* [A2].

There remains a notable absence of sophisticated technologies such as AI, big data analytics, or blockchain among the companies of interviewees. If there are any, these applications are only at a fundamental level. One manager added a pragmatic perspective: *"We apply AI at the basic level, just for Quick Chat on the website. I have not thought about big data yet. I mean "Cut your coat according to your clothes". Because the amount of data we currently have is not at the level that requires using big data"*. [A3]

Digital leadership and digital competence as key determinants of DT adoption in SMEs

Digital leadership

Digital leadership is identified as a critical determinant for the effective adoption of DT, with leaders who possess awareness, vision, commitment, and the ability to inspire being better equipped to guide their organisations through the challenges of transformation. When leaders are aware of the benefits of DT, they are more likely to push for the adoption of digital technologies. As A12 highlighted: *"If leaders see the potential of digital technologies in their management and firm operations, they are more motivated to push for change"* [A12].

Given the size and resource constraints of SMEs, commitment from the leader is perhaps the most critical attribute for the success of DT. As one participant stated: *"We often organise training programs for employees to improve their digital skills and knowledge. Despite financial constraints, once we have decided to implement DT, we will try to invest resources, including human and finance, to do so effectively"* [A6].

Hence, strong digital leadership is essential for successfully driving DT in SMEs. Once digital leadership is established, it can facilitate the development of digital competence among leaders and senior managers and leaders are encouraged to enhance their own understanding of digital technologies. By doing that, they will be better equipped to make informed decisions about digital technology adoption.

Digital competence

This theme encompasses the foundational skills, knowledge, and attitudes that leaders must possess to engage with and promote DT within their organisations effectively. A

consensus emerged among respondents that a manager's digital knowledge and skills are indispensable for successful DT adoption. As one interviewee noted: *"Because it is a small-scale company with a limited workforce, if the business owner wants to implement digitalisation, the owner himself must have the ability to use digital technology and sometimes must use it proficiently to deploy and control the work"* [A1].

Moreover, the findings show that manager with a favourable attitude towards DT can significantly enhance DT adoption within their organisations. As A10 stated: *"The business owner himself must like technology and like to learn and explore technology, then the level of DT adoption will be higher"* [A10].

Other managers also underlined the importance of a digital mindset: *"The mindset of the owner is extremely important; if they have worked for multinational corporations before, they see DT as important, they look further, and they will adopt DT very quickly and deeply"* [A4].

This statement highlights the importance of not only digital knowledge but also a proactive attitude and digital mindset among business leaders. It suggests that managers who actively engage with and explore new technologies are better positioned to recognise digital innovation opportunities and support DT efforts within their companies.

Risk-taking behaviour as a possible moderator for the relationship between digital competence, digital leadership and DT adoption

Leaders who demonstrate openness to change, embrace uncertainty and exhibit a willingness to explore new things are more likely to drive DT adoption within their organisations. As A4 explained: *"It also depends on the personality of the leader. Some leaders like to take risks and are willing to join, but some are afraid of risks and do not want to do it. So, applying DT depends on the leader's personality"* [A4].

Leaders with a high level of risk tolerance are more likely to champion DT initiatives, driving not only the decision to adopt digital technologies but also the speed and extent of their implementation within the organisation. One participant highlighted that: *"DT is very challenging for small businesses like us, so leaders must be willing to take risks. If they are willing to accept uncertainty, they are more likely to invest in digital solutions and experiment with advanced technologies. Then, they must equip themselves with the necessary knowledge and skills"* [A9].

Risk-taking behaviour facilitates the relationship between digital leadership, digital competence, and DT adoption. Leaders who embrace risk are more inclined to take a leadership role in adopting new technologies. Recognising the potential benefits, they are also more motivated to enhance their own digital knowledge and competencies. Thus, risk-taking behaviour not only strengthens the link between digital leadership and DT adoption but also shapes how leaders develop the necessary skills to navigate DT successfully.

DISCUSSIONS

First, the findings reveal a significant gap in SMEs' understanding of DT, limiting their ability to exploit its potential fully. This is because Vietnam is still in the early stage of technology development, so SMEs have a low level of technology and innovation (VCCI, 2020). While Vietnam has made notable progress in digitalisation, it still lags behind regional peers such as Singapore and Thailand in adopting comprehensive DT strategies (The Saigon Times, 2024). During the interviews, many participants equated DT with the simple use of software applications. However, such efforts reflect only the initial stages of digitisation and digitalisation. They fall short of the broader, strategic integration of digital technologies that drive business model innovation and long-term competitiveness.

Second, this study underscores the pivotal role of digital leadership in driving DT adoption among SMEs. DT is more than a single change, it is an entire structural shift (Trung & Phuc,

2020). This effort requires 'transformational leaders' who can foster innovation. These leaders must demonstrate determination, inspiration, leadership by example and motivating their teams. This is particularly evident in Vietnamese SMEs, where decision-making power is highly concentrated in the leader, making their role crucial in DT efforts. Existing literature has primarily examined the role of leadership in DT within a one-size-fits-all approach to enterprises (AlNuaimi et al., 2022). This study highlights the specific role of digital leadership in the unique context of SMEs. It further demonstrates that leadership remains a critical strategic factor in decision-making in the context of increasingly resource constraints and highly concentrated power, such as in SMEs.

Third, the finding also highlights the significant role of digital competence in enabling DT in SMEs. By equipping leaders with essential knowledge, skills, attitudes, and mindsets, digital competence enables them to effectively leverage digital technologies. Given SMEs' unique challenges, digital competence emerges as a key driver of innovation and competitiveness. Leaders with strong digital knowledge and skills are better positioned to understand, adopt, and implement new technologies effectively. This aligns with the findings of Malodia et al. (2023), emphasising the critical role of digital literacy and skills in DT and Leso et al. (2023), who highlight the role of awareness in DT in SMEs. However, these studies have not fully captured the multidimensional nature of digital competence. These fragmented approaches overlook the comprehensive nature of digital competence. This study addresses that gap by integrating knowledge, skills, attitude, and awareness into a single, unified factor—offering a more holistic understanding of how digital competence facilitates DT adoption. Importantly, Vietnam is currently lagging significantly behind its main regional countries in terms of available digital skills (Morisset, 2021), which poses a significant barrier to widespread DT implementation in its SME sector.

Fourth, risk-taking behaviour emerged as a moderating factor in the relationship between digital competence, digital leadership, and DT adoption in SMEs, representing a novel insight in this study. Kohnke (2017) noted that digitalisation requires more new managerial skills than before, with flexibility and risk-taking crucial. This is particularly relevant for SMEs, where limited resources necessitate careful decision-making, requiring leaders to balance risk and returns. Previous studies have highlighted the significant role of leaders' risk-taking behaviour in SMEs toward embracing blockchain technology (Polas et al., 2022). However, this study has shed light on a new perspective: in the context of SMEs in Asian settings such as Vietnam, which is characterised by high power distance and centralised decision-making. Risk-taking leaders are more likely to embrace new technology and recognise the need to develop the necessary knowledge and skills. This study highlights that risk-taking behaviour significantly influences the relationship between digital competence, digital leadership, and DT adoption in SMEs.

CONCLUSION

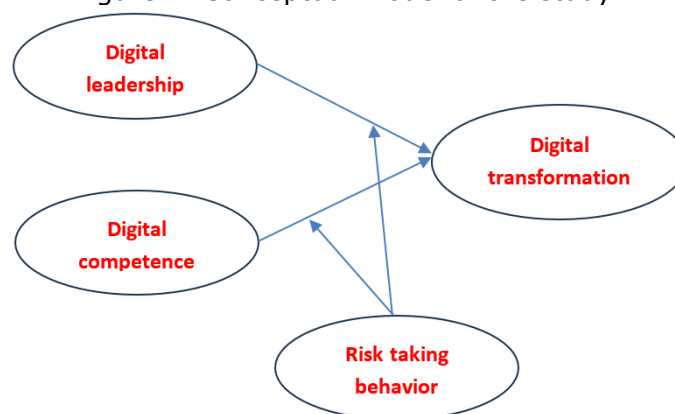
This research offers several theoretical and practical implications. Theoretically, it addresses the limited studies on DT adoption in SMEs by highlighting the critical role of managerial factors. In doing so, it extends the organisational context of the Technology–Organisation–Environment (TOE) framework by integrating managerial dimensions, which are often overlooked. By employing critical realism, this study addresses the call for more investigation into how managerial characteristics influence DT adoption, particularly within the context of Vietnamese SMEs. Furthermore, this study advances DT literature by considering the underexplored Asian context, where Confucian culture reinforces hierarchical leadership. Additionally, it introduces risk-taking behaviour as a moderating factor and proposes a managerial-driven conceptual model for further validation (Figure 1). Practically, these findings shed light on managerial issues when adopting DT to gain competitiveness. DT is a managerial challenge rather than a technical one, thus making managerial factors crucial for successful adoption. Although the Vietnamese government has been actively supporting SMEs in their DT journey through various policies, one notable initiative is the "Supporting SMEs in Digital Transformation" program (SMEdx) (Phi, 2021), which aims to enhance business efficiency and competitiveness by offering technological solutions, technical consulting and financial assistance. However, as Trung and Phuc (2020)

highlight, a lack of effective leadership remains one of the primary reasons many DT initiatives in Vietnam fail. Therefore, to address this challenge, in addition to financial incentives, policymakers should support SMEs with leadership development and digital skills training to foster successful DT adoption.

Limitations and future research

The current research is not without limitations. This study primarily relies on interviews with a relatively small sample of informants and is limited to the qualitative stage. Future research would be interesting if a quantitative investigation were employed to empirically test the proposed model in the context of Vietnam, offering broader generalizability and deeper insights into the identified relationships.

Figure 1. Conceptual model of the study



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A Systematic Conceptualisation Towards Digital Transformation Readiness

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INTRODUCTION

Digital transformation (DT) has become a key focus and has been conceptualised in diverse ways across academic literature and professional practice (Peng & Tao, 2022; Baiyere et al., 2025). Several studies define DT as the utilisation of modern technologies to drive substantial improvements in business operations (Fitzgerald et al., 2014; Correani et al., 2020; Verhoef et al., 2021). However, Balakrishnan and Das (2020) argue that the digital technologies used to implement digital business are merely components of a firm's broader digital capabilities. DT is not solely a technological issue; it also requires substantial adjustments in organisational culture, strategy, and workforce skills. According to Vial (2021), DT entails the holistic optimisation and restructuring of enterprise frameworks and workflows through the adoption of digital technologies and related capabilities. This transformation may lead to significant revisions of existing business models, or even their complete replacement with entirely new models (Matt et al., 2015; Gong & Ribiere, 2021). Notably, Wessel et al. (2021) emphasise that DT involves utilising digital technologies to fundamentally redefine an organisation's value proposition, rather than merely enhancing it. As a result, DT represents a comprehensive shift, culminating in the development of a new organisational identity (Wessel et al. 2021; Baiyere et al., 2025).

DT success relies not only on technology but also on a range of other critical factors, such as leadership cognition, an effective strategy, strategic partnerships with supply chain participants, a culture of innovation, and a skilled workforce capable of leveraging new technologies effectively (Lokuge et al., 2019; Pingali et al., 2023; Mahyarni & Okfalisa, 2024). Without adequate readiness in these areas, organisations risk failed implementations, wasted investments, and missed opportunities. Thus, an organisation's level of preparedness is crucial in determining the direction and success of DT (Pirola et al., 2019; Soomro et al., 2020; Gfrerer et al., 2021).

Despite extensive research, the literature overlooks the dynamism among DT readiness determinants. Effective readiness requires coordinated integration, creating a holistic ecosystem where each component reinforces the others (Khan et al., 2021; Machado et al., 2021; Hortovanyi et al., 2023). Understanding these relationships helps organisations prioritise efforts and ensure a balanced approach that maximises DT benefits.

Given the above, this study aims to explore the determinants that measure DT readiness and develop a conceptual model to illustrate how these determinants contribute to overall readiness. To achieve the research aims, the following two research questions are put forward:

RQ 1. What is the current state of knowledge about DT readiness?

RQ 2. How can DT readiness be assessed systematically?

- RQ 2.1. What factors are used to evaluate DT readiness?

- RQ 2.2. What is the dynamism among these factors?

The subsequent sections of this paper are organised as follows. The next section outlines the research methodology, followed by the empirical findings, including the descriptive analysis and determinants measuring DT readiness, which are elaborated in the subsequent section. Subsequently, a conceptual framework - the "House of DT Readiness"

- is proposed, followed by an explanation of the dynamism among determinants. Finally, the conclusion is presented, highlighting the study's contributions and limitations.

METHODOLOGY

This study follows a two-phase methodology (see Figure 1). The first phase focuses on selecting appropriate papers for a systematic review. In the second phase, the selected papers are analysed, and a systematic framework is proposed to assess DT readiness.

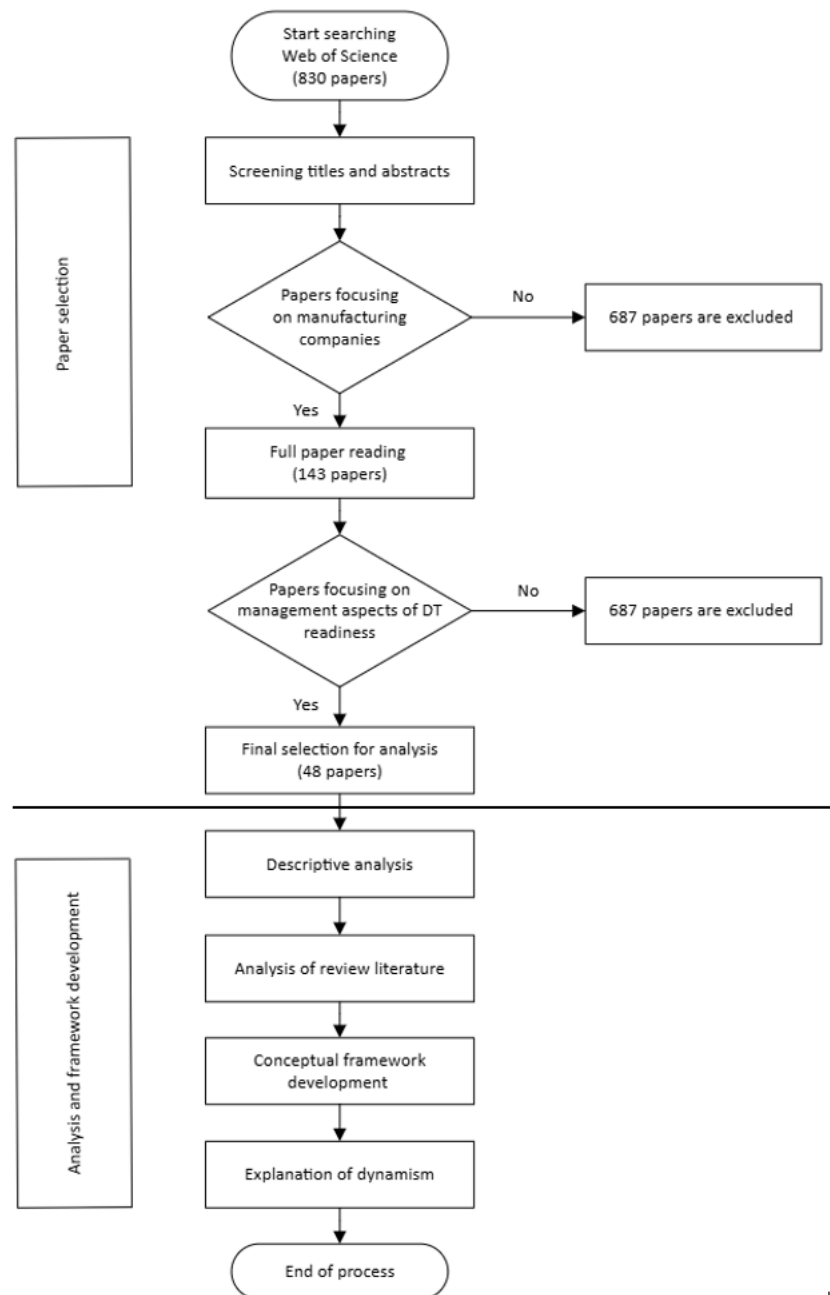


Figure 1. Flowchart of the research methodology

(Source: Author's own work)

In the first phase, to identify relevant articles on DT readiness, we conducted a systematic literature review using keywords, including "digital transfor* ready", "digital transfor* readi*", and "digital readiness" combined with terms such as "organi*", "enterpri*", "compan*", and "supply chain". The Web of Science (WoS) Core Collection was selected for its multidisciplinary scope and recognition in academic research (Graham et al., 2015;

Hausberg et al., 2019). We focused on articles published in indexed journals, excluding conference papers and book chapters, as their content is often referenced in journal publications (Goyal et al., 2013; Saha et al., 2020). Given our research scope in the business and management domains, we limited our search to the Science Citation Index Expanded (1900–present), Social Sciences Citation Index (1956–present), and Emerging Sources Citation Index (2005–present), and considered only articles published in English. The publication range was set from 2011 to 2024, aligning with Chawla and Goyal's (2021) observation that DT research gained attention around 2010, and Vial's (2021) literature review indicating the formal introduction of the DT concept in 2011. The search concluded on October 12, 2024, yielding 830 articles. During the screening, duplicates and articles not focused on factors measuring DT readiness in companies were excluded. As our study specifically examines DT readiness in manufacturing companies, papers from unrelated fields, such as healthcare or education, were also removed, resulting in 143 selected articles. Applying inclusion and exclusion criteria, we included articles with a management focus on DT readiness and excluded purely technical papers addressing topics like optimisation or algorithm development. Additionally, considering that DT and Industry 4.0 have different readiness requirements, articles centred on Industry 4.0 readiness were excluded. After a thorough review, 95 more articles were excluded, leaving 48 articles for comprehensive analysis.

In the second phase, the selected papers underwent descriptive analysis. Based on the findings, the determinants used to measure DT readiness were identified by using an affinity diagram, and the dynamism among these factors was examined. Finally, a conceptual framework was developed to systematically assess DT readiness.

FINDING

Descriptive analysis

Figure 2 shows the distribution of research studies on digital transformation readiness published from 2018 to October 2024. Although the literature search began in 2011, the first paper specifically addressing digital transformation readiness appeared only in 2018. According to Chawla and Goyal (2021), while research on digital transformation began earlier, the number of DT studies grew significantly from 2018 onward, with researchers shifting their focus from general conceptualisations to specific implementation challenges. The figure also highlights a notable rise in publications from 2021, with 40 of the 48 selected studies published between 2021 and 2024. This increase is largely attributed to the COVID-19 pandemic, which accelerated the urgency for DT across various sectors (Burlea-Schiopoiu, 2023).

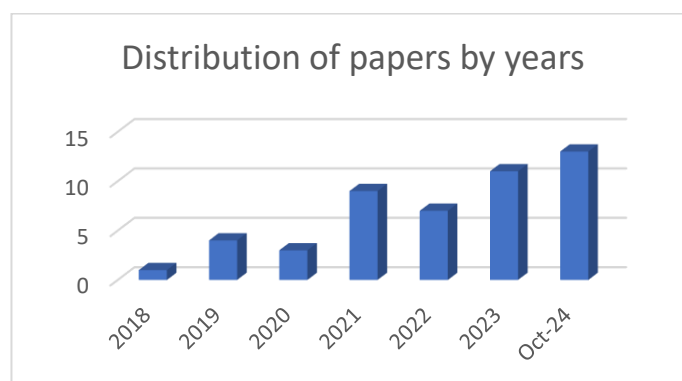


Figure 2. Distribution of papers by years
(Source: Author's own work)

The 48 selected papers are distributed across 38 journals, indicating a diverse range of publications contributing to this field. Notably, 'Sustainability' and the 'Journal of Manufacturing Technology Management' are the leading contributors, each publishing three of these studies.

Determinants measuring DT readiness

Following the process of the affinity diagram, the study ultimately categorised determinants into eight key dimensions: digital infrastructure readiness, digital human resource readiness, digital financial readiness, digital operational procedure readiness, digital supply chain integration readiness, digital strategy readiness, digital cognitive readiness, and digital cultural readiness. These factors comprehensively reflect the primary themes and recurring patterns identified in the academic literature, capturing the critical components that influence DT readiness (see Figure 3).

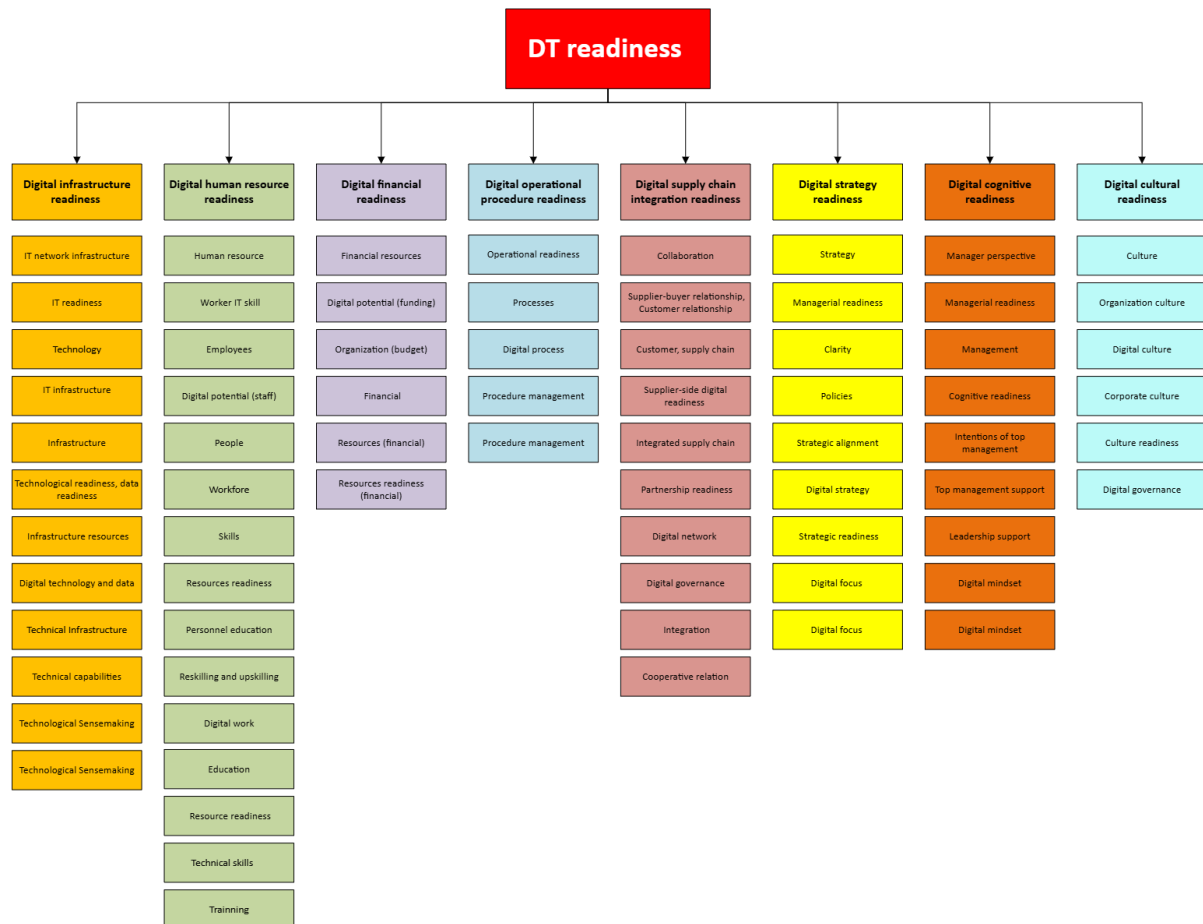


Figure 3. Affinity Diagram
(Source: Author's own work)

Digital infrastructure readiness: Digital infrastructure readiness is defined by the strength of an organisation's information technology (IT) portfolio and data in supporting DT (Lokuge et al., 2019). A well-prepared infrastructure is characterised by availability, stability, and flexibility. Availability ensures systems and data are easily accessible to optimise operations and ensure business continuity (Hussain & Papastathopoulos, 2022; Ben Ghrbeia and Alzubi, 2024; Naji et al., 2024a). Stability emphasises reliable operation with minimal disruptions (Hussain & Papastathopoulos, 2022; Anatan & Nur, 2023), while flexibility allows IT resources to adapt to evolving needs (Lokuge et al., 2019; Oke et al., 2024; Patil et al., 2024). Additionally, effective data management is crucial for DT, enabling agile, data-driven decision-making (Gürdür et al., 2019; Aras & Büyüközkan, 2023; Kroh et al., 2024). To mitigate risks, organisations must ensure strong security systems to protect against cyber threats (Aamer et al., 2023; Aras & Büyüközkan, 2023).

Digital human resource readiness: Digital human resource development, including hiring the right talent, identifying critical skills, offering training programs, and fostering a culture of innovation, is crucial for DT (Zhen et al., 2021; Ofosu-Ampong and Acheampong, 2022; Trischler & Li-Ying, 2022; Aamer et al., 2023; Pirola et al., 2023;). Employees trained in digital tools can effectively drive initiatives to accelerate the DT process (Kosmol et al., 2019; Lassnig et al., 2021; Chen et al., 2023; Pirola et al., 2023). Additionally, empowering employees to adopt new technologies is essential for successful DT (Vial, 2021; Oke et al., 2024). Employee acceptance and adoption of technology are key to DT success (Lokuget al., 2019). Companies must also enhance their workplace appeal through incentives like bonuses and promotions tied to DT initiatives (Hussain & Papastathopoulos, 2022; Tolstykh et al., 2024).

Digital financial readiness: DT requires investments in technology, workforce upskilling, and exploring new business opportunities. Securing a substantial, well-defined budget is crucial to drive and sustain DT efforts (Kosmol et al., 2019; Okfalisa et al., 2021; Min & Kim, 2024). Without adequate funding, progress may stall due to resource limitations, leading to missed opportunities and failure to achieve DT goals (Jun et al., 2022). Organisations must allocate financial resources effectively to leverage opportunities and maximise DT benefits (Shahadat et al., 2023; Kroh et al., 2024). Well-defined budgets can support investments in digital-born startups, which drive innovation and accelerate the transformation process (Kee et al., 2023; Chen et al., 2024; Masyhuri et al., 2024). Additionally, companies with limited resources should seek external financing or partnerships to support DT projects (Okfalisa et al., 2021).

Digital operational procedure readiness: Digital operational procedure readiness refers to an organisation's ability to integrate digital tools and technologies into its operations (Pirola et al., 2020; Oke et al., 2024). This includes streamlining workflows, optimising information flow, and managing documentation digitally to improve efficiency, reduce errors, and align with strategic goals (Aras & Büyüközkan, 2023; Oke et al., 2024; Kroh et al., 2024). Workflows, which are sequences of steps to complete tasks, can be optimised through technology to simplify business processes (Gürdür et al., 2019). Information flow ensures timely access to accurate data for informed decision-making and facilitates interaction between different sectors (Kosmol et al., 2019; Aamer et al., 2023). Digital integration of documentation flow improves the management, accessibility, and storage of documents (Pirola et al., 2020; del Socorro Encinas-Grijalva et al., 2024).

Digital supply chain integration readiness: Digital supply chain integration involves strategic collaboration to optimise internal and external processes through digital innovation (Aamer et al., 2023). Four key collaboration mechanisms are commonly identified: information sharing, goal congruence, decision synchronisation, and benefit/risk sharing. Information sharing ensures timely exchange of relevant data on market dynamics, resources, and operations (Pirola et al., 2020; Lassnig et al., 2021; Khan et al., 2021; Hussain & Papastathopoulos, 2022; Holopainen et al., 2022; Naji et al., 2024b) while goal congruence aligns supply chain partners' objectives with overall supply chain goals (Aamer et al., 2023). In addition, decision synchronisation enhances planning and operational decisions, improving performance (Aamer et al., 2023). And, benefit and risk sharing involve distributing costs, risks, and rewards among partners to foster collaboration and increase profitability (Xue et al., 2018).

Digital strategy readiness: Digital strategy readiness involves managerial initiatives to promote digital innovation (Lokuget al., 2019). It includes equipping the organisation with the knowledge to create a coherent plan and establish guidelines for digital innovation compliance. A well-defined strategy outlines DT goals and the initiatives to achieve them (Pirola et al., 2020; Halpern et al., 2021; Hoa & Tuyen, 2021; Lassnig et al., 2021; Hussain & Papastathopoulos, 2022; Min & Kim, 2024; Kroh et al., 2024). Without a clear strategy, organisations risk losing direction in resource allocation and decision-making (Trischler &

Li-Ying, 2022; Xie et al., 2023). DT decisions must align with business strategies and supply chain goals (Singh et al., 2021; Holopainen et al., 2022; Aamer et al., 2023). Clearly defined roles and responsibilities, alongside open communication of the strategy across all organisational levels, ensure alignment and reduce confusion (Halpern et al., 2021; Lassnig et al., 2021; Hussain & Papastathopoulos, 2022).

Digital cognitive readiness: DT depends on an organisation's cognitive readiness, which includes leadership knowledge and an understanding of DT's benefits and challenges (Lokuge et al., 2019; Holopainen et al., 2022). Additionally, this readiness involves management's ability to communicate the vision and foster a culture that embraces digital change, playing a key role in influencing employee performance (Kosmol et al., 2019; Holopainen et al., 2022; Hussain & Papastathopoulos, 2022; Pingali et al., 2023; Kee et al., 2023; Min & Kim, 2024). Most importantly, management's commitment ensures support for the success of the DT process (Montasser et al., 2023; Shahadat et al., 2023).

Digital cultural readiness: Digital cultural readiness reflects an organisation's core values that drive digital innovation (Lokuge et al., 2019). It includes a culture of collaboration, continuous learning, decentralised decision-making, and risk acceptance. Effective DT requires open communication, teamwork, and knowledge sharing (Singh et al., 2021). A strong learning culture enables employees to adopt new skills and technologies (Holopainen et al., 2022; Chwiłkowska-Kubala et al., 2023; Kroh et al., 2024). Encouraging experimentation and empowering employees to make decisions enhances agility in DT (Okfalisa et al., 2021; Singh et al., 2021; Kroh et al., 2024). Additionally, organisations must shift from risk aversion to risk acceptance in the DT process (Sivaraman, 2020; Okfalisa et al., 2021).

PROPOSED FRAMEWORK OF THE HOUSE OF DT READINESS

Proposed framework

Drawing from the literature, this study proposes the "House of DT Readiness" framework (see Figure 4). This framework is structured like a house, where each component symbolises a critical aspect of DT readiness, emphasising the dynamism of these elements to ensure a successful transformation process.

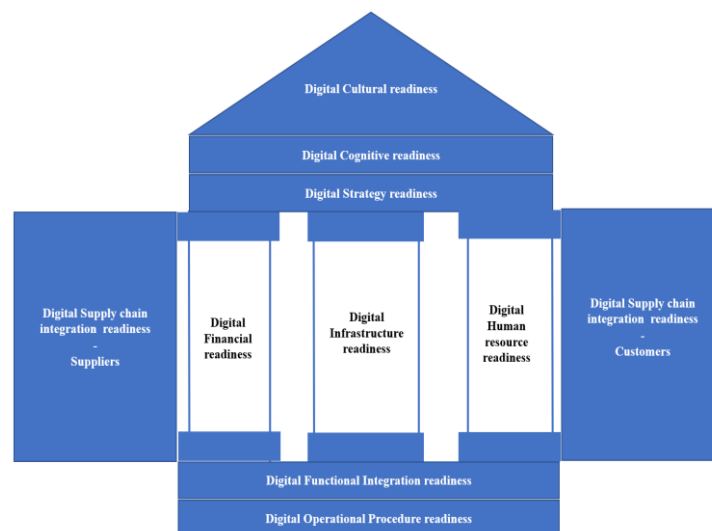


Figure 4. House of DT readiness
(Source: Author's own work)

"Digital Operational Procedure Readiness," one of the foundations, ensures optimised workflows for seamless digital integration. Core pillars include "Digital Infrastructure Readiness," focusing on robust technological systems; "Digital Human Resource Readiness," emphasising employee skills and adaptability; and "Digital Financial

Readiness," ensuring adequate funding for digital initiatives. "Digital Supply Chain Integration Readiness" represents the open doorways, promoting collaboration with external partners (i.e., suppliers and customers) and internal alignment, via the "Digital Functional Integration readiness" foundation. The roof comprises "Digital Strategy Readiness," outlining clear objectives, and "Digital Cognitive Readiness," reflecting leadership's commitment to digital priorities. At the pinnacle is "Digital Culture Readiness," symbolising a culture that supports innovation and adaptability, crucial for sustainable DT.

The "House of DT Readiness" framework serves as a valuable tool for organisations to evaluate their readiness for DT and pinpoint key areas for improvement. By systematically addressing each pillar, organisations can construct a solid framework that not only supports digital change but also positions them for long-term success in their DT pathway.

The dynamism among determinants measuring DT readiness

Organisational readiness theory defines readiness as a shared commitment to change (change valence) and confidence in execution (change efficacy), requiring adequate financial, human, and knowledge resources (Lokuge et al., 2019). Contextual factors influencing change include cultural, strategic, and partnership readiness. Building on this theory, the first three determinants of change efficacy are digital infrastructure, human resources, and finance. Digital infrastructure serves as the foundation for DT by enabling skills development, process optimisation, and data-driven decision-making (Hussain & Papastathopoulos, 2022; Holopainen et al., 2022). However, its effectiveness depends on employee proficiency, as digital skills are essential for leveraging technological advancements (Pingali et al., 2023; Pirola et al., 2023; Chen et al., 2024). In parallel, financial readiness is crucial in determining an organisation's capacity to invest in technology and the development of its workforce (Mittal et al., 2018; Holopainen et al., 2022).

Beyond the above-mentioned determinants, integrating technology into operations enhances transparency, streamlines workflows, and facilitates seamless information sharing, fostering digital supply chain integration (Boute et al., 2022; Oke et al., 2024). In contrast, effective supply chain integration further strengthens DT readiness by ensuring smooth data exchange and alignment between processes, technology, and strategy (Kroh et al., 2024; Oke et al., 2024). Moreover, a skilled workforce and strong technological infrastructure are essential for fostering digital operational procedures, enabling agile decision-making, and demonstrating the tangible benefits of DT to leadership (Holopainen et al., 2022; Oke et al., 2024). Most importantly, a well-defined digital strategy provides direction, ensuring a coordinated approach to transformation and overcoming implementation barriers (Pirola et al., 2020; Halpern et al., 2021; Oke et al., 2024).

All the resources mentioned above are driven by the key element of change valence, known as leadership commitment. Strong leadership is crucial for setting strategic direction, fostering commitment, and translating it into actionable initiatives (Holopainen et al., 2022; Oke et al., 2024). Leaders with digital awareness and skills can align technology investments with business objectives, ensuring effective resource allocation (Kosmol et al., 2019; Holopainen et al., 2022).

Finally, digital cultural readiness is a key yet challenging factor, influencing and being influenced by other DT components (Lokuge et al., 2019). A culture that embraces technological change accelerates DT, while resistance hinders adoption (Sivaraman, 2020; Holopainen et al., 2022; Kroh et al., 2024). Similarly, a collaborative culture strengthens supply chain integration, whereas a lack of collaboration undermines DT efforts (Singh et al., 2021).

In summary, the dynamism among these determinants creates a holistic ecosystem where each component reinforces the others, amplifying their collective impact on digital readiness (see Figure 5). Understanding these dynamic interconnections helps

organisations prioritise their efforts and ensure a comprehensive and balanced approach to DT that maximises the benefits of each determinant of readiness.



Figure 5. Dynamism among determinants measuring DT readiness

(Source: Author's own work)

CONCLUSION

This study explores the role and significance of digital readiness factors, emphasising their catalytic function in DT. It contributes to enhancing knowledge both theoretically and practically. Theoretically, it advances DT readiness by offering a systematic evaluation methodology, emphasising key readiness dimensions, and introducing a framework for resource alignment. Practically, it provides actionable insights through the "House of DT Readiness" framework, which integrates eight dimensions to help organisations assess their readiness, identify gaps, and develop targeted DT strategies. The results clearly address both research questions.

Despite its significant contributions, this study acknowledges certain limitations. It does not include readiness models designed for individual companies. While the proposed model is broadly applicable, sector-specific adaptations may be required. Nevertheless, the model's adaptability allows companies of various sizes and industries to assess readiness across multiple dimensions, facilitating the development of targeted strategies to accelerate DT efforts effectively.

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Sustainable Integrated Warehouse and Construction Planning: A Scenario-Based Approach with Application Control

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1. Introduction

The planning of warehouses and their structural implementation is an important part of modern logistics processes. Storage and picking systems have a decisive influence on the efficiency and effectiveness of material flows and other logistics activities, making them an important contribution, if not a potential competitive advantage. As these systems account for a large proportion of logistics costs, it is crucial to design them in a comprehensive and precise way during the planning phase (Ramprecht, 2020). In addition to warehouse planning, construction planning also plays a key role, as the building has a considerable influence on the cost-effectiveness and sustainability of the overall system (Möller, 2007). Linking the two planning areas makes it possible to take into account the mutual dependencies and thus achieve a more efficient and sustainable design.

Despite the advancement of digitisation, in practice, the planning of warehouses is often still carried out in separate processes, some of which are handled analogously. This applies to some cases of unrestricted development of new warehouses, as well as most cases with strict constraints, like a fixed plot size, or even preexisting buildings. This in turn leads to time-consuming workflows and makes it difficult to coordinate construction and warehouse planning. A procedure that integrates both planning areas offers a promising approach here. It could not only considerably shorten the planning time, but also provide a sound basis for decision-making by evaluating technical, economic and ecological criteria in various scenarios.

In order to meet these requirements a process was deduced, which was further implemented and validated in form of a software prototype, that integratively maps the entire planning process for warehouses - from the warehouse structure to the building infrastructure. The resulting application enables the planning of storage racks, load carriers, storage units, transport systems and picking systems as well as external walls, foundations and floor slabs. Relevant planning data is stored and automated calculations deliver precise results that also meet ecological requirements.

A key advantage of the software is its efficient information processing: well-founded planning decisions can be made with a small amount of input data. During warehouse planning, the application provides estimates of storage space requirements, shelf dimensions, required floor space and the costs of the warehouse equipment. Material requirements, material costs and CO₂-equivalent emissions are then determined during construction planning. The step-by-step, scenario-based analysis allows different alternatives to be evaluated quickly and gives planners the opportunity to flexibly adapt interim results. Scenarios here are initially defined as a weighting between the dimensions investment costs, degree of automation and ecological sustainability along the scale 0 (not considered) to 4 (highly prioritised). Any concrete factors can then be tweaked during the process, creating a new scenario.

The method, including its implemented prototype, presented here is an innovative tool that supports planners in linking warehouse and construction planning. It helps planners to gain an impression of the possibilities in a short space of time and to accelerate decision-making processes, improve planning quality and thus design sustainable logistics facilities.

2. State of the Art Storage Planning

The planning of a warehouse should always be process-oriented (TUP, 2020), as it helps to improve the planning process (Becker/Kugeler/Rosemann, 2012). Organisational theory distinguishes between organisational structure and process organisation. The organisational structure divides the overall task into subtasks. These subtasks must then be structured and coordinated to be able to get combined (Becker/Kugeler/Rosemann, 2012). The organisational structure is represented in warehouse planning within the conventional approaches with the help of phase models. An example of a planning model within logistics planning is the Gudehus model. Gudehus' planning model consists of six planning phases. The planning phases are processed iteratively to improve coordination during planning (Gudehus, 2012).

Due to the advancing digitisation and the increasing complexity in warehouse planning (Bendixen & Kemmler, 1971), new approaches to planning have emerged. These approaches pursue the goal of digitising and expanding conventional approaches, as well as relieving the planner with supporting software. The PInLog research project of the IFT at the University of Stuttgart is one such approach (Intralogistik BW, 2010). It aims to use software to optimally plan, test and implement the logistical tasks within an intralogistics system, taking into account various parameters and the resulting variants. For this purpose, 90 standardised basic systems were created, which contain the links between logistical processes, resources used, organisational procedures, calculation algorithms and the required input data. These basic systems are meaningfully linked with each other, dimensioned and evaluated. This allows planning processes to be computer-aided, cross-functional and objectively planned (Intralogistik BW, 2010). Another example and research project is DEPIAS (Yousefifar, 2014). DEPIAS stands for the decentralised, self-organised rough-cut planning of intralogistics systems with the help of a software agent system. In DEPIAS, logistics systems are understood as adaptive systems. The units in the system are referred to as intelligent planning objects and can interact with each other (Yousefifar, 2014). In order to create a comprehensible system, the interactions of the planning objects are subject to certain rules. The systems are selected and dimensioned through composition, configuration and adaptation (Yousefifar, 2014).

Construction Planning

Construction planning is a separate planning area and is divided into object planning and project planning. While object planning focuses on the object to be planned, project planning is responsible for providing the necessary planning framework and the planning procedure in the form of methods, tools and forms of organisation (Von Both, 2006). These two areas are separated from each other in terms of planning methods, although they are closely interrelated. Coordination of the areas is necessary despite their separation (Von Both, 2006). Construction planning is tied to social, political and technical framework conditions. With the increasing opening and globalisation of markets, the demands on project management are also increasing. Projects must be carried out efficiently and in a shorter time frame (Von Both, 2006). The resulting idea of increasing the division of labour has now reached such a high level that it can be assumed that effectiveness is at risk (Von Both, 2006). Planning models are also used to structure the planning process in the field of construction planning. Von Both's planning model or the HOAI can be cited here as examples. Von Both's planning model consists of four phases (Von Both, 2006), while the HOAI consists of nine so-called service phases.

The aforementioned digitisation and increasing complexity also has an impact on construction planning. The digitisation of work processes holds great potential to support planning (Rothenbusch & Kauffeld, 2020). This potential should be exploited by using software applications as digital tools and simplifying the planning process (Rothenbusch & Kauffeld, 2020). One method developed for this purpose is Building Information Modelling (BIM). BIM is an advanced method for digitally managing building information over the entire life cycle of a building (Eastman et al., 2018). It acts as a central database in which building components are stored as parametric, intelligent objects with geometric and planning-relevant data (Stange, 2020).

3. Methodology

The development of a software prototype for linked construction and warehouse planning, taking sustainability aspects into consideration was systematically divided into three central work steps. This structured approach enables clear objectives to be set and ensures that all relevant requirements and challenges are comprehensively taken into account.

At the beginning of the project, a detailed requirements analysis was carried out, which served as the foundation for the subsequent reference model. This analysis was based on two main sources: First, insights were gained from expert interviews with specialists in logistics, construction planning and architecture, who have extensive experience in the construction of production halls. Second, current scientific standards and best practices were reviewed.

The statements made by the interview partners helped to precisely define the framework conditions and requirements for the approach and resulting software implementation. It became particularly clear that the forthcoming application should be understood as a supporting tool that actively supports the planner in their work, but always giving them the opportunity to intervene and influence or change planning results. A non-visible, fully automated application that performs all tasks independently was considered to make little sense. Instead, great importance was attached to ensuring the transparency of the results and involving the planner in the process.

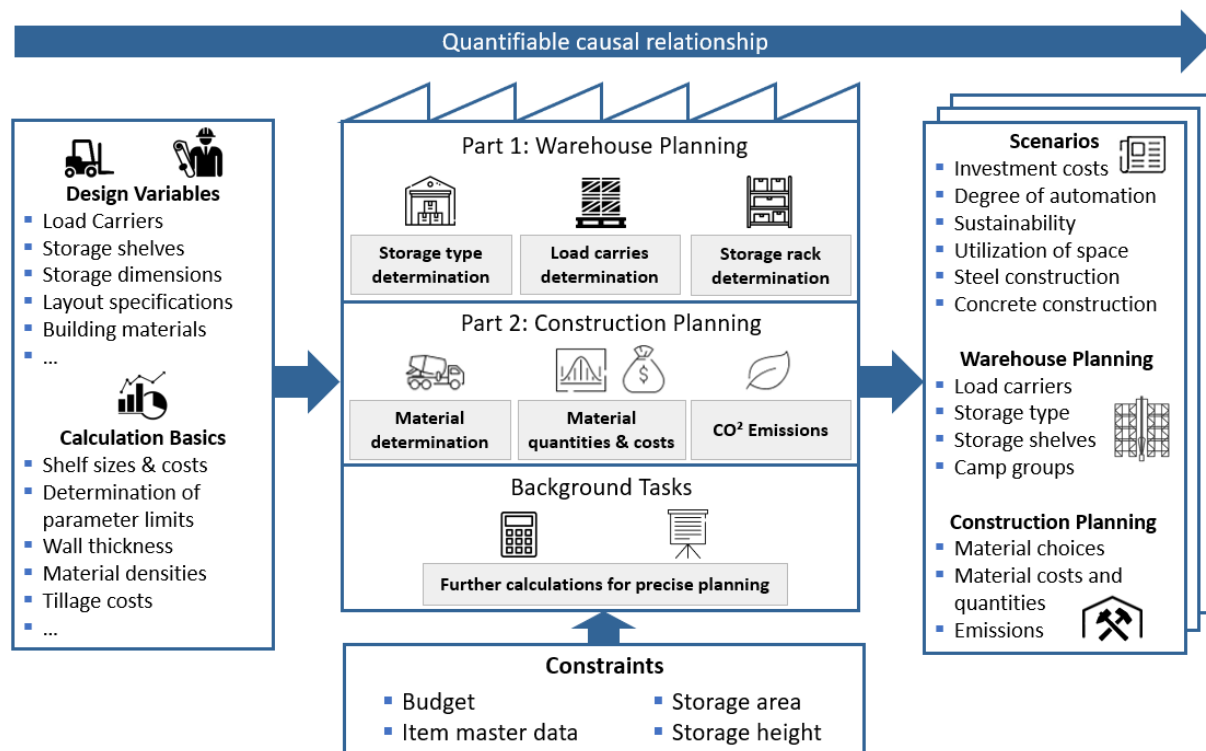


Figure 1: Conceptual representation of software prototype

Another result of the analysis was that the provision of different scenarios is seen as useful. This enables the planner to examine different approaches and make informed decisions instead of having to rely on a single, predetermined solution. The aim of the analysis was to capture the current approach to planning and, based on this, to create a conceptual reference model that takes into account both the specific needs of planners and approaches to promote sustainability.

The conceptual model of the planned application is derived from the requirements and the output presented as relevant. Figure 1 shows the concept created. The core process is symbolically represented in the middle of the application, namely the calculation and

comparison of different planning scenarios. The main tasks are systematically divided into three categories: warehouse planning, construction planning and overarching tasks that affect both planning areas.

The implementation is described in more detail in the following section. The application presents the calculated scenarios and their results transparently so that planners can easily compare different alternatives and make the most suitable decision for their objectives. The validation of the prototype is carried out in the final step shows that the application provides a sound basis for the planning of storage and construction projects, taking into account technical, economic and environmental aspects. The results of the validation are also described in more detail in the following section.

4. Development and Implementation

At the beginning, basic constraints and information must be gathered in order to carry out the calculations and decision-making processes. These include the item master data in a specific form, which describes the goods to be stored, the budget specifications, which define the financial framework conditions, as well as the dimensions of the available storage space, which represent physical restrictions. These inputs have a decisive influence on the calculation of the gross storage area, as, for example, higher buildings lead to a lower floor space requirement. In addition, further calculation bases must be provided in order to be able to compare different scenarios quantitatively. These calculation bases include the costs and sizes of the storage shelves, the number of storage compartments, the building material information and the parameter limits for the decision-making processes. An example for such limits is the number of storage locations up to which selected rack types can be used. This information is crucial for the use of so-called morphological boxes, which help with the selection of suitable storage racks, load carriers and layout specifications. On a side note, it was found that the use of excel sheets is very widespread throughout the industry, and as such various data points are parsable from such.

After entering the various parameters, variables and target values, the prototype is able to calculate a variety of scenarios. These scenarios provide standardised output information that includes both storage-related and construction-related results. In order to analyse different planning approaches, certain evaluation criteria are used, the weighting of which can be adjusted by the planner. Investment costs in particular are a central criterion on the basis of which scenarios can be compared with each other.

Within warehouse planning, the scenarios vary according to the weighting of these criteria. In the area of construction planning, both a concrete construction variant and a steel construction variant are determined for each of the five warehouse planning scenarios. This results in a total of ten different scenarios, which serve as a basis for the planner's decision.

The application is able to determine the appropriate load carrier for a good and its corresponding storage rack. To do this, the application includes storage type decisions and divides the stored goods into different storage groups. This determines the picking and transportation system for each of the identified storage groups. Finally, information for the possible construction of the previously planned logistics system is calculated and displayed. This includes material requirements, costs and the expected emissions in CO₂ equivalent. The results of all calculations can be viewed and adjusted if necessary.

When determining the load carrier, it is checked whether a good fit in or on a load carrier, is not too heavy, and takes into account a sensible distribution of the available articles. Furthermore, the goods must not be too small or too light for a load carrier that is not closed. Before the appropriate storage rack is determined, a decision-making process for the storage type is carried out. This involves checking whether storage in a rack is possible or whether floor storage is required.

Figure 2: Morphological box of a storage rack related decision-making process

Load carrier	Pallet			Grid box	
	Pallet rack Drive-through rack Pallet drive-through rack Cantilever rack Automated pallet rack Automated flow rack Satellite shelf			Pallet rack Drive-through rack Pallet drive-through rack Cantilever rack Automated pallet rack Automated flow rack Satellite shelf	
Stock quantity	Very low (≤150 pieces)	Low (151-300 pieces)	Medium (301-750 pieces)	High (751-4000 pieces)	Very high (>4000 pieces)
	Pallet rack Cantilever rack	Pallet rack Cantilever rack Drive-through rack	Pallet rack Cantilever rack Drive-through rack Pallet drive-through rack	Pallet rack Cantilever rack Drive-through rack Pallet drive-through rack Automated pallet rack Automated flow rack Satellite shelf	Automated pallet rack Automated flow rack Satellite shelf
Access frequency	Very rare	Rare	Medium	Frequently	Very Frequently
	Pallet rack Cantilever rack	Pallet rack Cantilever rack Drive-through racking Pallet flow rack	Pallet rack Cantilever rack Drive-through rack Pallet drive-through rack	Pallet rack Cantilever rack Drive-through rack Pallet drive-through rack Automated pallet rack Automated flow rack Satellite shelf	Automated pallet rack Automated flow rack Satellite shelf

The storage type and storage rack related decision-making processes are carried out by going through different morphological boxes. One is shown in Figure 2. The required morphological boxes are available for containers and small parts containers, pallets and grid boxes as well as load carrier-free storage. First, the system checks which load carrier is used to store an item. The possible shelves are then limited to the shelves marked in blue for the corresponding load carrier. In a second step, the storage quantity is queried and the possible racks marked in blue depending on the selection are compared with the existing racks. Shelves that are marked as possible in both queries are retained, the others are removed. In the same way, the access frequency is queried in a final step and a list of possible shelves is created. Depending on the scenario, the shelves on the list are compared and selected using a utility value analysis based on the comparison criteria.

The subsequent allocation of the stored goods to the various storage groups is carried out based on the storage rack and the required storage compartment height. If necessary, a new storage rack is determined for the different storage groups, as this results in new storage quantities.

The calculations and decision-making processes of the logistics-related data are presented for various scenarios. The scenarios consist of different combinations of possible storage racks in which the evaluation criteria are favoured differently. The prototype creates five scenarios. Three scenarios each favour one of the evaluation criteria and ignore the others. Another scenario is based on the prioritisation of the evaluation criteria specified by the user. The last scenario prioritises all evaluation criteria equally.

The fixed costs of the warehouse, the required storage space, and the number of storage compartments are calculated for each scenario. In addition, calculations for the construction are carried out and saved in two versions. For the various scenarios, only the specified maximum storage height is strictly adhered to, but not the budget. Under certain

circumstances, the storage area can also be slightly higher than the available building area. This gives the user the option, if there is a certain amount of leeway, to consider other scenarios as a possibility despite a higher investment or too large storage area.

The prototypes construction planning provides the material, quantity, costs and associated emissions for the logistics systems planned within the first steps. The construction material can be selected to some extent. The required concrete and steel classes are determined and specified. The user can cache the calculated or manually adapted solutions during the storage rack calculation. This means that on the one hand different solution approaches can be saved and contribute to the design of the final solution, and on the other that no solution has to be discarded and the final decision can be made retrospectively.

5. Validation

The validation of the developed software prototype was carried out with the aim of comprehensively testing its functionality and practical benefits in the area of warehouse and construction planning. In order to achieve realistic results, real article master data from a current warehouse planning project was used. Both the functionality of the prototype and its potential were evaluated in comparison to conventional planning methods. An excel sheet adhering to the previously mentioned format was used as data source. Users are provided with a template and a detailed explanation on the start page. Two different Excel files were created for the tests: one without an expansion factor and one with an expansion factor of 1.6, based on a planned expansion of the warehouse by 60%. These two scenarios made it possible to test the software under different conditions and compare the results.

In the first test, without an expansion factor, scenarios with 16 to 20 storage groups were created to accommodate 16,813 storage locations. Refrigerated and hazardous goods were grouped separately. The calculated areas showed an average deviation of 13.22% compared to the existing warehouse, with a maximum deviation of 22.04%. Costs for most scenarios were around €2.5 million, with highly automated and sustainable scenarios reaching up to €5.7 million. Regarding emissions, for the first test series without expansion factors, the emission values for construction materials in the concrete and steel construction scenarios were approximately 115 t and 110 t of CO₂ equivalent, respectively. The emissions for steel construction were slightly lower, indicating minimal variation between the two methods.

The second test, which incorporated an expansion factor, accounted for 27,164 storage locations. In this series, the average deviation of the calculated area increased to 19.85%, reflecting the non-linear relationship between storage quantity and floor area expansion. This non-linearity influenced other factors as well, including emissions. Steel construction emissions ranged between 840 t and 900 t of CO₂ equivalent, while concrete construction emissions rose to around 1,140 t. These results suggest that the relationship between storage quantity and building size is not linear, a finding consistent with earlier assumptions regarding floor area expansion. The distortion observed in the emissions was significantly more pronounced in concrete construction. The cost calculation in this series also revealed changes: scenarios with higher automation achieved cost savings through the use of more efficient rack types.

6. Discussion

The prototype developed represents a significant advance in integrated warehouse and construction planning, in particular by enabling creation, comparison and evaluation of different scenarios. It provides useful support for planners by promoting the transparency of calculations and making the planning of logistics systems more efficient. Nevertheless, there are some aspects that limit the functionality and applicability of the software and show potential for improvement.

A key area for future development of the prototype is the expansion of the available components and planning options in order to increase flexibility and adaptability. Currently, every calculation is based on a predefined layout which structures all halls in equally. This limits individual design and restricts planners from taking specific requirements into account. Greater flexibility in layout selection and adaptation would be desirable to ensure wider applicability. At the same time, it is clear that the selection and customisation of components is limited, which means that potential benefits in terms of cost and sustainability cannot be fully exploited. For example, the roof is only included in the calculations as an estimate, without specific optimisations or variants that could have a positive impact on overall costs or the carbon footprint. There is also a lack of consideration of innovative building concepts, such as double-story construction, which can have a significant impact on planning, for example through more efficient use of space and modified structural requirements. As the prototype is currently unable to simulate such scenarios or determine suitable data sets, structural flexibility remains limited. Further development of the software, which allows a more individual design of the hall structure and the integration of more diverse components, would both expand the application's possible uses and significantly improve the exploitation of potential benefits in terms of costs and sustainability.

Another aspect concerns the preparation of article master data. Although a conscious effort was made to minimise the amount of input data required, this step remains time-consuming and could be a hurdle for users. The integration of tools or algorithms for automated data preparation could bring a significant improvement here and increase the acceptance of the application.

Although the calculations and analyses of the transport systems provide initial useful estimates of operating capacity, they are not sufficient to complete a full planning process. There is a considerable amount of work between rough planning and detailed planning, which has not yet been covered by the software. A link to more detailed planning modules could simplify this process and optimise the transition between the planning phases.

Despite these limitations, the application provides a solid basis for integrated warehouse and construction planning. The ability to create different scenarios and the transparent presentation of the results are clear strengths. For the future, however, it would make sense to expand the functionalities in order to extend the structural development, to open up additional sustainability and cost benefits and to offer even more precise support for planners.

7. Conclusion

The software application demonstrates that automated planning systems combining the planning areas of warehouse planning and construction planning provide valuable support for the planning process. The planner is able to check all results step by step, adapt them and combine different scenarios. This flexibility allows the planner to remain in control and make well-founded decisions. The software therefore not only offers a quick initial assessment, but also promotes a transparent and efficient planning process by providing several scenarios and ecological comparison values. Particularly noteworthy is the possibility of estimating the imminent emissions of the logistics system being created and influencing them during the planning stage.

Overall, the prototype enables significantly faster rough planning and creates a solid basis for completing the entire planning process. It combines logistical and structural aspects in an innovative way and helps to make warehouse and construction planning not only more efficient, but also more sustainable.

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SUPPLY CHAIN ANALYTICS

Benchmarking Large Language Models for Reputational Risk Assessment in Supply Chains: A Case Study

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Abstract

Risk management is essential for maintaining efficient supply chain operations amid uncertainties, as disruptions can lead to severe financial and operational consequences. While traditional supply chain risk management (SCRM) strategies focus on mitigating operational risks, reputational risk remains an overlooked yet critical factor influencing supply chain resilience. Recent advancements in machine learning (ML) and large language models (LLMs) have significantly improved risk identification, inventory management, and supply chain transparency. Studies have demonstrated the effectiveness of models such as GPT-4, GPT-3.5-Turbo, and fine-tuned RoBERTa in analysing supply chain risks using prompt engineering and retrieval-augmented generation (RAG). However, existing ML studies lack a dedicated focus on reputational risk in supply chains, particularly in real-time news article analysis.

Additionally, there is no systematic benchmarking of different LLMs in SCRM applications under identical conditions. Moreover, emerging LLMs such as DeepSeek and LLaMA3-70B remain underexplored in SCRM contexts, especially considering the rapid advancements in the field and the recent emergence of highly capable open models. This study addresses these gaps by exploring an LLM-driven framework for reputational risk assessment using news article analysis and conducting the first comparative evaluation of multiple LLMs for supply chain risk detection. The findings aim to enhance AI-driven risk management strategies and provide insights into the effectiveness of LLMs in improving supply chain resilience. Moreover, this study establishes a foundation for future research by systematically evaluating LLMs for reputational risk assessment in supply chains, providing researchers with a clear starting point for exploring different LLMs in risk management research.

Introduction

Risk management is crucial for efficiently operating supply chains amid uncertainties, as disruptions can have severe financial and operational consequences. Over the years, researchers have contributed to SCRM by defining, implementing, and mitigating risks (Ghadge et al., 2012). The importance of effective risk management is evident in major supply chain disruptions, such as Ericsson's \$400 million loss in 2000 due to a fire at a Phillips semiconductor plant, Toyota's production decline of 40,000 vehicles per day following the 2011 Japan earthquake and tsunami, and the 2011 Thailand floods, which disrupted both computer and automotive supply chains (Ho et al., 2015). In supply chain management, professionals address various risks that could disrupt supplies. Therefore, recognising and managing this risk is essential (Lemke et al., 2013). ML enhances SCRM by identifying high-risk suppliers, predicting delays, and enabling proactive risk mitigation (Rezki & Mansouri, 2024). Recent advancements in LLMs have significantly contributed to SCRM by enhancing risk identification, inventory management, transparency, and optimisation. Studies show that models such as GPT-4, GPT-3.5-Turbo, Gemini, and fine-tuned RoBERTa have been applied using prompt engineering and retrieval-augmented generation (RAG) to improve decision-making and risk assessment. LLMs demonstrate strong capabilities in event impact analysis, supply chain transparency, and automating risk detection from large-scale textual data. However, recent studies have explored LLM applications in SCRM, including inventory optimisation, supply chain transparency, and risk assessment, yet significant research gaps remain. One key gap is the lack of studies on reputational risk in supply chains using LLMs. Existing literature mainly addresses operational risks, while reputational risk, a crucial factor in supply chain resilience, remains

underexplored, particularly in real-time news analysis. Given digital media's growing impact on corporate reputation, an LLM-driven framework for identifying reputational risks is needed. Additionally, no systematic comparison of different LLMs in SCM applications exists. While individual models like GPT-4 have been studied, there has been no benchmarking study evaluating multiple LLMs under identical conditions. Since different architectures vary in reasoning, factual accuracy, and text comprehension, a comparative study is essential to assess their effectiveness in SCM-related risk detection. Another gap is the lack of studies incorporating newer LLMs, such as DeepSeek, LLaMA3-3-70B, and GPT-4o Mini, into supply chain risk management. Existing research mainly focuses on mainstream models, without evaluating emerging LLMs that may offer improved efficiency, accuracy, and contextual reasoning. As LLM technology advances, assessing these models' performance in real-world reputation risk detection using news article analysis is crucial. This study addresses these gaps by applying LLMs specifically for reputational risk assessment in supply chains, leveraging news article analysis as a primary data source. It also provides the first comparative evaluation of DeepSeek, LLaMA3-3-70B, and GPT-4o Mini in this domain, offering a systematic benchmarking framework. By evaluating multiple LLMs under controlled conditions, this study aims to provide insights into their applicability for supply chain reputation risk detection, contributing to AI-driven risk management strategies in SCM.

Reputational Risks

Since the mid-1980s, senior managers have recognised corporate reputation as a key driver of competitive advantage. Academic literature highlights its role in financial performance, purchasing decisions, product/service quality, and stakeholder loyalty. A strong reputation provides competitive inimitability (Nakra et al., 2000). Scholars emphasise that reputation is shaped by all business units and employees in their interactions with stakeholders (Post & Griffin, 1997; Nakra et al., 2000).

Reputational risks arise from internal or external events that negatively impact stakeholder perceptions. These risks stem from economic, social, or environmental factors affecting firms or their supply chains (Roehrich et al., 2014; Hoejmose et al., 2014; Lemke et al., 2018). Managing reputation is particularly crucial in supply chains, where Fombrun et al. outline three core elements: it is perception-based, collectively shaped by stakeholders, and inherently comparative (Lemke et al., 2011; Fombrun et al., 1996; Lemke et al., 2018). Reputation is formed through direct experiences, asset management, and communications (Lemke et al., 2018; Reese & Kossovsky, 2011). Supply chain reputation is complex, influenced by corporate actions and industry affiliations, leading to reputational spillovers. Manufacturers and distributors typically own their reputation, while suppliers borrow it through associations. Failures in social responsibility, such as unethical sourcing, affect all participants, with companies closer to consumers facing greater exposure. To mitigate risks, firms adopt corporate social responsibility (CSR) frameworks, including ethical sourcing, supplier codes of conduct, or vertical integration of compliant partners. Proactive reputation management and CSR practices are essential for risk mitigation and long-term legitimacy (Lemke et al., 2013). Effective risk management in supply chains is driven by organizational image, liability, employee safety, cost reduction, regulatory compliance, and customer relations (Kleindorfer et al., 2005; Mandal, 2011). Risk mitigation strategies include postponement, speculation, hedging, security, and avoidance (Mandal, 2011).

Large Language Models in SCRM

Accurate prediction of availability dates is critical for logistics operations and risk mitigation. ML techniques help identify high-risk suppliers, anticipate delays, and take proactive measures to minimise disruptions in supply chain (SC) performance (Rezki and Mansouri, 2024). ML enhances SCRM by predicting risks, identifying anomalies, and leveraging historical data insights. Despite its potential, ML remains underutilised in SCRM due to a lack of guidelines, limited researcher familiarity, and a gap between management-focused SCRM and engineering-centric ML, complicating effective integration (Yang et al., 2023). Various ML techniques address SCRM challenges, with recent advances positioning LLMs as a strong tool in domains like customer satisfaction and risk management.

Srivastava et al. examine BERT-based models in supply chain management (SCM), synthesising 33 peer-reviewed articles and 3,421 social media documents to identify key themes: supply chain optimisation, risk management, knowledge management, and contract intelligence. Their study provides a structured framework for managers to leverage LLMs in SCM (Srivastava et al., 2024). Jannelli et al. explore LLM-powered autonomous agents for consensus-seeking in SCM, reducing reliance on manual coordination. Their modular LLM-based frameworks facilitate negotiation, reasoning, and planning, outperforming traditional tool-based approaches (Jannelli et al., 2024). Similarly, InvAgent, an LLM-powered multi-agent system, addresses inventory management challenges by leveraging zero-shot learning and Chain-of-Thought reasoning, demonstrating improved adaptability compared to heuristic models (Quan and Liu, 2024). Shahsavari et al. introduce CERIA, integrating LLMs and Bayesian Networks to quantify supply chain risks. By analysing news articles and assigning risk likelihood scores, the framework enhances real-time risk intelligence (Shahsavari et al., 2024). Jin et al. propose a Supply Chain Knowledge Graph Mining System using LLM-based Named Entity Recognition and Relation Extraction to improve SC transparency, identifying over 20,000 companies and 9,000 relationships (Jin et al., 2024). Zhu et al. integrate RAG with LLMs to optimise supply chain operations, improving demand forecasting, inventory management, and supplier risk assessment through multi-hop querying and chunk optimisation (Zhu and Vuppalaipati, 2024). Zhao et al. present LARDSC, a software prototype integrating LLMs with Neo4j for risk assessment and visualisation, effectively identifying 73 potential risks from 61 suppliers across 676 news articles (Zhao et al., 2024). Shahsavari et al. developed the LUEI framework to detect supply chain risk events from news sources without pre-labelled data. Using SBERT embeddings and Bayesian Networks, the framework achieves superior accuracy (98.31%), precision (93.75%), and recall (88.23%) compared to traditional event detection models (Shahsavari et al., 2024). Li et al. introduce OptiGuide, leveraging GPT-4 and combinatorial optimisation to improve SC decision-making transparency through in-context learning rather than fine-tuning (Li et al., 2023). Cheng et al. propose SHIELD, integrating LLMs with domain expertise to enhance risk assessment in the EV battery supply chain. Using schema learning, event detection, and Graph Convolutional Networks, the system outperforms baseline models in disruption prediction (Cheng et al., 2024). In conclusion, different LLMs apply varied methodologies across supply chain domains. Zero-shot prompting and prompt engineering are frequently used for real-time decision-making, while fine-tuned models like RoBERTa enhance predictive accuracy. The use of RAG further highlights the shift toward context-aware LLMs that integrate structured knowledge sources. Future research should explore how hybrid approaches, such as combining fine-tuning with RAG, can further improve LLM performance in supply chain optimisation and risk management.

Research Work

This study compares the effectiveness of three LLMs, DeepSeek, LLaMA, and OpenAI's GPT, in detecting reputational risks from news articles. DeepSeek and LLaMA were deployed on Finland's Puhti supercomputer, while OpenAI's model was accessed via API, reflecting different computational constraints in analysing news articles and identifying supply chain risks. The models processed text using an instruction-based prompt, extracting and prioritising relevant risks. The overall process involved preparing the data, structuring inputs, running the models, and extracting structured risk insights. To optimise performance, computational resources were efficiently managed, ensuring accurate and reliable outputs. The inference pipeline involved preprocessing, structured input formatting, GPU-based execution, and structured risk extraction, accompanied by the following prompt, where the company name is adjusted accordingly:

"You are provided with a piece of news. Carefully read and analyse it to identify any reputational risks related to the Zalando company, with a particular focus on supply chain-related risks. If you find risks, summarise them, indicate the priority of the risks (e.g., High, Medium, Low), and suggest specific actions needed to mitigate them. Ensure the response is structured clearly and concisely."

OpenAI's GPT-4o-mini was deployed via API-based inference, using the same prompt. To ensure diverse evaluation, companies were selected based on news frequency: Nokia (telecommunications), Zalando (fashion retail), and Pfizer (pharmaceuticals), mentioned 33,231, 1,074, and 35,005 times in 2023, respectively. Risk categorisation was based on Lemke et al. (2013), with additional categories such as Cybersecurity & Data Breach Risks and Financial Risks added to address gaps in the original framework. Thereby, our study provides a structured benchmarking approach to evaluate LLMs in supply chain reputational risk detection.

Table 1. Reputational risk factors in the Supply chain (Lemke et al., 2013)

Reputational Risk Type	Supply Chain Risk Category
Corporate Image Risk	Regulatory, Legal, Compliance, Financial Risks
Risks Product/Service Class Risk	Operational, Quality Control, Cybersecurity & Data Breach Risks
Risks Country of Origin Risk Supplier	Ethical, Political & Geopolitical Sourcing Risks
Brand Users' Image Risk	Consumer & Demand Risks
Corporate Culture Risk	Governance, Labor Law Risks
Brand Image Risk	Environmental & Market Competition Risks
Experience Risk	Logistics, Customer Satisfaction Risks

We analysed 60 news articles from 2023, with 20 articles selected for each of the three companies, Nokia, Zalando, and Pfizer, based on industry sector and frequency of occurrence in the dataset. All three annotators independently labelled each of the 60 articles using one of three possible options: *YES*, *NO*, or *CANNOT ESTABLISH*. The dataset was annotated to evaluate three models in identifying risk categories. To ensure consistency, annotation rules were discussed beforehand. Three annotators independently labelled the data based on predefined risk categories, and disagreements were analysed to assess model reliability. This setup systematically evaluates how well models recognise reputational supply chain risks. For example, one news article discusses claims by cardiologists Dr. Aseem Malhotra and Dr. Chris Neil regarding potential cardiovascular risks linked to the Pfizer mRNA COVID-19 vaccine. They suggest the vaccine may accelerate coronary inflammation, potentially leading to severe cardiac events, including the sudden death of Australian cricket legend Shane Warne. Dr. Malhotra calls for its suspension, citing substantial cardiac risk evidence. Table 3 summarises the identified risks, their priority levels, and recommended mitigation actions generated by the models.

Table 2. Identified Risks from Multi-Model Analysis of Pfizer mRNA Vaccine-Related News.

Deepseek	GPT4o-mini	Llama3.3
-Damaged public trust -Decreased sales -Legal implications	-Adverse Effects Allegations -Public Perception and Trust -Regulatory Scrutiny -Supply Chain Disruptions -Legal Risks	-Association of Pfizer's COVID mRNA vaccine with cardiac effects -Calls for suspension of the vaccine -Allegations of excess deaths -Supply chain integrity and safety

Results and Analysis

This study aims to evaluate the performance of GPT-4o Mini, DeepSeek, and Llama 3.3 70B in analysing news articles related to Nokia, Zalando, and Pfizer. The evaluation focuses on the accuracy and coherence of model-generated risk analysis and the validity of manual annotations assessing these outputs. The number of identified risks varies across models and companies. Llama consistently detects the most risks, averaging 3.60 for Zalando, 3.35 for Nokia, and 3.80 for Pfizer, indicating high sensitivity. DeepSeek identifies the

fewest risks, with mean values of 1.85 for Zalando, 2.30 for Nokia, and 2.50 for Pfizer, suggesting a conservative approach. OpenAI's model exhibits high detection rates, averaging 4.15 for Zalando, 3.90 for Nokia, and 4.20 for Pfizer. Standard deviation values highlight prediction variability. Llama's higher deviation, particularly for Zalando (1.20), suggests fluctuating risk identification, while OpenAI's lower deviation, especially for Nokia and Pfizer, indicates more stable results. Minimum and maximum values show DeepSeek occasionally detects zero risks, whereas OpenAI consistently maintains higher minimum values. Both Llama and OpenAI reach a maximum detection threshold of 5 across all companies, while DeepSeek peaks at 3, indicating a more limited range. These findings suggest Llama is highly sensitive, DeepSeek is conservative, and OpenAI balances high detection with consistency. The variations in risk identification highlight differing classification thresholds, impacting model applicability based on required risk tolerance.

The data selection process began with a random selection of 100 news articles, followed by an initial model-based risk prediction. Each article was skimmed and marked as "YES" if the model identified a risk and "NO" if it did not. To ensure a diverse representation of risk types, a final subset of 20 articles was randomly chosen, consisting of 15 "YES" and 5 "NO" cases. This selection strategy was designed to assess the model's ability to detect various types of risks in news articles. Subsequently, to evaluate model performance on the Nokia, Zalando, and Pfizer datasets, three human annotators labelled each sample. The evaluation of the models was computed by measuring accuracy using a structured methodology, involving three labels: YES, NO, and CANNOT ESTABLISH. The "Yes" category indicates that the model successfully identified the correct risk category. "CANNOT Establish" refers to cases where the risk category remains ambiguous or unclear. "No" represents instances where the model failed to accurately classify the risk category, and the ground truth was determined through majority voting between three annotators. If a tie occurred between "YES" and "NO" or included "CANNOT ESTABLISH", the final label was set to "NO". Afterwards, model performance on the Nokia, Zalando, and Pfizer datasets was evaluated based on the average agreement with the majority vote, where "YES" was treated as the positive class to address class imbalance. Accuracy was calculated as the proportion of instances in which the model's prediction matched the majority-labelled ground truth. Accuracy was preferred, as the ground truth was approximated via majority voting rather than an externally validated label set. This approach ensured that the reported metrics reflected inter-annotator agreement and model reliability. The final results, as shown in Table 3, were reported for each model, allowing for a fair performance comparison across datasets.

Table 3. Model performance

	DeepSeek	OpenAI	Llama
Company	Accuracy	Accuracy	Accuracy
Nokia	0.90	0.80	0.95
Zalando	0.75	0.80	0.90
Pfizer	0.95	0.80	0.85

As shown in Table 3, the evaluation, based on the mean majority agreement score, reveals varying performance across models and datasets. Llama-3.3-70B-Instruct demonstrated the highest accuracy for Nokia (0.95) and Zalando (0.90), while DeepSeek-R1-Distill-Llama-70B performed best for Pfizer (0.95), surpassing Llama (0.85) and OpenAI GPT-4o Mini (0.80). While Llama outperformed DeepSeek and OpenAI in certain cases, its

advantage was not consistent across all datasets. DeepSeek showed variability, performing well for Pfizer but lagging in other contexts. OpenAI's model maintained a stable performance but did not exceed Llama or DeepSeek in any dataset. The results indicate that model effectiveness is dataset-dependent, with Llama excelling in some cases and DeepSeek demonstrating higher alignment with human annotations for Pfizer. These findings emphasise the importance of considering domain-specific factors when selecting models for reputational risk assessment.

Discussion

The comparison of the three models reveals distinct differences in summarising and assessing reputational risks. GPT-4o Mini generates the most concise summaries, reducing text by 3,802 characters on average, but often omits critical risk factors and occasionally infers risks not explicitly mentioned. DeepSeek provides a balanced analysis with a 2,118-character reduction and strong risk extraction. Llama 3 70B shows variability, sometimes detailed and other times overly concise, averaging a 3,297-character reduction. While generally aligned with source content, it occasionally fabricates risks or over-interprets minor details. Table 3 highlights that Llama outperforms in risk identification, but OpenAI identifies a broader scope, including financial risks often overlooked by LLaMA and DeepSeek. However, OpenAI's extensive coverage results in potential false positives, sometimes attributing an affiliate's reputational issues to the main company. LLaMA and DeepSeek take a more cautious approach, recognising reputational influence along a spectrum rather than a binary presence or absence. While OpenAI extracts more risks, this does not guarantee higher accuracy. OpenAI occasionally flags irrelevant risks, whereas LLaMA and DeepSeek only assign risks when strong associations exist. DeepSeek's primary limitation is its reliance on explicit company mentions; without them, it fails to detect risks. However, its human-like language generation provides clear justifications for its assessments. In contrast, LLaMA and OpenAI use structured formats that, while organised, lack DeepSeek's natural explanatory flow. Contextual complexity handling varies among models. OpenAI tends to overanalyse when a company is mentioned in passing, leading to excessive inference, particularly in supply chain risks. LLaMA and DeepSeek offer more restrained, contextually appropriate responses. However, OpenAI's detailed analysis is beneficial when the company is the central subject, effectively extracting relevant risks. All three models demonstrate consistency in identifying recurring risks across Zalando-related articles, recognising patterns despite differences in their underlying mechanisms. Future research could integrate industry-specific knowledge to enhance contextual accuracy, improving how models interpret news events within a broader business landscape for more precise risk identification.

Conclusion

This study presents a systematic evaluation of three large language models, OpenAI's GPT-4o Mini, LLaMA 3.3-70B, and DeepSeek-R1-Distill-Llama-70B, for reputational risk identification in supply chains. The findings highlight significant performance differences, with LLaMA demonstrating the highest accuracy and alignment with human annotations across most datasets. DeepSeek, while more conservative in risk identification, performed particularly well for Pfizer-related news, suggesting that model effectiveness varies based on industry-specific contexts. OpenAI's model identified the most risks but exhibited a higher rate of false positives, often inferring risks beyond those explicitly stated. It is important to note that the LLaMA model used in this study was significantly larger than the other models, which may have contributed to its superior performance. Future research could explore similar evaluations using larger OpenAI models or alternative datasets to assess whether the observed trends persist across different model scales and domains. This study also identifies key limitations in current LLM-based risk assessment methods. While all models effectively extracted reputational risks, inconsistencies in contextual interpretation and variability in handling indirect risks highlight the need for further refinements. Future research should investigate hybrid approaches that integrate domain-specific knowledge and fine-tuned models to enhance contextual accuracy. Additionally, an industry-specific risk classification framework may improve the precision of model

predictions. As a next step, this research aims to leverage the best-performing model, LLaMA, to develop a binary reputational risk identification model. This model will classify whether reputational risks are present or absent in a given news article, streamlining automated risk detection for supply chain management. By refining LLM-driven risk classification and incorporating more structured evaluation frameworks, future work will contribute to more robust AI-powered solutions for reputational risk assessment. Additionally, we acknowledge that human annotation may contain errors, which could influence model performance evaluation. The models' effectiveness may also vary when applied to other companies or different news sources, as the dataset used in this study consisted of a relatively small sample of 90 news articles. Moreover, the data selection approach may introduce a bias toward risk-containing articles, potentially inflating the model's apparent effectiveness while limiting insights into false negatives and the model's behaviour on entirely risk-free news. Therefore, future research with larger, balanced, and more diverse datasets may provide further insights into the generalizability and robustness of these models for reputational risk assessment.

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Human Learning in AMR-Assisted Order Picking: An Exploratory Study

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INTRODUCTION

Human learning has been widely studied in production and operations management. Learning curves (LCs), in particular, are commonly used to represent workers' performance improvements through experience or task repetition, especially in manual operations. Since Wright introduced the first LC model in 1936, many other models have been developed to further refine and expand this concept (Glock et al., 2019).

With the rise of Industry 4.0, the integration of collaborative robots (cobots) in workplaces is driving a shift in manual work systems towards human-robot collaboration (HRC). This shift raises critical questions about the allocation of tasks between humans and cobots, with one key consideration being the learning effects on humans, as highlighted by Cohen et al. (2019).

Intralogistics work environments have become a focal point for the implementation of cobots, particularly autonomous mobile robots (AMRs). For instance, Europe dominated the AMR market with a share of 35.32% in 2020 (Fortune Business Insights, 2024). In intralogistics, AMRs are often utilised for order picking (OP) across various human-robot interaction settings. One such is a hybrid OP, where picking tasks are shared between humans and AMRs working independently on the same order (Winkelhaus et al., 2022). In contrast, assisted OP (AOP) involves AMRs directly assisting the human pickers by following them and transporting picked items, enabling pickers to focus exclusively on picking tasks (Grosse, 2024; Koreis et al., 2023; Koreis, 2025; Pasparakis et al., 2023). Compared to manual OP (MOP) in which the human picker must drive an industrial truck while picking items, AOP offers several advantages, including increased performance, reliability, and flexibility (Pugliese et al., 2022). A field study by Koreis et al. (2023) compared AOP with MOP and found that cobot assistance reduced OP time by up to 33.57%.

However, Loske (2022) noted that the impact of new technologies on human learning in OP remains both unpredictable and underexplored. To address this gap, we conducted a study by applying five LC models from the literature to a dataset from a laboratory experiment simulating MOP and AOP. Our study shows that AOP learning is primarily driven by cognitive elements of the task, with little to no motor improvement. Additionally, AOP exhibited fewer variations (likely less human-related variation compared to MOP), resulting in more predictable and structured LCs. These findings offer insights for potential design improvements in the cobot in terms of interaction and feedback, and targeted picker training, which could lead to supporting the cognitive learning component and thereby effective HRC. From a managerial perspective, return on investment calculations often rely on task performance predictions. The speed at which human workers adapt to working with cobots affects how quickly the collaboration becomes profitable. Therefore, incorporating realistic LC estimates informed by real-world observations of cognitive and motor task contributions can be effective for generating more accurate performance projections.

LITERATURE REVIEW

Several studies on learning effects in MOP have been published over the years. Grosse and Glock (2013) conducted an empirical study, collecting data on MOP and fitting it to six different LC models. Their findings indicated that the Wright, De Jong, 03-parameter hyperbolic, and dual-phase LC models effectively captured learning effects, while the Stanford B and time-constant LC models were unsuitable for the dataset. Additionally, they observed that the learning rates (LR) of order pickers in MOP ranged between 84.25% and

97.67%. Grosse and Glock (2015) integrated routing and zoning strategies into Wright's LC model, highlighting the critical role of worker learning in improving OP efficiency. They emphasised the importance of incorporating learning-aware planning models in warehouse operations. Winkelhaus et al. (2018) conducted experiments and found that declarative learning (e.g., acquiring knowledge such as item locations) leads to faster improvements compared to procedural learning (e.g., developing skills to perform tasks) in MOP. They also noted that mental fatigue negatively impacts OP performance, particularly by slowing procedural learning.

Despite the rapid transformation from MOP to HRC in OP systems within Industry 4.0, few studies have empirically examined human learning in such settings. Loske and Klumpp (2020) addressed this gap by comparing LCs between semi-automated OP systems (person-onboard automated storage and retrieval systems [AS/RS] with augmented reality visual guidance) and MOP systems with pick-by-voice headsets. However, their approach avoided fitting a predefined parametric LC and instead derived the LC directly from the data using a nonparametric method. Their data envelopment analysis revealed that automation accelerated LC of the human pickers, resulting in higher initial efficiency and faster progression. In a subsequent study, Loske (2022) extended this work by comparing another semi-automated OP system (person-onboard AS/RS with advanced dynamic storage assistance for grasping and stacking) with MOP using pick-by-voice. Similar to their earlier findings, this study demonstrated that human pickers in semi-automated systems exhibited flatter LCs. The reduced opportunities for learning were attributed to the system handling most of the repetitive, skill-building tasks. Koreis (2025) reported a pilot test in a warehouse, comparing human-robot teams (AOP) and human-manual teams (MOP). They used non-parametric modelling on OP time vs experience measure in days repeated at work. AOP showed strong initial OP time gains, but it plateaued over time and a high variation in performance was noted based on worker interaction methods. In contrast, MOP showed continuous OP time improvement with each additional day of experience. We extend the knowledge on human learning in HRC in OP, in particular, AOP, by fitting five LC models, namely Wright's LC model (WLC), Stanford B model (SBM), De Jong's model (DJM), S-curve model (SCM) and Jaber-Glock LC model (JGLCM) (see Table 1 for details) for predicting performance over time. Additionally, we compared fitting the same LC models on MOP.

The WLC model serves as the base for the other four models. The SBM model includes an additional factor on WLC, to account for the influence of prior experience on the LC (Grosse et al., 2015). Since order pickers are likely to have previous experience with the OP process when they transform from MOP to AOP, it is reasonable to assume that AOP is not entirely without prior experience. Therefore, we incorporated the SBM model in our curve fitting analysis. The DJM model adds a factor 'M', to WLC, representing the degree of automatization of the task, where the proportion of the task time that remains constant (or "incompressible") regardless of learning (Dar-EI, 2000; Grosse et al., 2015). Therefore, lower M values indicating less machine-controlled content (more manual effort) and higher M values indicating more machine-controlled content in a task. Given that the level of automation differs between MOP and AOP, we included the DJM model to evaluate its explanatory power in the data set we have in hand. Additionally, the SCM model, which combines features of both the SBM and DJM models (Grosse et al., 2015), was included to account simultaneously for prior experience and the degree of automatization. Finally, the JGLCM model, derived considering the cognitive-motor components of a task (Jaber and Glock, 2013; Grosse et al., 2015), was incorporated because these components may differ between MOP and AOP due to varying interactions with assistive technology.

METHODOLOGY

In this paper, we fitted the LC models to experimental data provided by Ranasinghe et al. (2025). These LC models were chosen because they measure learning as a reduction in time per task repetition (Grosse et al., 2015), a characteristic that matches the data we received which recorded the time spent in each picking cycle. These data originated from

experiments for both MOP and AOP performed in a model warehouse setting in a university laboratory. The participants representing students and university staff performed OP tasks, using a manually pushed/pulled cart and an AMR in separate trials to transport the picked items. We collected picking cycle time data for five participants, with each participant completing 12 picking cycles for each OP method.

To fit the data to the LC models, we employed the method proposed by Jaber and Glock (2013), which minimises the mean square error (MSE) by optimising the model parameters. In other words, minimising the MSE helps find the best-fitting parameters of the LC. The optimisation was performed using MATLAB R2024b software and its 'fmincon' function. Furthermore, we computed the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) for the fitted curves as measures of fit (Ranasinghe et al., 2016). The optimisation was based on the parameter constraints as listed in Table 1. Additionally, initial values along with the lower and upper bounds for these parameters were provided to the optimiser, based primarily on the literature on empirical LC modelling (see Table 2).

We first fitted each participant's data for each OP method to the five LC models. Next, we calculated an average picking time curve for each of the two OP methods, using data from all five participants and fitted the LC models to these average curves. The results are summarised in Tables 3 and 4.

Table 9 LC models fitted to the data (Grosse et al., 2015)

LC model	Equation	Parameters	
Wright's model (WLC)	$y_x = y_1 \cdot x^{-b}$ $b = \frac{\text{Log}(\phi)}{\text{Log}(2)}$	y_x	Time to complete x^{th} repetition of the task
		y_1	Time to complete the 1 st repetition of the task
		b	Learning exponent (slope of the LC); $1 > b > 0$
		ϕ	Learning rate
Stanford B model (SBM)	$y_x = y_1 \cdot (x + B)^{-b}$	B	Prior experience factor; $B > 0$
De Jong's model (DJM)	$y_x = y_1 \cdot (M + (1 - M) \cdot x^{-b})$	M	Incompressible factor based on the degree of automatization of the task; $1 \geq M \geq 0$
S-curve model (SCM)	$y_x = y_1 \cdot (M + (1 - M) \cdot (x + B)^{-b})$		Same as above
Jaber-Glock LC model (JGLCM)	$y_x = p \cdot y_1 \cdot x^{-b_c} + (1 - p) \cdot y_1 \cdot x^{-b_m}$	p	percentage of splitting y_1 into two components; cognitive and motor; $1 \geq p \geq 0$
		b_c	Learning exponent under pure cognitive conditions; $b_c \geq b_m$
		b_m	Learning exponent under pure motor conditions; $b_m \geq 0$

Table 10 Initial values assumed, the constraints of the parameters used for the optimisation, and relevant empirical references

	Initial value		Range (Lower bound, Upper bound)		References
	MOP	AOP	MOP	AOP*	

b	0.28	0.37	(0,1)	(0,1)	Scale of learning slopes and four classifications by Dar-EI (2000, p. 63)
B	0	12	(0,Infinity)	(12,Infinity)	Since 12 picking cycles were completed in MOP prior to AOP. Dar-EI (2000, p. 37)
M	0.05	0.4	(0,0.25)	(0.5,1)	Recommended values by De Jong (1957) and Dar-EI, 2000, p. 38)
p	0.3	0.7	(0,1)	(0,1)	Results of Jaber and Glock (2013) curve fitting
b_c	9.04	1.23	(0,Infinity)	(0,Infinity)	
b_m	0.15	0.00	(0,1)	(0,1)	

RESULTS AND DISCUSSION

The resulting MSE, AIC, and BIC values are shown in Table 3, with the minimum of these measures for each picker highlighted in bold font. The primary pattern from the results is that AOP consistently exhibits lower MSE values than MOP across all the LC models, indicating a better fit. Similarly, the AIC and BIC scores favour AOP models over MOP. For MOP, the SBM model appears to fit the best, given its consistently lower MSE (observed for three individual pickers and the average curve) and relatively favourable AIC/BIC values. Although WLC outperforms all other LC models in AIC/BIC values for MOP, its higher MSE suggests a poorer fit. Conversely, for AOP, JGLCM model outperforms the other LC models in MSE, achieving the lowest MSE for every picker and the average curve (except for picker 1). This may suggest that AOP learning is more predictable, potentially because automation reduces variability. More structured learning patterns, as indicated by the lower overall MSE compared to MOP, may also imply that automation reduces human-related performance variations, as also highlighted by Ranasinghe et al. (2025). As with MOP, WLC exhibits the lowest AIC/BIC values in all AOP cases but with higher MSE values. A graphical representation of the best fitted LC models to the average curve is given in Figure 1.

Based on the minimum MSE value, the parameter estimates for the corresponding LC model are highlighted in bold font in Table 4. Initial picking cycle time (γ_1) is in the 19–26 seconds range, except some variability among individual picker and method (MOP vs. AOP) and significantly large γ_1 in SBM. Parameter for prior experience, ' B ' values in SBM and SCM vary significantly among the best fitted MOP LC curves. Higher M in AOP (in DJM and SCM) confirms that AMR has a larger contribution to the time which is incompressible (Dar-EI, 2000). In other words, the AMR has replaced the manual pushing and pulling of the cart, that does not improve through human accumulation of experience with time or repetitions.

JGLCM separates the cognitive and motor learning components in AOP. Different b_c and b_m values in best fitted LC models for AOP suggest that cognitive learning is faster than motor learning in order picking. Parameter p in JGLCM, which represents a proportional factor on the initial cycle time between the cognitive and motor components, ranges approximately from 0.13 to 0.48 across all the pickers, the average curve being 0.28. The higher p (0.48) means the initial picking cycle time is more influenced by cognitive processes (e.g., learning how to interact with the AMR, plan picking sequences and locations), while a lower p (0.13) means motor/physical execution plays a bigger role in the initial picking cycle time. Since we used the constraint that $b_c > 1$, as highlighted by Jaber and Glock (2013) (i.e., the cognitive learning processes can have learning rates (i.e., f) faster than 50%), for all the best fit cases of JGLCM, $b_c = 1$. This shows that the person rapidly reduces the cognitive learning time with each OP cycle. Whereas the motor learning exponent (b_m) in all the best fitted cases are close to 0, showing little improvement in physical execution. Picker 3 and 5 shows essentially no motor improvement ($b_m = 0$), thus the respective portion of the time stays constant. In such cases cognitive learning causes the cycle time reduction represented in the LC. This shows that the LC is mostly driven by the cognitive component of the AOP task.

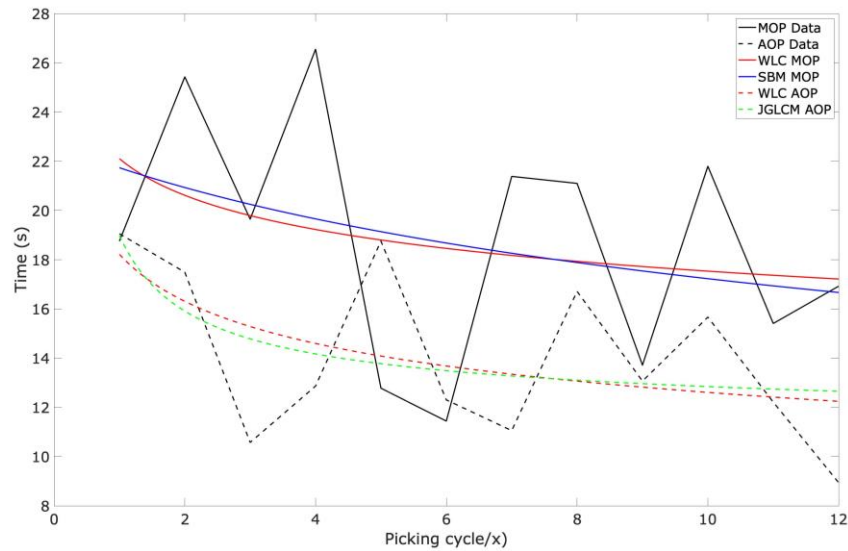


Figure 7 Data vs best fitted LC models for average curve

CONCLUSION

This study contributes to the understanding of human learning in HRC within AOP systems. We modelled the learning process of five participants in simulated MOP and AOP operations using five established learning curve models from the literature: Wright's LC model, Stanford B model, De Jong's model, the S-curve model, and the JGLCM. The JGLCM model provided the best fit for AOP, highlighting a clear separation between cognitive and motor learning components. Notably, the results indicate that cognitive learning drives the performance improvement in AOP and minimal changes in motor performance. These findings have important practical implications for designing and deploying AMR-assisted OP systems that enhance worker performance. They indicate that HRC in such work settings should prioritise improving cognitive interaction and feedback mechanisms, as well as developing targeted training programs to facilitate rapid cognitive adaptation by the worker. Future research should extend these findings by exploring longer-term learning effects and diverse operational contexts in real-world HRC in intralogistics environments.

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Picker No.	MOP														
	WLC			SBM			DJM			SCM			JGLCM		
	MSE	AIC	BIC	MSE	AIC	BIC	MSE	AIC	BIC	MSE	AIC	BIC	MSE	AIC	BIC
1	22,5 570	41,3 925	42,3 624	20,5 468	42,2 724	43,7 272	22,2 558	43,2 312	44,6 860	25,64 21	46,9 308	48,8 705	22,5 570	45,3 925	47,3 322

2	50,7 287	51,1 179	52,0 877	50,7 471	53,1 222	54,5 770	50,7 287	53,1 179	54,5 726	49,5 061	54,8 251	56,7 648	50,7 287	55,1 179	57,0 575
3	89,2 480	57,8 970	58,8 668	88,3 999	59,7 825	61,2 372	88,6 904	59,8 218	61,2 765	130,2 526	66,4 337	68,3 733	89,2 480	61,8 970	63,8 367
4	17,7 319	38,5 044	39,4 742	17,7 403	40,5 101	41,9 648	17,7 319	40,5 044	41,9 591	17,7 177	42,4 948	44,4 344	17,7 319	42,5 044	44,4 440
5	22,3 417	41,2 775	42,2 473	21,8 416	43,0 058	44,4 605	22,2 902	43,2 498	44,7 045	22,49 42	45,3 591	47,2 987	22,3 417	45,2 775	47,2 171
Avg	19,3 378	39,5 447	40,5 146	18,9 840	41,3 232	42,7 779	19,2 341	41,4 802	42,9 349	21,41 17	44,7 673	46,7 069	19,3 378	43,5 447	45,4 844
Picker No.	AOP														
	WLC			SBM			DJM			SCM			JGLCM		
	MSE	AIC	BIC	MSE	AIC	BIC	MSE	AIC	BIC	MSE	AIC	BIC	MSE	AIC	BIC
1	10,7 131	32,4 576	33,4 274	10,2 619	33,9 413	35,3 960	10,2 441	33,9 204	35,3 751	13,54 01	39,2 679	41,2 075	10,7 131	36,4 576	38,3 972
2	9,27 37	30,7 262	31,6 960	9,61 60	33,1 612	34,6 159	9,39 63	32,8 838	34,3 385	11,69 62	37,5 112	39,4 508	9,11 15	34,5 145	36,4 541
3	10,2 354	31,9 102	32,8 800	11,7 289	35,5 446	36,9 993	10,6 472	34,3 835	35,8 383	16,22 22	41,4 365	43,3 762	9,59 98	35,1 409	37,0 806
4	9,51 35	31,0 326	32,0 024	9,58 09	33,1 172	34,5 719	9,56 55	33,0 980	34,5 527	12,43 82	38,2 493	40,1 889	9,48 89	35,0 015	36,9 411
5	10,9 001	32,6 652	33,6 350	11,3 750	35,1 770	36,6 317	11,0 798	34,8 614	36,3 162	12,17 59	37,9 935	39,9 331	10,3 560	36,0 508	37,9 904
Avg	7,49 40	28,1 692	29,1 390	7,87 82	30,7 692	32,2 239	7,62 73	30,3 808	31,8 356	10,39 12	36,0 915	38,0 312	7,34 44	31,9 272	33,8 668

Table 4 Parameter estimates for each picker for LC model

Picker No.	MOP															
	WLC		SBM			DJM			SCM				JGLCM			
	Y1	b	Y1	B	b	Y1	M	b	Y1	M	B	b	Y1	p	bc	bm
1	25,1 898	0,1 051	193,0 410	17,74 83	0,6 969	25,2 630	0,25 00	0,12 23	21,2 003	0,00 00	10,41 30	0,00 00	25,1 898	0,12 00	0,10 51	0,10 51
2	17,3 711	0,0 000	10306, 3358	3983, 9296	0,77 01	17,3 711	0,25 00	0,00 00	14,9 953	0,2 500	2,812 3	1,0 000	17,3 711	0,00 00	0,00 00	0,00 00
3	39,6 646	0,3 374	53,65 15	0,994 4	0,4 629	39,4 251	0,25 00	0,38 29	23,3 452	0,00 00	1030, 7466	0,00 00	39,6 646	0,16 19	0,33 74	0,33 74
4	16,2 184	0,0 000	3422,9 537	1370, 8342	0,74 07	16,2 184	0,24 29	0,00 00	16,0 282	0,0 026	0,000 0	0,8 262	16,2 184	0,13 42	0,00 00	0,00 00
5	16,4 419	0,0 325	154,0 795	36,67 78	0,6 094	16,5 484	0,25 00	0,04 17	15,5 787	0,06 02	0,000 0	0,00 00	16,4 419	0,00 00	0,10 31	0,03 25

Avg	22,1 042	0,1 006	37,33 15	5,933 7	0,2 793	22,0 877	0,25 00	0,11 46	18,7 427	0,00 56	16,78 01	0,00 00	22,1 042	0,00 46	0,10 06	0,10 06
Picke r No.	AOP															
	WLC		SBM			DJM			SCM				JGLCM			
	Y1	b	Y1	B	b	Y1	M	b	Y1	M	B	b	Y1	p	bc	bm
1	19,3 701	0,1 414	275,54 18	20,87 35	0,87 59	18,4 815	0,9 608	1,0 000	15,3 859	1,00 00	13,01 16	0,04 18	19,3 701	0,35 67	0,14 14	0,14 14
2	18,6 988	0,1 388	63,884 7	12,00 00	0,50 32	18,3 083	0,50 00	0,17 69	14,9 186	1,00 00	13,69 64	0,00 00	19,5 100	0,2 711	1,0 000	0,0 291
3	19,7 710	0,2 372	151,91 86	12,00 00	0,83 86	19,1 171	0,50 00	0,30 45	13,5 398	1,00 00	14,33 54	0,00 00	21,1 087	0,4 836	1,0 000	0,0 000
4	17,6 963	0,1 645	186,42 85	17,28 20	0,83 25	17,3 321	0,50 00	0,21 34	13,5 541	1,00 00	13,67 69	0,00 00	18,0 053	0,1 260	1,0 000	0,1 185
5	15,6 742	0,1 199	37,204 3	12,00 00	0,36 64	15,2 558	0,50 00	0,14 51	12,8 901	1,00 00	13,40 48	0,00 00	16,8 579	0,3 175	1,0 000	0,0 000
Avg	18,2 180	0,1 599	76,446 8	12,00 00	0,58 62	17,8 004	0,50 00	0,20 48	14,0 577	1,00 00	13,71 87	0,00 00	18,9 841	0,2 783	1,0 000	0,0 463

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SUSTAINABILITY IN LOGISTICS AND SUPPLY CHAINS

Addressing SMOG-Related Disruptions in Pakistan's Logistics Sector: An Environmental Perspective

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1. Introduction

Global climate change and environmental degradation have resulted in an increase in both the intensity and frequency of natural disasters, emphasizing the urgent need for sustainable practices across all industries. Countries across Asia have experienced rapid industrial and economic growth, population increases, and urbanisation. Increased air pollution in the regionally expanded urban area and its density have resulted in the exposure of large urban populations to poor air quality (Alimonti & Mariani, 2024). Pakistan has one of the most rapidly increasing urban populations in the region. It is estimated that a total of 4,705,933 DALYs (number of disability-adjusted life years) are lost in Pakistan with 121,301 individuals dying annually from ambient air pollution-related illnesses (Razzaq et al., 2024).

The State of Global Air report (2020) identified Pakistan as one of the countries with the highest PM_{2.5} concentrations and deaths attributable to inadequate air quality. Premature fatalities attributable to air pollution increased from 135,000 in 2015 to 236,000 in 2019. The winter pollution season increases health problems, producing hazardous conditions that markedly decrease visibility and elevate the danger of respiratory and cardiovascular diseases (Mandal et al., 2024).

Subsequently, Smog adversely affects efficient logistics by cancelling transportation schedules, multiplying fuel consumption, and increasing the cost of operations (Qureshi & Saeed, 2022). Poor visibility disturbs travel times, causes switching, and might completely disrupt procedures in severe circumstances. These interruptions increase costs for logistics providers and disturb supply networks, adversely affecting customer satisfaction and service quality (Attar et al., 2024). Moreover, regular exposure to dangerous pollution levels causes health hazards to drivers and logistics staff, resulting in higher absenteeism and lower workforce efficiency. Addressing such challenges needs the development of resilience within supply networks to maintain operations against negative environmental circumstances. Research underlines the significance of flexibility as a critical competence for supply networks to predict, withstand, and recover from disruptions such as pollution (Bag et al., 2024).

While extensive research on environmental concerns in logistics, the specific effects of smog in Pakistan are still remain unexplored. Prior research has regularly neglected the distinct issues presented by lasting smog in urban areas such as Lahore and Karachi. This study examines the impact of pollution on logistical operations, influencing efficiency and expenses. Additionally, it examines the constrained adaptation strategies present in the logistics sector of developing economies. This study examines how the adoption of new technology can improve the impacts of smog, hence improving resilience and efficiency for logistics providers in Pakistan.

2. Literature Review

2.1 Theoretical background

This study is grounded in Sustainability Theory, highlighting the need of adopting strategies that fulfil present operational needs while preserving resources and protection the environment for future generations (Silva & Sehnem, 2024). Sustainability Theory is gaining importance in logistics and supply chain management, primarily due to environmental threats such as smog, which impacts operational efficiency and postures

health issues. The theory underscores the need for enterprises to participate economic, environmental, and social objectives, known as the Triple Bottom Line (TBL) approach, to create flexible, adaptive, and ecologically responsible operations (Elkington, 1998).

In the context of logistics, smog represents both an environmental hazard and an indirect significance of logistics activities, mostly emissions from vehicle fleets. Sustainability Theory provides a background for logistics firms to decrease environmental impacts through adaptive strategies, such as emissions reduction, fuel optimisation, and the implementation of environmentally friendly technologies (Miklautsch & Woschank, 2022). These green techniques not only mitigate the effects of smog on logistics operations but also promote wider environmental goals by reducing the sector's overall pollution footprint (Dekker et al., 2012). This aligns with Pakistan's governmental efforts to combat air pollution and the global shift towards sustainable development, including the United Nations Sustainable Development Goals (UN SDGs) (World Bank, 2021).

2.3 Hypothesis development

2.3.1 Environmental hazard and logistics performance

Environmental Hazards (EH) are found to negatively affect Logistics Performance in this study. Adverse environmental conditions, such as smog or bad weather, may hamper logistics operations, ensuing in delays, increased costs, and reduced customer satisfaction. Prior study confirms that environmental variables significantly influence logistics efficiency and performance. (Wiredu et al., 2024). So, we conclude that Environmental Hazard negatively influences Logistics performance.

H1 Environmental Hazard negatively influences Logistics performance.

2.3.2 Environmental Hazard and Logistics Efficiency.

Environmental hazards, including severe weather, pollution, and other troubles, noticeably affect the operational efficiency of logistics systems (Ghadge et al., 2020). These threats require creative and adaptive strategies to sustain efficiency in challenging environments. Previous research emphasises the influence of environmental issues in driving organisations to implement sustainable and efficient logistics methods in response to disruptions (Hao et al., 2023). So, we hypothesise that Environmental Hazard Negatively Influences Logistics Efficiency.

H2 Environmental Hazard negatively influences Logistics Efficiency.

2.3.3 Technology Adoption and Logistics Performance

The use of sophisticated technologies, including real-time tracking systems, predictive analytics, and automated processes, improves operational efficiency and effectiveness in logistics operations (Helo & Thai, 2024). By adopting technology advancements, logistics firms can optimise procedures, minimise errors, and enhance service quality, resulting in superior performance outcomes. Studies have constantly demonstrated that the implementation of technology is crucial in improving logistics effectiveness. Namweseza et al. (2024) illustrate that the adoption of advanced routing systems significantly enhances transportation efficiency, resulting in improved performance strategies. So, we conclude that TA positively influences LP.

H3 Technology Adoption positively influences Logistics Performance.

2.3.4 Technology Adoption and Logistics Efficiency.

The implementation of new technologies, like IoT, blockchain, and predictive analytics, enhances organisations' capacity to manage logistics during environmental hazards. (Shoomal et al., 2024). Prior research also revealed that Technology adoption enhances visibility, tracking, and decision-making, enabling firms to mitigate disruptions more effectively. Previous studies suggest that technology adoption amplifies logistics efficiency

under environmental challenges (Karuppiyah et al., 2024). We conclude that the adoption of advance technologies has positive impact on logistics efficiency. So, we conclude that TA positively influences LE.

H4 Technology Adoption positively influences Logistics Efficiency.

2.3.5 Logistics Efficiency positively influences Logistics Performance.

Studies discovered that effective logistics actions, considered by optimized routing, cost reduction, and timely deliveries, play a pivotal role in enhancing overall performance. Improved logistics efficiency enhances customer satisfaction and reduces costs, which are critical to organizational competitiveness. Studies affirm that enhanced logistics efficiency leads to better organizational performance metrics, including profitability and market share (Lin et al., 2023; Özcan et al., 2024). So, we conclude that logistics Efficiency positively influences Logistics Performance.

H5 Logistics Efficiency positively influences Logistics Performance

H5a Logistics Efficiency mediates the relationship between Environmental Hazard and Logistics Performance.

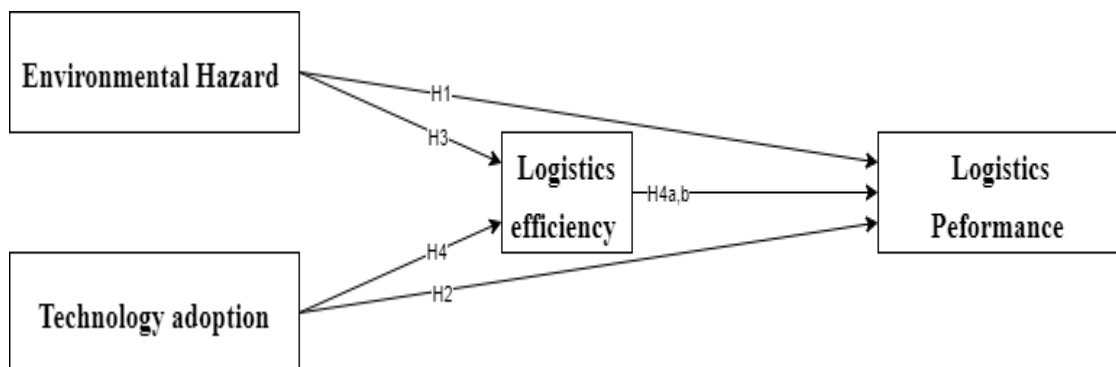
H5b Logistics Efficiency mediates the relationship between Technology adoption and Logistics Performance.

3. Methodology

3.1 Conceptual framework

The research framework examines the direct effects of environmental hazards on logistics performance and logistics efficiency. Similarly, technology adoption directly effects logistics performance and logistics efficiency. Additionally, the mediating role of logistic efficiency between technology adoption and environmental hazard on logistics performance are investigated.

Fig.1



3.2 Research Design

This study employs a quantitative research approach to investigate the correlations among hazards to the environment, logistics efficiency, logistics performance, and technology adoption. The main aim is to formulate and evaluate hypotheses based on Sustainability Theory through a conceptual research framework. A cross-sectional design was employed, whereby data were gathered from logistics sectors of Pakistan at a single time to examine the correlations among the variables.

3.3 Measure

Variables	Items	Sources
EH	Smog disrupts logistics	(Chen & Chen, 2024)
EH	Smog impacts routes, schedules	(Saleem et al., 2019)
EH	Monthly smog disruptions	(Ban et al., 2017)
EH	Poor air quality affects logistics	(Szymczyk & Kadłubek, 2019)
EH	Smog causes delays	
EH	Smog is key in planning	
LE	Smog delays deliveries	(Revilla & Sáenz, 2014)
LE	Increased fuel use in smog	(Bektaş & Laporte, 2011)
LE	Schedule changes due to smog	(Kwasiborska et al., 2023)
LE	Efficiency drops in smog	(Chowdhury & Quaddus, 2017)
LE	Driver productivity affected	(Yan et al., 2014)
LE	Delays from low visibility	(Kwasiborska et al., 2023)
TA	Tech optimizes routing in smog	(Autry et al., 2010)
TA	AI improves logistics in smog	(Liu et al., 2016)
TA	Predictive analytics for smog	(Tu, 2018)
TA	Real-time tracking during smog	
LP	Smog effects on-time deliveries	(Kwasiborska et al., 2023)
LP	Smog impacts service quality	(Peng & Xiao, 2018)
LP	Customer dissatisfaction in smog	(Uzir et al., 2021)
LP	Complaints rise in high-smog periods	
LP	Harder to meet expectations in smog	

4. Results.

We analysed the data using SmartPLS 3, a software application for partial least squares structural equation modelling (PLS-SEM). The table 2 displays the demographic and professional attributes of the sample. The majority of responses are young males aged 18 to 35 with a university degree. The majority have managerial or driving positions with 6 to 15 years of experience. The primary sectors represented are transportation and supply chain, with a lesser emphasis on storage. No participants possess a PhD.

Table 2: Demographics

Variables	Category	Frequency
age	18-25	37
	26-35	33
	36-45	26
	46-above	09
Gender	Male	87
	Female	18
Education	High school	32
	University	50
	Master	23
	PhD	0
Job	Driver	31
	Manager	57
	Logistics coordinator	17
Experience	0-5	17
	6-10	40
	11-15	44

Sector	16-above	04
	Transportation	45
	Supply chain	40
	Warehousing	20

4.1 Measurement model

The table 3 demonstrates that the items for each construct have robust factor loadings, demonstrating their effectiveness as indicators of the underlying constructs. However, some items were removed (LP1, TA1, TA2) as its values were less than the threshold. Cronbach's Alpha (CA) scores above 0.7 for the majority of constructions, indicating strong internal consistency. Composite Reliability (CR) ratings above 0.7, signifying that the constructions are dependable. Average Variance Extracted (AVE) values exceed 0.5, indicating that the structures account for greater variance than measurement error. The model exhibits strong reliability and validity.

Table 3. Items loading Reliability and Validity constructs

Item	Factor Loading	CA	CR	AVE
EH-1	0.843	0.884	0.916	0.685
EH-2	0.876			
EH-3	0.871			
EH-4	0.819			
EH-5	0.722			
LE-1	0.800	0.838	0.880	0.597
LE-2	0.891			
LE-3	0.775			
LE-4	0.735			
LE-5	0.635			
LP-2	0.708	0.771	0.852	0.591
LP-3	0.767			
LP-4	0.778			
LP-5	0.818			
TA-3	0.717	0.711	0.734	0.644
TA-4	0.783			

Discriminant validity

The table 4 displays the correlation matrix for the constructs (EH), (LE), (LP), and (TA). The diagonal numbers denote the square root of the Average Variance Extracted (AVE) for each construct, all exceeding 0.7, signifying strong convergent validity. The off-diagonal elements indicate the correlations among constructs. For example, EH and LE exhibit a modest positive correlation (0.205), whereas EH and LP demonstrate a slight positive correlation (0.093). SP and TA exhibit a moderate positive correlation of 0.350, indicating a minor association. The correlations remain within acceptable thresholds, with no value over 0.85, so confirming robust discriminant validity among the components.

Table 4. Fornell-Larcker Criterion

	EH	LE	SP	TA
EH	0.828			
LE	0.205	0.773		
LP	0.093	0.293	0.769	
TA	0.092	0.058	0.350	0.803

4.2 Structural model

The structural model in this study examines the relationships between the latent constructs EH, LE TA and, LP. It specifies the causal paths and directional relationships between these constructs based on theoretical foundations. The model tests how EH and TA influences LE, LP, and, providing insights into both direct and indirect effects. Standardised path coefficients indicate the strength and significance of these relationships, with higher values reflecting stronger impacts.

Table 5. Direct relation (H1 to H4)

Hypothesis	Original Sample	T Statistics	P Values	Decision
EH -> LP	-0.430	3.302	0.008	Accepted
TA -> LP	0.338	4.296	0.000	Accepted
EH -> LE	-0.225	2.807	0.005	Accepted
TA -> LE	0.036	3.321	0.000	Accepted
LE -> LP	0.286	3.286	0.000	Accepted

Table 6. Mediation table

Hypothesis	Original Sample	T Statistics	P Values	Decision
TA -> LE-> LP	0.089	2.752	0.006	Accepted
EH-> LE -> LP	0.010	2.226	0.013	Accepted

5 Discussion

This study examines the influence of smog and technological adoption on logistics performance and efficiency in Pakistan. The study's findings indicate a substantial negative association between atmospheric pollution and both logistical performance and efficiency. This supports (H1) and (H2), which asserted that environmental dangers (smog) adversely affect logistical performance and efficiency. Higher pollution levels result in disruptions, delays, heightened expenses, and reduced customer satisfaction, hindering overall operating efficiency. The study shows a positive correlation between the adoption of technology and logistics performance and efficiency. This confirms (H3) and (H4), signifying that technology adoption enhances both performance and efficiency dimensions. Advanced technology such as real-time tracking, predictive analytics, and efficient routing systems mitigate the adverse impacts of smog, enhancing responsiveness and operating efficiency.

Further, this study investigates the mediating function of logistics efficiency. It provides evidence for (H5a), indicating that logistics efficiency mediates the connection between environmental threats and logistics performance. Effective logistical systems can mitigate certain adverse effects of pollution on overall performance. (H5b), which proposed mediation between technology adoption and logistics performance via logistics efficiency, is also supported by previous study. Shoomal et al., (2024) emphasize the essential significance of logistics efficiency in improving logistics performance, especially with the use of new technologies. This research verifies the idea that effective logistics operations act as a vibrant intermediary that enhances the advantages gained from sophisticated technological applications in supply chain systems.

5.1 Practical implications

To mitigate the harmful effects of pollution on Pakistan's logistics sector, a complete policy is required. First, the government should execute tighter emission limits for vehicles and industry, while shifting to cleaner energy sources such as electric vehicles and renewable energy for industrial activities. Concurrently, significant investment in transportation systems, particularly electric buses and trains, will reduce dependence on private automobiles and lower overall emissions. Second, a national program should be developed to encourage the use of innovative technology in the logistics business. This might include providing support for the procurement of GPS tracking devices, route optimisation

software, and other efficiency-enhancing technology, as well as training programs to generate the required technical ability. Third, a inclusive air quality monitoring system should be considered and implemented to offer real-time data on smog levels, allowing logistics providers and relevant agencies to respond more proactively.

5.2 Theoretical Implications

This study significantly increases our theoretical knowledge of logistics resilience and sustainability. It shapes on Sustainability Theory by empirically demonstrating the critical standing of environmental issues (smog) in affecting logistics performance and efficiency, highlighting the necessity for a Triple Bottom Line approach. The study refines the concept of logistics resilience by showcasing the mediating role of technology adoption and operational efficiency in mitigating the negative effects of environmental hazards. Finally, the research contextualises the positive impact of technology within a specific environmental challenge, underscoring the importance of considering context-specific factors when evaluating the effectiveness of technological interventions in improving logistics outcomes.

5.3 Limitations and future recommendations

The cross-sectional methodology of this study makes it stimulating to create conclusive causal connections, and the attention on Pakistan limits the findings' generalizability. The sample's representativeness and dependence on self-reported statistics require more consideration. Future research should use longitudinal studies, diverse samples, and qualitative data, investigate the mediating mechanisms in more depth, analyse a broader range of technologies, and conduct policy-focused research to measure the cost-effectiveness of involvements and policy recommendations for mitigating the impact of smog on Pakistan's logistics sector.

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Developing Sustainable Tourism Logistics with Enhancing Eco-Tourism Destinations in Eastern Economic Corridor (EEC), Thailand

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Abstract

After covid pandemic, tourism industry faces with huge challenge. Tourism has become a significant industry to drive Thailand's economy growth. Under Thai government policy, Eastern Economic Corridor (EEC), has been promoted, as special economic zone to attract global trade and investment. The ECC integrates Chonburi, Rayong, Chachoengsao provinces to develop industrial and economic zones. There are many beautiful and fantastic tourism destinations in EEC. However, the destinations lack sustainable development and connectivity. Ever-increasing tourism has logistically created problems there related to the sufficiency of its infrastructure systems and facilities. Increasing demands negatively affect to natural resources and an escalation of environmental pollutants. Further, these problems reflect the need for providing effective logistical planning and management in tourism industry in EEC.

Logistics plays an indispensable role in the tourism industry. The development of tourism logistics for creative eco-tourism requires an understanding of the behaviour and needs of tourists, together with designing a responsive logistics system for them. This study applies principles of logistics management to the tourism industry under the hypothesis that moving tourists from origin to destinations more efficiently and effectively. It also includes providing an effective transport networking system, would increase and support tourism in EEC. A demand forecast for tourism in next decade was statistically calculated in order to provide recommendations for the improvement of infrastructure systems and facilities.

An objective is to examine demand forecast model for tourism industry in EEC. The results can be used for designing and planning infrastructure systems and facilities, including strategies for transport networks and logistics systems to support the future growth. Data are collected from secondary and primary sources, e.g. questionnaire and in-depth interview. The questionnaire is distributed to 400 potential participants, with 382 questionnaires being returned, for a 95.5 percent return rate. Validity and reliability are examined.

The result shows that a time series would be an effective model for a demand forecast. It reveals that tourism destinations in EEC would double in the next decade. Effectively designed infrastructure and facilities are required to support sustainable tourism in EEC. The internet and digital platform, and artificial intelligence (AI) are strategic issues for future tourism logistics development. Further, new and fantastic tourist facilities would be increasingly developed in EEC, underscoring the need for an appropriate plan for managing environmental pollution.

Finally, a reverse logistics system for garbage management would need to be effectively utilised. Rapidly increasing garbage is a problematic issue for logistics related to a sustainable, green, eco-friendly environment. This study concludes that strategic and integrated logistical management is necessary, with active participation from stakeholders.

Keywords: Tourism logistics, strategy, demand, technology, forecasting, Thailand

1. Introduction

After covid pandemic, tourism industry faces with huge challenge. Tourism has become a significant industry to drive Thailand's economy growth. Under Thai government policy, Eastern Economic Corridor (EEC), has been promoted, as special economic zone to attract global trade and investment. The ECC integrates Chonburi, Rayong, Chachoengsao provinces to develop

industrial and economic zones. There are many beautiful and fantastic tourism destinations in EEC. However, the destinations lack sustainable development and connectivity. Ever-increasing tourism has created problems there related to the sufficiency of its infrastructure systems and facilities. Increasing demands negatively affect to natural resources and an escalation of environmental pollutants. Further, these problems reflect the need for providing effective logistical planning and management in tourism industry in EEC.

Logistics plays an indispensable role in the tourism industry. The development of tourism logistics for creative eco-tourism requires an understanding of the behaviour and needs of tourists, together with designing a responsive logistics system for them. This study applies principles of logistics management to the tourism industry under the hypothesis that moving tourists from origin to destinations more efficiently and effectively. It also includes providing an effective transport networking system, would increase and support tourism in EEC. A demand forecast for tourism in next decade was statistically calculated in order to provide recommendations for the improvement of infrastructure systems and facilities.

The logistics management in the tourism industry is currently recognised as a strategic tool for enhancing tourist satisfaction in relation to lower travel costs, one-stop services, other conveniences and safety. The research study (Briguglio 1995; Bryden 1973) shows that tourism industry typically fails to understand how to apply logistics concepts as well as how to put logistics strategies into action. The objective is to examine demand forecast model for tourism industry in EEC. The results can be used for designing and planning infrastructure systems and facilities, including strategies for transport networks and logistics systems to support the future growth. It also examines other logistical aspects (i.e. role of demand forecasting and managing reverse logistics system for garbage).

2.Literature Review

This study reviews the literature related to the role of tourism and eco-friendly tourism to the economic growth of Thailand. It also considers the adoption of logistics planning and management in the tourism industry. Two relevant sources (Bryden 1973; Ekkapong C., et al. 2021; Tairova M. M. 2018) point out that logistics planning and management contributes to the success of sustainable tourism development. These sources also review definitions of logistics management as they pertain to sustainable development of tourism, but there is few research providing definition and implications of tourism logistics, and how it contributes to tourism success. (Ekkapong C., et al. 2021; Kayumovich K. O. et al. 2020).

Lanfant, M. F., et. al. (1995) defines tourism logistics involves the strategic planning and execution of transporting tourists and their goods seamlessly from origin to destinations to ensure efficient and sustainable travel experiences. Tourism logistics involves the planning, control, and coordination of various resources to facilitate the flow of goods, services, and information, essential for the tourism sector. (Lanfant, M. F., et. al. 1995). This field ensures that the necessary infrastructure, transportation, and support mechanisms are in place to offer a seamless travel experience for tourists. (Studysmarter, 2025) Logistics in tourism refers to the complex processes required to ensure that tourists can travel smoothly and enjoyably from their point of origin to their destination, and back. This includes several key components. (Tairova M. M. 2018).

It is important to understand a clear and concise concept of logistics from a tourism perspective. Logistics is mostly understood in term of business industries, and there are some research studies done exclusively in relation to tourism. People typically relate logistics (Bowersox & Closs, 1996) to transportation or accommodations, particularly connecting it to aspects of physical and information flow (Butler, 1980; Theppitak, 2006). To apply logistics to tourism industry, people, or tourists, shall be considered as physical flow from one point to another, and examined in terms of lower costs, higher safety and more convenience through excellent coordination and collaboration (Bowersox & Closs, 1996).

Butler (1980) points out that before logistical planning for tourism infrastructure and facilities can be achieved, there is needs to be an accurate demand forecast. Demand forecasting for tourism into the next decade is statistically calculated in order to provide improvement for logistics infrastructure systems and facilities, which can in turn support growth and expansion. However, some researches have been done in area of tourism logistics (Butler 1980; Conlin and Baum 1995). It also reveals patterns of tourist behaviour and other factors influencing travel decisions, including identifies problematic issues with tourist destinations (Conlin and Baum, 1995).

Conlin and Baum (1995) states that there is a relationship between adoption of logistics management in the tourism industry and the success of sustainable tourism development. Logistics management means moving people, or tourists, from one point to another point (Theppitak, 2006). It facilitates how to prepare hotels and accommodations, how to build transport networks between and within locations to support sustainable tourism (see Figure 1). However, there is the gap in literature for application logistics in tourism industry. This study applies a logistical approach to the tourism industry under the hypothesis that moving tourists from an origin place to destinations in EEC more efficiently and effectively. It includes providing an effective transport networking system, would increase tourist satisfaction in EEC. Tourism is qualitatively different from the other domains within the cultural sector, as it cannot be readily classified as a sector in the traditional sense, i.e. as measured by either particular markets or industrial outputs. Therefore, it is better understood as a demand-driven, consumer-defined activity.

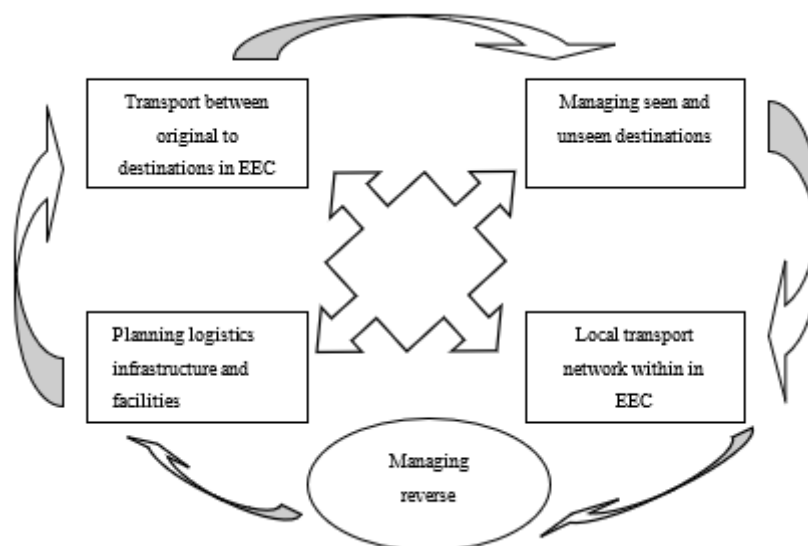


Figure 1 : Relationships between activities in tourism logistics

When considering the factors influencing adoption of logistics management in tourism industry, particularly, tourism in special economic zones, the literature points out the major factors are economic, political and technology. The research (Conlin and Baum, 1995) also highlights the relationship between such factors and the adoption of logistics management, like fluctuating tourist counts and tourist satisfaction.

It concludes there is a literature gap related to the examination of issues related to adoption of logistics management (and its effectiveness) within the tourism industry, and specifically in special economic zones. In particular, there needs to be an examination of the factors contributing to the logistics adoption phase and the factors influencing sustainable tourism development. This study therefore proposes a theoretical framework (Figure 2) derived from a previous study (Theppitak, 2006).

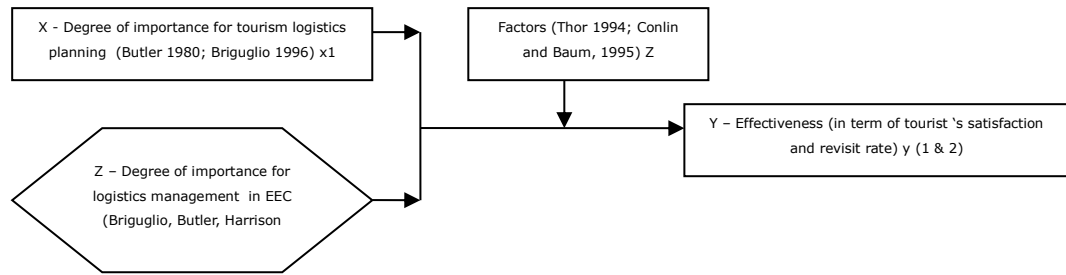


Figure 2: Theoretical framework of the study

Figure 2 shows the theoretical framework of variables in this study. Building a sustainable tourism industry, especially tourism in special economic zones, required widely applied logistics concept and strategies. Success of sustainable tourism development requires a high priority of importance on adoption of logistic planning. The research shows that more importance placed on the logistics planning, more effectiveness is gained for developing tourism, in term of tourist satisfaction. A main objective is to find ways to improve tourist satisfaction.

This study examines relationship between variables (X , Y , Z). It defines a degree of importance to the adoption of logistics planning and management as *an independent variable* ($X1$ and $X2$) and defining the effectiveness of logistics management to eco-tourism in EEC, in terms of tourist satisfaction (i.e. convenience, comfort and safety for transport network, infrastructure and facilities in EEC.), and return rate of tourist as *a dependent variable* ($Y1$ and $Y2$).

Furthermore, this study discovers that other influential factors, such as economic, political and technology, are significant to effective adoption of logistics management to develop or enhance eco-tourism in EEC. These influential factors are defined in the framework as *an intervening variable*, (Variable Z), which influences both the independent variable (Variable X) and the dependent variable (Variable Y). It is therefore assumed that the level of such influencing factors has a direct correlation to the degree of importance placed on the adoption of logistics management, as well as to the effectiveness of eco-tourism in EEC.

3. Research Methodology

This study initially conducts a literature review related to the role and patterns of eco-tourism development in special economic zones from a logistics perspective, including the examination of challenges and obstacles occurred. It also explores the use of logistics management in the tourism industry. The objective of this study is to investigate the relationship between variables related to effective adoption of logistics management for eco-tourism in EEC, and the effectiveness for sustainable eco-friendly tourism development.

An interview technique is used jointly with questionnaire surveys in order to obtain relevant and in-depth information from tourists in EEC. To obtain the data, the study uses a sample of 400 randomly selected tourists, which includes both Thai and foreign tourists travelling in EEC. This number of face-to-face questionnaires is based on a randomly stratified sampling. The rate of response is very good, with 382 respondents, or 95.5 percent of the total questionnaires. The data collection period takes three months.

3.1 Research Questions

To answer the above issues, the study defines the following questions:

1. What is the role of logistics to sustainable eco-friendly tourism development?

2. How can behaviours of tourists be used to design tourism logistics infrastructure and facilities in EEC?
3. What are factors influencing the design and implementation of tourism logistics strategy in EEC?
4. What are efficiencies and effectiveness of tourism logistics management?

3.2 Research Hypotheses

Based on these research questions, hypotheses are established in order to examine a relationship between tourism logistics planning and management and the effectiveness of improving tourism in EEC. This study therefore examines a relationship of the variables under following hypotheses.

H₁ = There is a relationship between logistics planning and tourist satisfaction.

H₂ = There is a relationship between logistics management and increasing return rate of tourists in EEC.

3.3 Population & Sampling Procedure

This study uses the number of tourists who travelled to eco-tourism in EEC during December through February 2024. 400 questionnaires are randomly distributed for the sampling. After three months, there are 385 questionnaires returned, for a response rate of 95.5 per cent. This study also interviews 74 tourists to gain their opinions related to tourism logistics in EEC. Two pre-testing are conducted with Cronbach's alpha (α) at 0.77 and 0.79 respectively.

4. Finding results

The survey covers demographical data related to attitudes and behaviours of tourists when travelling in EEC, including examining hypothesis. The research implication related to transport system, logistics infrastructure and facilities are discussed.

Table 4.1 : Gender of tourists

Gender	Percent
Male	54
Female	46
Total	100

Table 4.1 shows kind of respondents. Male tourists are the greatest number of respondents in the samples or 54 percent, followed by female tourists or 46 percent. The study represents actual information for tourism in EEC and it shows that the male tourists are a major target.

Table 4.2: Aging of targeted tourists

Age (years)	Percent
13 – 20	24
21 - 28	30
29 - 36	14
37 – 44	12

45 - 52	15
Over 52	5
Total	100

Table 4.2 represents age of targeted tourists visiting in EEC. The result shows that major tourists or 30 percent had age between 21-28 years. Secondly, 24 percent has age between 13-20 years. The figure shows that the targeted groups of tourists in EEC are now youth and mature people.

Table 4.3 : Nationality of targeted tourists

Nationality	Percent
ASEAN	33
European	10
Indian	14
Russian	18
Chinese	28
Total	100

Table 4.3 shows nationality of tourists. The survey reveals that major respondents are ASEAN countries or 33 percent. In this number consisted of Thai respondents is at 18 percent. Chinese, Russian and Indian tourists are 28, 18 and 14 percent, respectively.

Table 4.4 : Educational level of respondents

Educational level	Total
Secondary	6
High school	9
Higher school	23
Bachelor	34
Higher Bachelor	28
Total	100

Table 4.4 shows educational level of tourists. The result reveals that most of respondents or 38 percent have educational level lower than bachelor degree. Bachelor and postgraduate degree are 34 and 28 percent, respective. The result reflects to expectation level to traveling activities, lifestyles, facilities and infrastructure in EEC.

Table 4.5 : Average income of respondents

Revenue per month (Baht)	Percent
Lower 5,000	8

5,000 – 10,000	10
10,001 – 15,000	13
15,001 – 20,000	20
20,001 – 25,000	32
Higher 30,000	17
Total	100

Table 4.5 represents average income of respondents. The study reveals that average income of most tourist groups or 51 percent is lower than 20,000 baht. The greatest number or 32 percent of them has income between 20,001 – 25,000 baht. The income levels facilitate to design and develop infrastructure and facilities in EEC consistent with targeted tourists' income.

Table 4.6 : Frequency of travelling to EEC. (Excluded last travelling)

Frequency of travelling in EEC. (Times)	Percent
1	14
2 – 3	23
4-5	35
More than 5	30
Total	100

Table 4.6 reveals frequency of traveling to EEC. The result shows that most of respondents or 35 percent had been travelling to EEC 4-5 times. Secondly, 30 percent of them travels more than 5 times. As 14 percent travels only one time. This frequency of visiting to EEC reflects to expectation, perception and satisfaction of tourists when travelling to EEC.

Table 4.7 : Nature of travelling

Nature of travelling	Percent
Come alone	12
Come with friends	38
Come with family	32
Come with tour/ training/ seminar	18
Total	100

Table 4.7 reveals tourist behaviours. The survey indicates that greatest number of tourists or 38 percent travels with their friends, and 32 percent with family respectively. The information facilitates for designing pattern of transport and developing infrastructure and facilities to support sustainable tourism.

Table 4.8 : Number of people in tourist group

Number of persons in a group	Percent
1 – 5	34
6 – 10	25
11 – 15	14
16 – 20	19
More than 20	8
Total	100

Table 4.8 reveals number of people in tourist group. The greatest number of tourists or 34 percent identifies that their group has 1-5 tourists. 25 percent of them identifies that travelling with 6-10 tourists per group.

Table 4.9 : Pattern of vehicles to EEC

Vehicle to EEC	Percent
Public transport	18
Personal car	36
Tourist bus	23
Motorcycle	8
Other (Please identify)	15
Total	100

Table 4.9 shows patterns of vehicle for travelling to EEC. The survey shows that most of tourists or 33.3 percent travelled to EEC by personal car, 23 percent of them visited by tourist bus, and 18 percent by tourist bus respectively. However, some of them identifies that they use taxi or rent cars from Bangkok to EEC.

Table 4.10: Pattern of staying overnight in EEC.

Staying overnight in EEC	Percent
Yes	57
No	43
Total	100

Table 4.10 represents pattern of staying overnight in EEC. The survey shows that most of tourists or 57 percent stay overnight in EEC for long weekend or special holiday. The tourists point out that there is convenience both infrastructure and facilities in EEC. On the other hand, 43 percent indicates that they did not stay overnight in EEC.

Table 4.11: Type of Accommodation

Type of accommodation	Percent

Hotel	38
Resort	29
Private resident	21
Others (e.g. stay with friends)	12
Total	100

Table 4.11 shows type of accommodation in EEC. The greatest number of respondents or 38 percent stay at hotels. 29 percent of them stays in resorts and 21 percent stayed at private residents. Others or 12 percent stays with local friends or relatives. This information reveals that the tourists are expecting to stay in pattern of hotels and accommodations and travelling in EEC.

Table 4.12: Summary hypothesis testing

Variable		Correlation	p-value
Independent	Dependent		
X1	Y1	0.740	0.000
Z	Y2	0.520	0.000
X2	Y2	0.715	0.000

Table 4.12 shows summary of hypothesis testing. It tested that effective adopting logistics planning in tourism industry in EEC (X_1) have relationship with improving tourist satisfaction (Y_1). Further, effective tourism logistics management (X_2) increasingly encourage and promote increasing tourists' return rate in EEC. (Y_2). Factors (i.e. economic, political and technology) has moderately relationship with encourage and promote increasing tourists' return rate in EEC. (Y_2). The result shows that effective adopting tourism logistics planning (X_1) has strongly relationship with generating tourist satisfaction (Y_1). It also reveals that tourism logistics management (X_2) has also moderately relationship with increasingly promoting tourists' return rate to EEC. (Y_2). In term of logistics planning covers properly matching demand of tourists and services supply in EEC provinces, including organising logistics networks (e.g. linking between seen and unseen destinations, public transport, accommodation) within the EEC. Further, factors are reshaping a new way to work in tourism logistics. Currently, new innovative and technology (i.e. AI, Robot, software and internet) can support for analysing potential tourist demand, route, transport and accommodations. Tourism logistics management covers how well logistics management is used to promote and enhance tourism industry in EEC, including providing reasonable costs, safety, convenience and satisfying tourist need.

5. Discussion and Implications

5.1 Role of logistics to sustainable eco-friendly tourism development?

The findings reveal relevant patterns and trends of tourism industry in EEC. It identifies that the direction for development of eco-friendly tourism in EEC. are unclear. Current development for destinations lacks continuity, connectivity and seamless. Many destinations sufficiently lack budgets, resources, and maintenance and repairs (M&R). Government agencies cannot well plan and manage their infrastructure and facilities. There are urgent needs for application of logistics management to create and develop sustainable tourism.

Theppitak (2005) states in a definition that logistics is "the process of planning, organising and controlling the flow of physical and information from origin to the end point to increase value with less costs to satisfy all stakeholders." Therefore, logistics in the context of tourism is defined as "the management of the flow of physical (including tourists or vehicles) and information (information related tourists, demand, transport and accommodations)." Under the definition, tourists are being considered as "goods," being moved from point to point. Transport system, between provinces, as well as within the island, would need to be designed to support the move of tourists in terms of lower costs, safety, comfort and convenience. Therefore, scope of tourism logistics also covers functions i.e. transport, infrastructure and facilities. (in Figure 1)

To support and foster more and better tourism in EEC, infrastructure (e.g. electricity, water and telephone) must be readily available. Also, future facilities (for all travel activities, including currently undeveloped areas) must be well planned and organised. These facilities include hotels and other accommodations, public transport, and bus stop. Proper demand forecasts of tourist behaviours and lifestyles are critical. In-depth and accurate logistics is the only proper way to prepare for future tourist accommodations, facilities and travelling activities.

Tourism logistics also includes reverse logistics activities. Reverse logistics can be defined as the management of the flow of materials or information back to a desired point. It covers the management of garbage disposal and unusable materials. In circumstance, it includes how to recover tourists who suffering or injuring to hospital. There are many methods to manage garbage, with different costs occurring, including non-monetary costs like pollution. This study can also be used logistically to incentive and support sustainable, more eco-friendly tourism in EEC..

5.2 Behaviors of tourists and designing tourism logistics infrastructure and facilities in EEC

When consider importance and satisfaction levels with public transports systems between original and destinations in EEC. It shows that tourists have moderately expectation levels of service quality (e.g. convenience, safety and fee). They have satisfactory levels lower than their expectation levels. It is the main sources of dissatisfaction. This reflects that public transport, fees and safety would be considered to improve urgently. Tourists are satisfied when their perceptions equal or above their expectations. Therefore, the gap between tourists' expectation and perception needs to be closed.

To improve public transport systems between destinations in EEC, it would improve in two ways. First, reengineering existing public transport systems by focusing on hardware (i.e. transport, infrastructure and facilities), software (i.e. information to tourists) and peopleware (i.e. training local people with service minded). Second, new efficient and friendly environmental transport system (i.e. Solar Cell, hydrogen and EV) would be considered.

The result shows the levels of importance and satisfaction tourists have for travel destinations. Surveyed tourists reveal they have high expectation for travelling destinations in term of beauty, atmosphere, cleanliness and safety. However, the result shows that there are some dissatisfactions with cleanliness and sanitary system, including safety of security systems in destinations.

Managing tourism logistics in term of existing destinations, is not considered only lower costs and higher services level, but it also means to manage continuity and connectivity of routes, rest area and facilities. Tourists inform that no new destination has been built in EEC. Unseen destinations would be effectively established and promoted. Obvious and clear signs between destinations become a source of satisfier.

When considering the levels of importance and satisfaction tourists identifying related to public transport (and facilities), while travelling in EEC. This study asks the tourists to rate

the public transport systems from origin to destinations in EEC, including public transport systems within a province. Most of the tourists indicates high expectations related to availability, convenience, safety and expenses. The study reveals that they are mostly satisfied with the availability and comfort of transport systems in EEC. However, they are somewhat dissatisfied with the safety and fees of public transport systems.

When considering the public transport system within a province, tourists have high expectations for fee standardisation, comfort and availability of transport. But, they are dissatisfied to actually find a lack of fee standardisation within destinations. Logistical implication would consider in a whole system, and then set fee standardised in each destination. The difficulty is how to communicate and motivate to local people for following to same standard without their resistance and conflict.

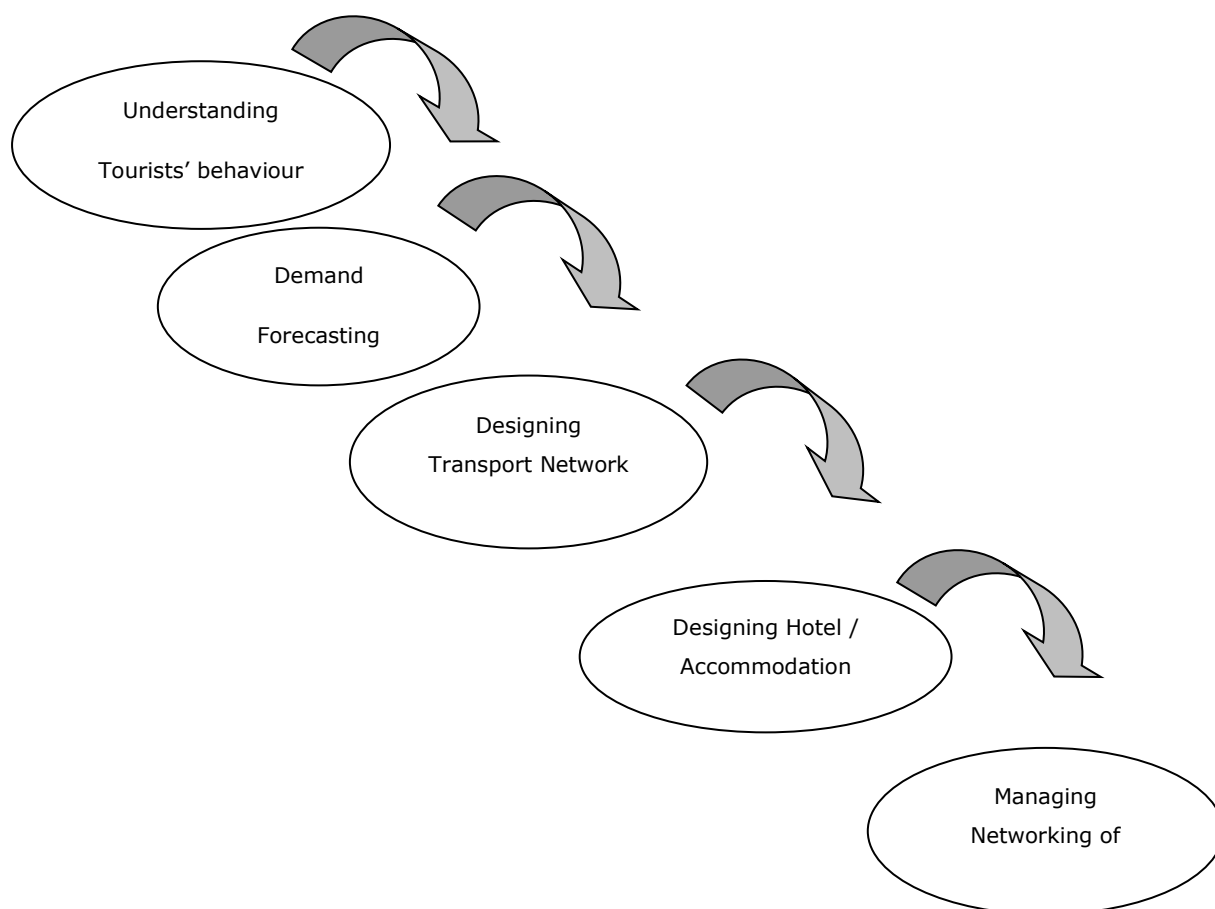


Figure 3: Conceptual design for sustainable tourism logistics in eco-tourism in Thailand

The interesting issue for infrastructure requires for supporting tourism in EEC, it includes electricity, road, water, and telephone systems. The results reveals that most of the tourists (more than 57 percent) stay overnight in destinations. The question is that why some tourists did not stay overnight in EEC. The interviewed results shows that most of tourists identifies to unavailability and inconvenience in term of shortage, including high prices compared with earned services. They have high expectations for the costs and availability of tourism infrastructure in EEC. But they are dissatisfied with the actual fees charged for services and the availability of infrastructure.

These results reflect that there is a need to think and analyse a whole system. It would start with demand forecasting future demand to provide properly infrastructure and facilities. The study examines statistical information in last five years (2021-2025) and it shows that seasonal time series would be the demand forecasting model which fits to tourism industry in EEC. New innovative tools (i.e. AI or Algorithm) would be used to analyse and plan for logistics infrastructure and facilities. Further, one of serious problems is garbage and pollutions occurring from tourism. Now the issue is increasingly becoming serious problems to friendly environmental tourism. It needs to apply concept of effective reverse logistics for creating and enhancing sustainable, eco-friendly tourism in EEC.

In summary, the main research finding concludes that:

- Tourism logistics planning has a strong and positive relationship to tourist satisfaction.
- Tourism logistics management has a strong and positive relationship to return rate of tourist to EEC.
- Factors (i.e. economic, political and technology) have a moderate relationship to tourist satisfaction and they influence to decision making for travelling in EEC.
- Lacking of effective demand forecast method creates problems in mismatching between supply and demand, preparing infrastructure and facilities.
- Public transport (between origin to destinations in EEC) contributes to tourism's satisfaction and success.
- The EEC currently lacks tourism logistics planning and management.
- New innovative tools, (i.e. AI, internet or algorithm) would be used to analyse and plan for logistics infrastructure and facilities.
- Garbage from tourists is increasingly becoming serious problem, it needs to design effective and efficient reverse logistics systems.
- Effective tourism logistics enhance customer satisfaction, boost local economies, and are crucial for minimising environmental impact and maximising resource utilisation.
- Finally, it concludes that effective tourism logistics management is a key success to tourism in EEC.

6. Conclusion

Effective adoption of logistics planning and management for tourism industry, especially in EEC provinces, would enhance effectively to be eco-friendly tourism. It starts from understanding tourist behaviour and then analyses demand forecast for the next decade. The result is a starting point for effectively designing and developing sufficient and appropriate tourism infrastructure and facilities. It points out that a seasonal time series would be an appropriate model of demand forecasting. In the next decade, tourism industry in EEC would increase to twice its current level due to development of Eastern Airport City project and the High-Speed Rail Linked 3 Airport project.

Today, tourists have increasingly travelled to destinations in EEC. Effective design for future infrastructure systems and facilities must support sustainable tourism in EEC. New technology (i.e. AI, internet or algorithm) is significant role for future direction of tourism logistics. Likewise, development plans for new travel destinations must include an appropriate plan for managing environmental pollution. Finally, garbage management would be effectively planned using a reverse logistics system, as rapidly increasing garbage has become a problematic issue related to the logistics of maintaining a green, eco-friendly environment.

It provides valuable information for stakeholders, especially government agencies and public policy makers. Logistically planned transport management facilitates growing tourist travel to and from provinces, providing hotel, resort and residential-accommodation owners with consistently increasing demand. While it would prevent the unrestrained

destruction of natural resources and environments in destinations. This study leads to the conclusion that strategic and integrated tourism logistics management is needed, with active participation from relevant stakeholders.

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Validation of Novel Automated Cold Storage with Nested Frozen Volumes in Chilled Environments for Improved Labour Conditions

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INTRODUCTION

Cold storage warehouses typically require human labour to work at extreme temperatures, below freezing, while also experiencing frequent temperature variations when moving between ambient (20°C / 68°F), chilled (4°C / 39°F), and frozen (-25°C / -13°F) zones. The challenging working conditions result in high turnover rates, negatively impacting cold storage productivity and increasing the cost of operations. Labour is one of the highest costs in cold storage logistics [1], amongst a decreasing trend in the labour force participation index [2]. The high, labour turnover rate results in an inexperienced workforce, responsible for handling sensitive temperature product. Therefore, a higher probability for degraded quality, cold storage product is created due to the unique and challenging working conditions of cold storage warehouses.

One approach to improve working conditions in cold chain logistics is introducing automation to further remove human labour from the coldest environment. With an automated storage system, robotics interface with employees by storing product and retrieving product. An opportunity is created with automation in cold storage warehouses to separate product storage temperatures from labour working temperatures. While the emphasis of the automation benefit is on employee working conditions, it can also bring other benefits. The storage temperature of cold chain products can be monitored and are better controlled for temperature sensitive items [3]. Warehouse management systems using automation have been explored to enhance the cold chain by ensuring food safety during storage [4]. Even backbone, refrigeration systems and distribution centres (warehouses) have been identified as opportunities for automation to improve the sustainability and reduce the energy consumption of the cold supply chain [5]. Automation is mentioned as a key feature of smart warehouses equipped with IoT devices and AI-driven systems to advance sustainability agendas through improved energy efficiency and reduced waste [6].

A cube, automated storage and retrieval system, ASRS, for piece or case picking was selected to advance cold storage logistics by combining chilled and frozen storage into one ASRS. The goal is to remove human labour from physically entering frozen temperature environments to reach frozen product. The cold storage, cube ASRS has an internal, nested frozen volume, that is isolated from the surrounding chilled environment. Any labour interfacing with the cube ASRS stays within the chilled environment while the robotics can travel above the chilled and frozen storage areas to retrieve product from either temperature zone.

The cube ASRS selected is from AutoStore System. Bins or storage containers are stacked to support different storage heights depending on building ceiling clearances and customer storage volume requirements. The storage containers have fixed dimensions in width and length, but are offered in three different depths to support various product sizes. A full-height cube ASRS was selected with stack of 16 storage containers at 330 mm (13 in.) tall each, to reach a combined height of ~5.3 m (17.4 feet). Robots move on a grid track above the stacked storage containers to pick up and move containers around. Storage containers can be moved to the perimeter where a picking station at the ground level presents the container to an employee for picking product. The robots can also move storage containers around different stacks to dig and reach containers at lower levels in the cube system. One

benefit of selecting a cube ASRS for cold storage is the their ability to compact a warehouse to 25% of the original floor area to store the same amount of product. Increasing the storage density of a refrigerated warehouse can reduce the required energy consumption to store the same volume of product. Cube ASRSs also allow for quick expansion by adding more storage stacks next to an existing cube. Developing an effective cube ASRS for cold storage would reduce energy consumption from higher storage density and reduced surface areas for heat gain, and would open up floor space to support rapid and low cost expansion from growth in demand. A 3D concept of the combined, chilled and frozen, cube ASRS approach is presented on the left side of Figure 8.

Prototype development started and was iterated on at an internal, Research and Development laboratory to reach a successful design with isolated and separated chilled and frozen temperatures for different storage zones within the cube ASRS. While the prototype successfully reached an effective design, it still needed to be proven in a final use case. A customer site (right image in Figure 8) was selected to install the combined chilled and frozen, cube ASRS. Verification on the frozen and chilled storage temperatures were performed over three testing phases. The verification started with introducing wireless temperature probes into loaded storage containers. Each probe was inserted into a thermal test package (MADI S.r.l.¹) to mimic frozen product and introduce thermal mass. The storage containers were placed in predetermined locations in the cube ASRS to measure the product storage temperature within the dense packing of stacked containers, side-by-side.

The first phase of testing started with no ASRS activity to verify the frozen volumes were designed, installed, and commissioned correctly. Thermal mass in terms of storage product is needed for accurate validation of the volume without potential loss of product. To mimic the thermal mass of storage product, stone bricks in 7.5 kg or 15 kg (16.5 lbs. to 33 lbs.) weight increments were loaded into storage containers in each frozen volume to reach about 60% of its total weight capacity. The second phase introduced emulated ASRS digging activity where robots move containers around, some with thermal mass, and also moved them to picking stations on the ground level at the perimeter of the ASRS. The final verification phase had the actual customer load their chilled and frozen product into the cube ASRS. All thermal bricks were removed as a requirement. To ensure consistent measurements of storage temperature across all three phases, the storage containers with temperature probes were blocked from the ASRS controller to ensure their positions/locations would stay fixed in the cube at both height and proximity.

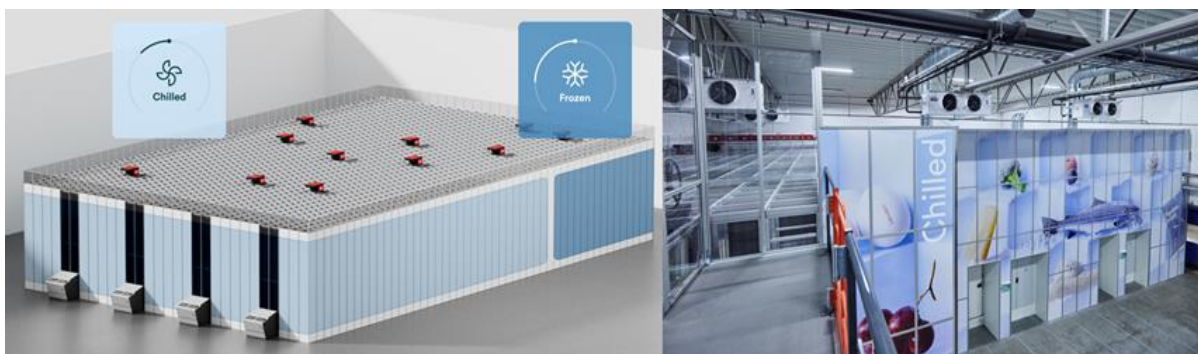


Figure 8: Cube Automated Storage and Retrieval System for Combined Cold Storage Automation with Nested Frozen Volume within Chilled Environment – 3D Model Concept (Left) and Image from the Customer Validation Site (Right).

¹ <https://www.madisnc.com/en>

NESTED FROZEN DESIGN

The design of the nested frozen volume requires a dedicated mechanical room, also known as a freezing chamber, that exchanges air with the internal storage volume to maintain an isolated, frozen storage temperature. Figure 9 illustrates the nested frozen volume approach of the cube ASRS. A mechanical room connects to the nested volume to control the storage temperature. The frozen volume still sits within the cube ASRS and is nested or surrounded by the chilled environment and storage containers. For an effective and isolated, frozen volume, the dimensions of the volume within the cube ASRS are fixed. Multiple volumes can be introduced for more frozen storage capacity where each volume has its own mechanical room.

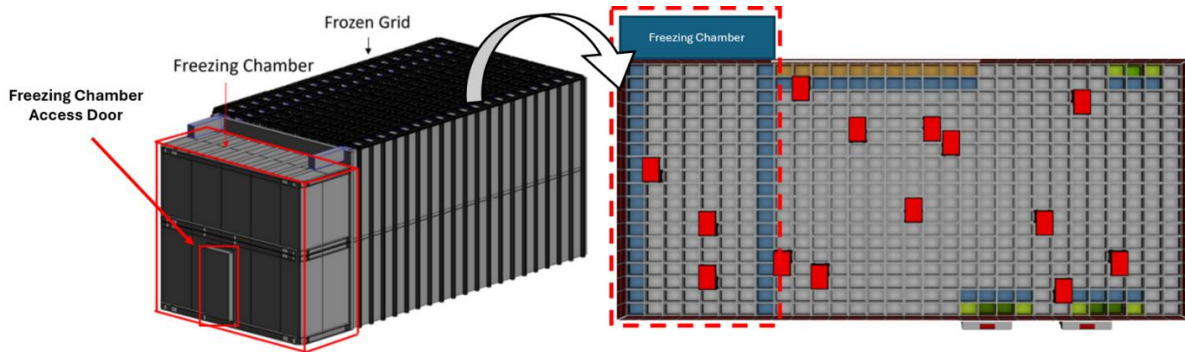


Figure 9: Standalone 3D Image of Nested Frozen Volume with Callout Labels (Left) and 2D Top-Down View of Combined Chilled and Frozen Automated Cube Storage (Right)

The freezing, mechanical room physically sits outside the cube ASRS but is connected to an internal volume that is isolated vertically on all four sides using insulated panels. The top of the frozen volume must be left open within the cube ASRS for robot access to the storage containers or bins within. Freezing temperature air is circulated between the mechanical room and nested volume to maintain a frozen, storage temperature. Two diagrams are presented in Figure 10 that show airflow directions from the side of the volume into the centre and between the volume and the mechanical room.

To prevent the metal, robot grid track from accumulating frost above the frozen volume, a dry, warm air curtain is blown under the track, across the top of the volume, from both sides. For maintaining the frozen storage temperature in the chilled environment, two frozen temperature air streams are blown horizontally across and vertically down the nested, insulated volume. The freezing mechanical room creates negative pressure at the bottom of the nested, connected volume to return the freezing temperature air blown into, and drawn down around, the stacked storage containers. The two air curtain layers on the top of the frozen volume require shorter stacks of containers or bins to avoid blocking these air streams. The prototype testing also provided feedback that if the stack of containers was too tall, the top container would not stay at a sufficiently frozen temperature. The frozen volume has about 3 layers of stacked containers removed to maintain airflow pathways and a sufficient frozen storage temperature for all containers.

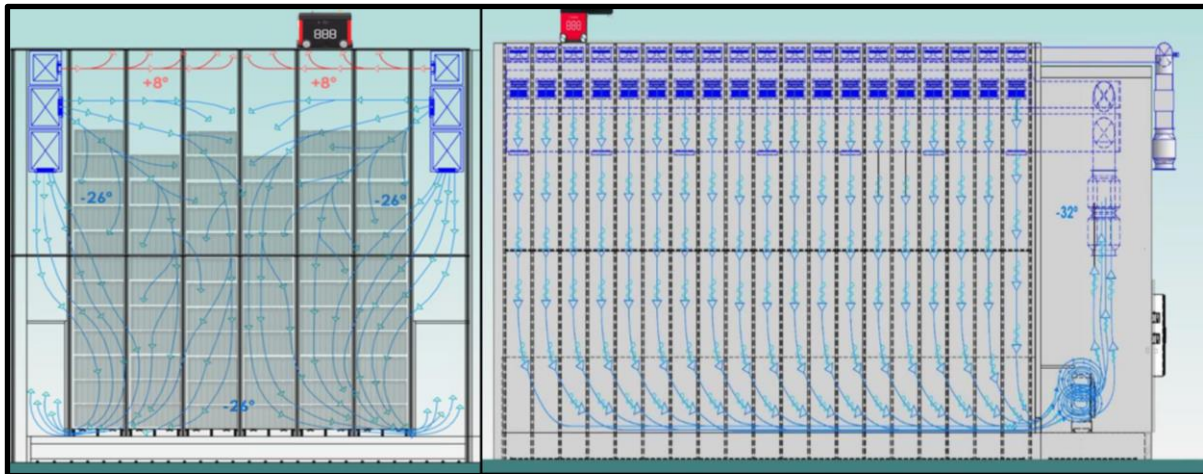


Figure 10: Section Views of Frozen Volume Operation Showing Airflow Pathways from Warm and Cold Air Curtains (Left) and Freezing Chamber Mechanical Room (Right)

CASE STUDY VALIDATION

After iterating the design of the nested, frozen volume in a controlled environment, under simulated usage, it was experimentally validated with actual customer product. A detailed test campaign was developed in conjunction with a 3rd party research lab, SINTEF, to collect sufficient data of a cube ASRS, operating as a combined, chilled and frozen, cold storage warehouse.

Site Details

An existing cold storage warehouse designed for chilled temperatures was repurposed to install the cube ASRS with combined chilled and frozen storage. A section of the warehouse was separated by an insulated wall to be lightly conditioned as a warmer, chilled, or cooled area. The cube ASRS spans both sections where a bridge is formed through an opening in the insulated, separation wall. Figure 11 presents a 2D, top-down view of the cube ASRS layout with each temperature zone labelled. The bridge between cooled and chilled is evident with 6 cells of grid track connecting both temperature zones. The ground-level stations where storage bins are presented to employees picking or loading product are shown on both cooled and chilled zones. The mechanical room for each frozen volume is separated as two, individual rooms but are represented as one continuous box. Figure 11 also maps the location of temperature sensors introduced into storage containers within the cube ASRS as part of the measurement plan.

preventing actual product from being stored in other containers in a stack, the sensor locations could remain fixed during the 12-day validation duration.

FINDINGS

Temperature measurements were collected during the 3rd and final validation phase with customer usage of the cube ASRS instead of simulated usage. The picking or loading of frozen, chilled, or cooled product was monitored over 12 days against temperature measurements from the storage containers within the cube ASRS. The sensors were spread across two, separated frozen volumes, one large, chilled volume, and a smaller, slightly separated, cooled temperature volume.

Frozen Volume

The recorded temperatures in each frozen volume are separately plotted over the 12-day period in Figure 12. In both frozen volumes and across both top and bottom layer containers, all temperatures measured within were under the validation frozen limit of -18°C (-0.4°F). The legend for has each measurement location labelled by the letter corresponding to the 2D map identifying each temperature zone and each sensor location.

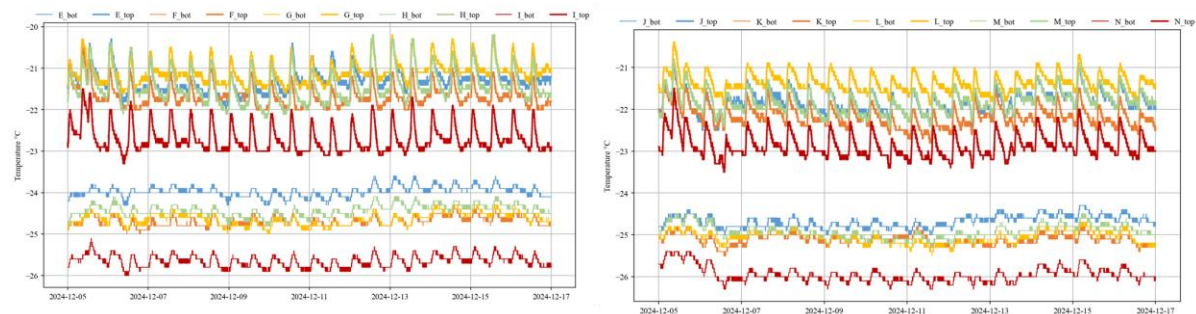


Figure 12: Frozen Volume 1 (Left) and 2 (Right) Internal Storage Container Temperatures during Validation Study

A consistent trend is captured with temperature measurements at the top of a stack reading slightly higher than the bottom layer measurements. The bottom storage areas are less influenced by the warmer, chilled temperatures at the top, above the open, frozen volume. The mechanical room requires a defrost cycle every 12 hours and requires the suspension of cooling on the frozen volume. Each defrost cycle results in a slight warming of the frozen volume, but is short in duration to minimise the temperature rise. A short, repeating pattern is captured by a temperature peak over time across all sensor locations due to the defrost schedule. While frozen temperature measurements reflect interactions with the cube ASRS system and the necessary defrost cycles, all measurements are still under the -18°C (-0.4°F) validation threshold.

Chilled Volume

The temperatures measured in the chilled containers across both top and bottom layers during the 12-day validation period is plotted in Figure 13. The same labels of the locations in the chilled area are used. The bottom data series in the plot corresponds to the amount of storage container or bin operations by the customer across all temperature zones. The container operations are from customer orders requiring stored product to be pulled from the cube ASRS and presented at a ground-level port to an employee. Overall, the chilled volume shows top level temperatures around 3°C to 4°C (37°F to 39°F) and bottom layer temperatures from 0°C to 2°C (32°F to 36°F). The chilled temperatures recorded are all within the allowable range set in by the validation criteria of 2°C (36°F) with $\pm 2^\circ\text{C}$ (3.6°F) allowable range.

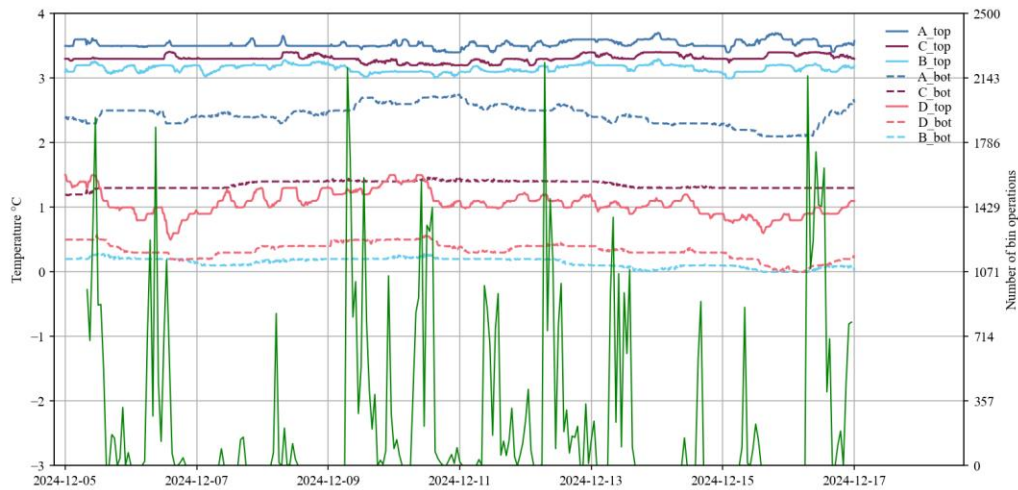


Figure 13: Chilled Volume Internal Bin Temperatures and Frequency of Frozen Volumes Storage Bin Operations during Validation Study

Cooled Volume

For the cooled volume, temperatures recorded over the 12-day period are plotted in Figure 14. Similar to the general trends observed in the frozen or chilled areas, the cooled temperature measurements at the top layer were slightly warmer than the bottom measurements. Overall, the temperatures are within 5.5°C to 8°C (42°F to 46°F) and are within the validation criteria after accounting for sensor inaccuracies. **Error! Reference source not found.**

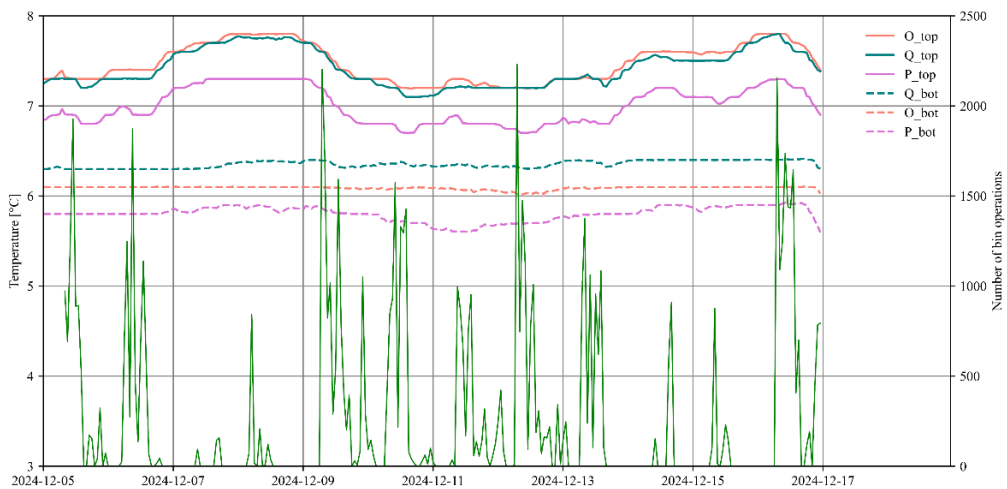


Figure 14: Cooled Volume Internal Bin Temperatures and Frequency of Frozen Volumes Storage Bin Operations during Validation Study

Combined Chilled and Frozen Volumes

Temperature measurements for each frozen volume and the chilled storage volume are postprocessed to summarise their general trends. The minimum, maximum, and average for each unique volume are plotted against the 12-day validation period in Figure 15. The storage container or bin operations are also plotted to compare the amount of cube ASRS activity versus temperatures measured during the validation period.

The chilled temperature summaries show little to no variation at roughly 0°C to 4°C (32°F to 39°F), minimum to maximum, creating a smooth trend over time. The measurements identify the strong stability of the chilled storage temperatures and their isolation from frozen temperatures in the adjacent volume. Both frozen volume summary temperatures follow similar trends for all maximum, minimum, and average temperatures calculated. The defrost cycles are offset for each volume avoid defrosting both mechanical rooms at the same time. The peaks in frozen temperatures capture this offset. The temperature range for each frozen volume was between -26°C to -22°C (-15°F to -8°F), minimum to maximum. The open top design for a frozen volume to be nested within the cube ASRS is confirmed to be isolated, providing a stable storage environment for frozen product.

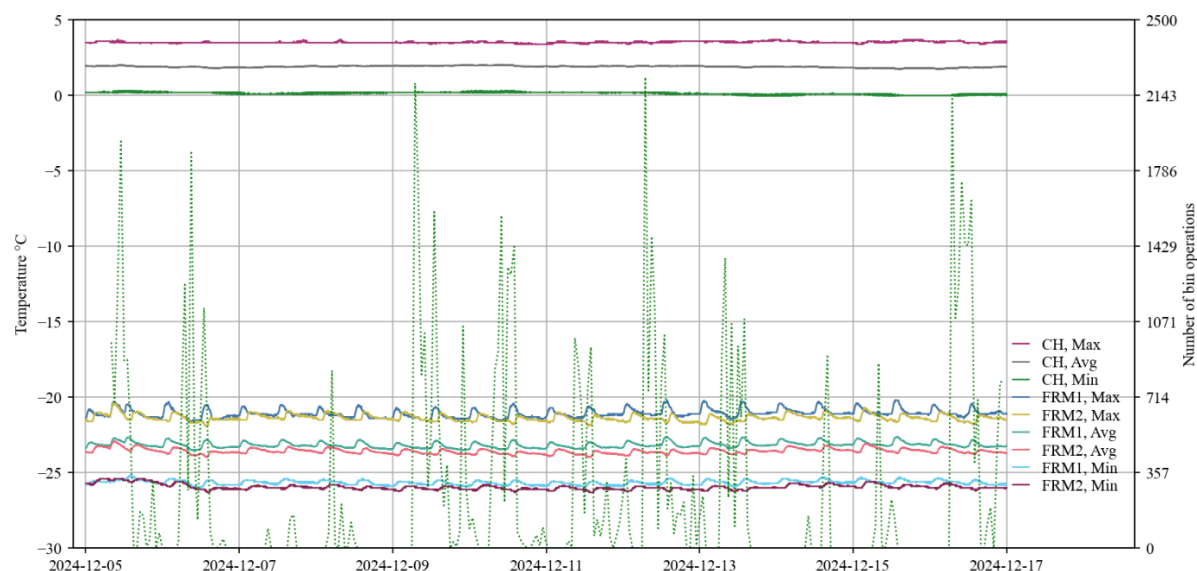


Figure 15: Chilled (CH) and Frozen Volumes (FRM1/2) Temperatures – Average, Minimum, and Maximum Extremes Compared to Frequency of Bin Operations during Validation

DISCUSSION

The approach of nesting a frozen volume within a chilled, cube ASRS can expand the application range of automation into cold storage logistics. The combined chilled and frozen cube ASRS removes labour from working in frozen environments and allows the picking of frozen goods at chilled temperatures. The improved, warmer working conditions with reduced temperature variation will lead to reduced workforce turnover rates that currently impact cold storage logistics. The customer site also validated a third temperature zone, cooled, which could add further value to a combined, cube ASRS in cold storage.

A cube ASRS being effective for combined, cold storage temperatures introduces the density benefits of a compact ASRS. The storage product is closer together, reducing the amount of surface area for heat gain and infiltration. Lower cold storage heat gain rates provide energy savings from reduced, refrigeration cycles. Improved infiltration rates reach better storage temperature control with enhanced temperature stability.

The chilled temperatures measured at location D had the smallest variation between top and bottom measurements due to its proximity to the insulated wall of the first frozen volume. The top layer of chilled containers were typically around 3°C to 4°C (37°F to 39°F) but some frozen air is thought to be brought up when the ASRS is accessing the adjacent frozen volume to location D. While this chilled storage location has a relatively colder trend than other chilled locations measured, it still is above the 0°C (32°F) validation criteria threshold established.

For each frozen volume, the coldest temperatures measured were both in the same approximate location, I and N, within each volume, furthest from the mechanical room, and closest to an insulated wall. The locations are suspected to have higher, relative flow rates of frozen, cold air delivered by the air curtain into the volume. The lower temperature trend at this location is still within the validation criteria of -18°C (-0.4°F) and is only 1°C (1.8°F) colder than other locations within the same frozen volume.

Between the two frozen volumes, the one sandwiched between the chilled and frozen areas had slightly, 1°C (1.8°F) warmer temperatures than the other frozen volume. The ASRS activity in the adjacent chilled volume is suspected to explain the warming interaction measured. Regardless of the slight, 1°C (1.8°F) variation between each frozen volume, both report all measurements below -18°C (-0.4°F) across the top and bottom layers.

CONCLUSION

A novel approach was developed to nest a frozen volume within a cube ASRS to combine cold storage volumes within a single, automated system. The frozen storage volume is nested and isolated within a chilled storage warehouse by insulation and air curtains. After prototype testing validated the design under simulated cold storage operation, it was deployed to a customer site for actual usage. Wireless temperature sensors were spread throughout two nested, frozen storage volumes, a chilled volume, and a cooled volume. Temperature measurements collected during a 12-day period with actual customer usage, picking product, validated the storage temperatures to be isolated within each storage volume. The chilled storage stayed within $\pm 2^{\circ}\text{C}$ (3.6°F) of a 2°C (36°F) temperature level to verify the adjacent and open frozen volumes were isolated. Each frozen volume measured temperatures below -18°C (-0.4°F) to validate a stable and isolated frozen volume. A cube ASRS has combined different cold storage areas into one automated system to remove human labour from working in extreme, cold temperature environments.

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BUILDING RESILIENCE FOR SUPPLY CHAINS

Analysis of the Main Barriers Affecting Sustainable Agriculture Management in Egypt

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Abstract

Egypt's agricultural sector plays a vital role in ensuring food security and driving economic growth. However, it also generates approximately 27 million tons of crop residues annually, much of which is managed through unsustainable practices such as open burning and landfilling. These methods contribute to greenhouse gas emissions, water depletion, soil degradation, and biodiversity loss. This study examines the six key barriers to sustainable agricultural waste management in Egypt, with sustainable agriculture management (SAM) as the independent variable influencing the severity of these obstacles. The identified barriers include waste management, financial limitations, weak policies and regulations, technological and knowledge gaps, socio-cultural resistance, and environmental or geo-economics challenges. Employing a mixed-methods research approach, including survey data and Structural Equation Modelling (SEM), the study finds a strong correlation between increased adoption of SAM practices and a reduction in barrier severity. Specifically, improved SAM practices are shown to alleviate infrastructural constraints by 45%, reduce financial and technological limitations by 35–40%, and remediate socio-cultural and environmental challenges by 30–35%. Based on these findings, the study proposes policy recommendations focusing on investments in rural processing infrastructure, targeted financial incentives, regulatory enhancements, capacity-building initiatives, and community awareness programs. These strategies are crucial for transform agricultural waste into valuable resources and advancing Egypt's Vision 2030 objectives for sustainable development.

Keywords: Agricultural waste, sustainable agriculture management, infrastructure, financial constraints, policy, technology, socio-cultural resistance, environmental challenges, Egypt Vision 2030.

1. Introduction

Egypt's agricultural sector is a cornerstone of the national economy; even though the country has only about 3.3 million hectares of arable, land concentrated primarily in the Nile Delta and reclaimed desert areas. The intensification of agricultural activities has led to the production of nearly 27 million tons of crop residues each year (Bank, 2018) . Unfortunately, over 65% of these residues are disposed of through unsustainable practices such as open burning and landfilling quality (El-Ramady et al., 2020). These disposal methods are responsible for significant greenhouse gas emissions estimated at around 8 million tons of CO₂ equivalent per year and contribute to water scarcity, soil degradation, and declining air (Dabees et al., 2022).

Sustainable agriculture management (SAM), which encompasses strategies such as efficient irrigation, integrated nutrient management, and residue recycling, offers a promising approach to transform agricultural waste into valuable (Velasco Muñoz et al., 2021). Despite the implementation of national initiatives like Egypt's Vision 2030 and the Sustainable Agricultural Development Strategy (SADS 2030), several systemic barriers continue to hinder the adoption of sustainable waste management practices (Vision, 2030). This paper focuses on six primary barriers that impede sustainable agricultural waste

management in Egypt and empirically examines the impact of SAM practices on reducing the severity of these obstacles.

2. Literature Review

Sustainable management of agricultural waste in Egypt has become an increasingly critical area of study, driven by escalating environmental challenges and the imperative to transform vast quantities of crop residues into valuable resources. Researchers have demonstrated that the mismanagement of agricultural by products is not simply a localised waste problem but a complex issue with significant impacts on climate change (Barakat et al., 2022), soil fertility, and water resource sustainability. This review synthesises key studies and theoretical perspectives, with a focus on how sustainable agriculture management (SAM) practices can help overcome the barriers to effective waste management (Koul et al., 2022).

2.1 Sustainable Agriculture Management (SAM)

SAM encompasses a range of practices, including efficient irrigation, integrated nutrient management, and organic residue recycling, that are designed to optimise resource use and reduce environmental degradation. Empirical studies have shown that the implementation of SAM practices can improve water use efficiency (Barbosa Junior et al., 2022), lower dependency on chemical fertilisers, enhance soil health, and reduce greenhouse gas emissions. Adaptive SAM strategies are increasingly recognised as essential in mitigating the adverse effects of climate change, particularly in regions experiencing growing water scarcity (Tittonell et al., 2020).

2.2 Agricultural Waste Barriers

Egypt's agricultural sector produces nearly 27 million tons of crop residues each year. Despite this substantial resource, unsustainable disposal methods most notably open burning and landfilling remain prevalent. Open burning alone is estimated to emit around 8 million tons of CO₂ equivalent annually, significantly degrading air quality and contributing to climate change (Shalaby et al., 2011). In regions where rice straw burning is common, the resulting black cloud episodes have severe public health and environmental repercussions (Dabees et al., 2022). Such practices lead to the loss of valuable biomass and the depletion of soil organic matter, while also contributing to inefficient water use.

An emerging concept is reverse agriculture, which involves the systematic collection, processing, and reintegration of agricultural waste into the production cycle. While reverse logistics is well established in the manufacturing sector (Dabees et al., 2023) (Ali et al., 2018), its application in agriculture remains underexplored. Recent studies suggest that technologies like anaerobic digestion and pyrolysis can transform waste into renewable energy, organic fertilisers, and soil amendments, thereby closing the production loop (Goodman, 2020).

2.3 Policy and Regulation Barriers

Egypt has set ambitious targets for sustainable development through initiatives such as Vision 2030 and the Sustainable Agricultural Development Strategy considering the legal obstacles which need to cope with global changes (Ibrahim et al., 2020).

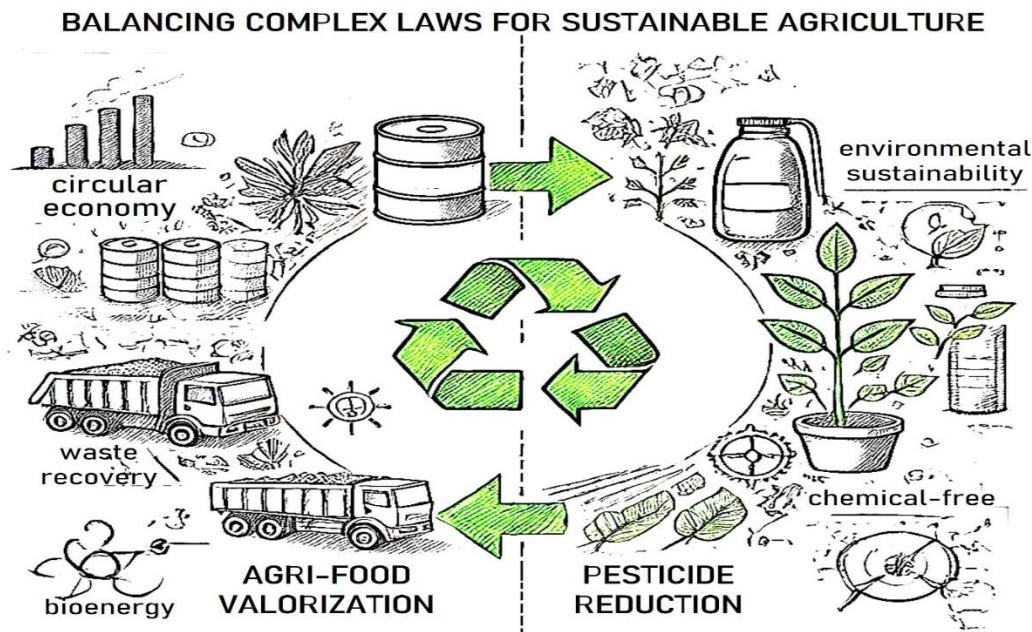


Figure. 1 Regulation Barriers for SAM (Nicastro et al., 2024)

Nevertheless, fragmented regulatory frameworks and inconsistent enforcement hinder the implementation of supportive policies across government agencies. Research indicates that such regulatory fragmentation results in a 30–40% lower adoption rate of sustainable practices compared to nations with more cohesive policies (Tellioglu and Konandreas, 2017). Furthermore, inadequate guidelines and limited financial incentives continue to dissuade investments in modern waste management technologies (Shalaby et al., 2011).

2.4 Financial Barriers

Financial limitations are among the most frequently cited barriers to sustainable agricultural waste management. A significant number of smallholder farmers, who form the backbone of Egypt's agricultural production, lack access to affordable credit and capital (Lago-Oliveira et al., 2023). Studies reveal that nearly 80% of these farmers are unable to invest in advanced residue recycling technologies, such as mechanised composting or anaerobic digesters (Tellioglu and Konandreas, 2017). Additionally, the existing subsidy framework, which traditionally favours chemical fertilisers, further discourages the adoption of sustainable alternatives (Tittonell et al., 2020).

2.5 Technological Barriers

Technological and knowledge gaps, along with entrenched socio-cultural practices, also impede the transition toward sustainable waste management. Research indicates that only about 18% of farmers are familiar with modern techniques such as composting and biochar production (Hefnawy and Ahmed, 2024). The limited reach of extension services in rural areas exacerbates this knowledge deficit, making it difficult for farmers to adopt innovative practices. Furthermore, deep-rooted cultural practices such as the traditional method of open burning pose significant challenges to change (El-Ramady et al., 2020).

2.6 Socio-Cultural Barriers

Socio-cultural resistance represents a notable barrier to the adoption of sustainable practices. Many farmers continue to rely on traditional methods despite clear evidence of the benefits of modern waste management. However, targeted community engagement

and awareness campaigns have shown promise in shifting attitudes and promoting sustainable practices (Sroka et al., 2019). In addition to these cultural factors, environmental challenges particularly those related to climate change and water scarcity further complicate waste management efforts (Lago-Oliveira et al., 2023).

2.7 Environmental Challenges

Egypt's environmental and geopolitical context adds further complexity to agricultural waste management. Water scarcity, aggravated by climate change, is a critical issue in agricultural production. In reclaimed New Lands, water usage may reach 22,700 m³/ha, compared to 20,350 m³/ha in the Nile Delta (Hefnawy and Ahmed, 2024). Moreover, Egypt's reliance on the Nile that supplies approximately 97% of its renewable water exposes the country to geopolitical risks, particularly amid disputes over water rights and upstream projects such as Ethiopia's Renaissance Dam (Tittonell et al., 2020). These pressures highlight the necessity for adaptive SAM practices that address both environmental sustainability and resource scarcity. In summary, the literature highlights that sustainable agricultural waste management in Egypt is a complex challenge requiring a comprehensive approach. Effectively implementing SAM practices can convert agricultural residues into valuable resources while reducing environmental impact.

3. Methodology

3.1 Research Design

This study employs a mixed-methods approach, incorporating statistical analysis using SPSS to examine the relationship between sustainable agriculture management (SAM) practices and the severity of challenges in sustainable agricultural waste management. In our conceptual framework, SAM serves as the dependent variable, while the perceived intensity of six distinct barrier categories functions as the independent variables. Quantitative data will be analysed using SPSS to identify patterns, correlations, and statistical significance, while qualitative insights will complement the findings to provide a comprehensive understanding of the research problem. This approach ensures a robust analysis by integrating numerical data with contextual interpretations, enhancing the depth and reliability of the study's conclusions.

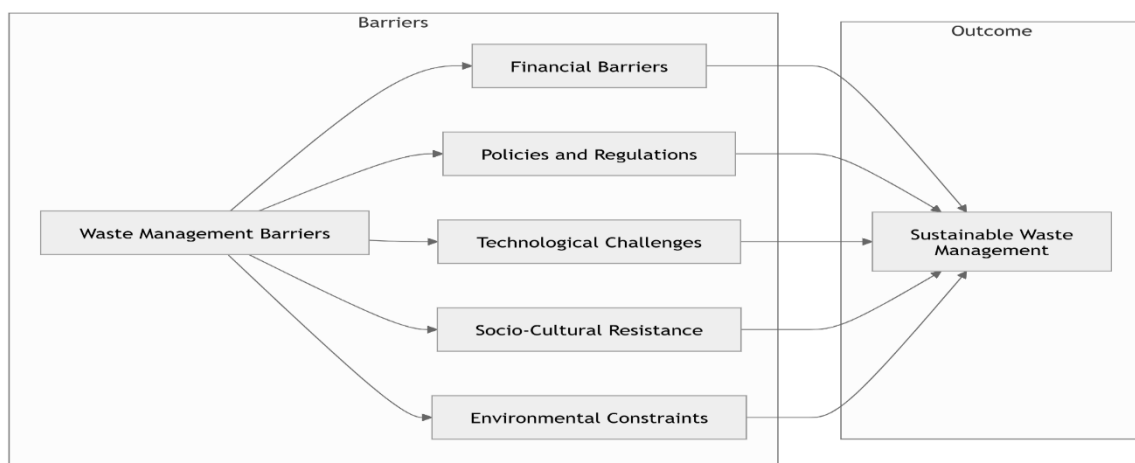


Figure.2 Sustainable Waste Management (SAM) Framework

3.2 Data Collection

The data was collected using a structured questionnaire, designed after reviewing previous studies on waste management and reverse logistics. The questionnaire had two main parts: the first assessed sustainable farming practices like efficient irrigation, recycling organic waste, managing nutrients, and using modern farming methods. The second part examined six types of challenges farmers face, rated on a scale from 1 (strongly disagree) to 5 (strongly agree). A total of 133 farmers and agricultural stakeholders from different regions of Egypt took part in the survey. The measurement model was carefully tested to ensure validity and reliability.

3.3 Hypotheses

The research based on the following hypotheses:

H1: Enhanced sustainable agriculture management practices will significantly reduce the perceived severity of infrastructural barriers.

H2: Improved SAM practices will alleviate financial constraints and investment challenges.

H3: Strengthening SAM is associated with better policy compliance and regulatory adherence, thereby diminishing related barriers.

H4: Higher levels of SAM will help bridge technological and knowledge gaps in waste management.

H5: Adoption of SAM will lead to a reduction in socio-cultural resistance towards modern waste management practices.

H6: Effective SAM practices will mitigate the environmental challenges affecting waste management.

4. Results

The survey collected 133 valid responses from farmers, company representatives, and extension stakeholders across different regions, including both smallholders (less than 3 feddans) and larger farms, ensuring a diverse perspective on waste management practices. Descriptive statistics revealed that only 18% of respondents had adopted modern sustainable agriculture management (SAM) practices, while 65% still relied on traditional methods like open burning. Structural Equation Modelling (SEM) analysis tested the relationship between SAM adoption and the severity of six barrier categories, showing strong model fit (CFI = 0.96; RMSEA = 0.054). The path coefficients (denoted as β) represent the strength and direction of the relationships between SAM and each barrier category. A negative β indicates that as SAM improves the perceived severity of the barrier decreases. Statistical significance shown by p-values, where $p < 0.01$ indicates strong significance and $p < 0.05$ indicates moderate significance. The results are as follows: The results indicated that improved SAM practices significantly reduce perceived infrastructural barriers ($\beta = -0.45$, $p < 0.01$), financial constraints ($\beta = -0.38$, $p < 0.05$), policy frameworks ($\beta = -0.42$, $p < 0.01$), and technological and knowledge gaps ($\beta = -0.40$, $p < 0.01$). Additionally, SAM adoption moderately lowers socio-cultural resistance ($\beta = -0.35$, $p < 0.05$) and environmental and geo-economics challenges ($\beta = -0.33$, $p < 0.05$). These findings suggest that investments in efficient irrigation and organic residue recycling, key components of SAM can reduce infrastructural and policy-related barriers by 40–45%. Moreover, financial and technological constraints improve as SAM practices become more widespread, highlighting the potential of resource-efficient farming to enhance environmental outcomes while addressing systemic challenges.

5. Discussion

The SEM results highlight that adopting sustainable agriculture management (SAM) practices plays a crucial role in mitigating the perceived severity of the six key barriers to sustainable agricultural waste management in Egypt. Specifically, investments in efficient irrigation systems and organic residue recycling both integral components of SAM are linked to 40–45% reduction in infrastructural and policy-related challenges, demonstrating that resource-efficient farming practices can alleviate systemic constraints. Furthermore, financial and technological barriers are notably diminished with the adoption of SAM, as modern agricultural techniques improve cost-effectiveness and access to advanced farming tools. Beyond these quantitative improvements, the results suggest that a holistic approach integrating SAM with strong policy support and infrastructure development is essential for long-term sustainability. The collaboration of multiple stakeholders including government agencies, financial institutions, extension services, and private enterprises is vital in driving the widespread adoption of SAM. Effective policy reforms that incentivise sustainable farming, coupled with strategic investments in technology and infrastructure, can significantly accelerate progress. Additionally, awareness campaigns and targeted training programs are needed to address socio-cultural and environmental barriers, fostering a shift in perceptions and enhancing farmers' knowledge of sustainable practices. These findings emphasise that a coordinated and well-supported transition towards SAM can transform agricultural waste management, improving both environmental and economic outcomes in the long term.

6. Conclusion

The SEM results affirm that Sustainable Agriculture Management (SAM) is a transformative strategy for reducing barriers to sustainable agricultural waste management in Egypt. By mitigating infrastructural, financial, policy, technological, socio-cultural, and environmental challenges, SAM paves the way for a more resilient and efficient agricultural sector. However, its success hinges on a coordinated effort that combines modern practices with policy reforms, infrastructure improvements, and stakeholder collaboration. As Egypt strives for sustainable development, SAM offers a blueprint for balancing environmental stewardship with systemic progress.

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The Impact of Port Logistics Service Quality on Customer Satisfaction and Loyalty: An Analysis of Differences by Business Type

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INTRODUCTION

Port logistics serves as a critical node in the global supply chain, facilitating international trade efficiency and economic growth. In 2023, Vietnam's total cargo throughput reached 756.8 million tons, reflecting a 5% year-over-year increase, with maritime transport handling nearly 90% of the country's import-export volume (General Statistics Office, 2023). However, the sector faces major challenges, including inflationary pressures, geopolitical tensions (e.g., the Russia-Ukraine conflict), and soaring transportation costs - rising by nearly 60% (UNCTAD, 2022). Financial burdens have further intensified due to interest rate and exchange rate fluctuations in major economies such as the U.S. and EU (Oxford Economics, 2024). Consequently, Vietnam ranked 43rd in the Global Logistics Performance Index (LPI), lagging behind regional competitors like Singapore and Thailand (World Bank, 2023).

In response, enhancing port logistics service quality has become an investment priority. The Vietnamese government has allocated approximately VND 313 trillion for infrastructure upgrades and service enhancements from 2021 to 2030 (Vietnam Maritime Administration, 2021). However, resource allocation remains a key challenge, as misdirected investments in equipment, cargo handling efficiency, or digital transformation may fail to meet customer expectations (Talley, 2006).

Tan Cang - Cai Mep Thi Vai Terminal Co., Ltd. (TCTT), a subsidiary of Saigon Newport Corporation, has been a key player in the Cai Mep - Thi Vai international port cluster since 2016, handling 35% of Vietnam's import-export container volume. Despite an average annual growth rate of 12% (2019 - 2023), TCTT faces congestion on key transport routes (e.g., National Highway 51), high logistics costs, and underdeveloped inland waterway infrastructure, leading to increased expenses and extended transit times. Additionally, limited integration among terminals, automation gaps, and inefficiencies in customs procedures reduce operational effectiveness (Ba Ria - Vung Tau Newspaper, 2024).

This study investigates the relationship between port logistics service quality, customer satisfaction, and loyalty, focusing on differences across business types, including shipping lines (direct customers), freight forwarders, import-export companies, and manufacturing/service providers (often indirect customers). Recognising the influence of INCOTERMS, such as Free on Board (FOB) terms prevalent among Vietnamese exporters, the research accounts for varying decision-making authority in port selection. For instance, under FOB, buyers typically choose the port, limiting exporters' influence on service quality evaluations (Tongzon, 2009). By leveraging the ROPMIS framework (Thai, 2008), this study aims to address these complexities, guiding TCTT's investment strategies to optimise service quality, enhance customer satisfaction, and foster loyalty. The findings will strengthen TCTT's competitive position against rivals and attract B2B clients, ultimately fostering long-term growth for TCTT and Vietnam's port logistics sector.

LITERATURE REVIEW

Since the 1980s, research on service quality, customer satisfaction, and loyalty has developed foundational frameworks that remain influential in port logistics studies. Oliver's (1980) Expectation-Disconfirmation Theory posits that satisfaction arises when service performance meets or exceeds customer expectations. Grönroos' (1984) Technical/Functional Quality Model distinguishes between technical (outcome-based) and

functional (process-based) service aspects. Parasuraman et al.'s (1985) SERVQUAL model introduced five dimensions - Reliability, Responsiveness, Assurance, Empathy, and Tangibles - while Cronin and Taylor's (1992) SERVPERF emphasised performance-based measures. Dabholkar et al. (2000) further explored antecedents and mediators of service quality, highlighting the complexity of customer perceptions. These models provide a theoretical foundation for port logistics research but require adaptation to address the sector's operational and managerial nuances.

Research on the Determinants of Port Logistics Service Quality

Early port logistics studies, such as Foster (1979) and Murphy et al. (1987), identified key port selection factors, including infrastructure and accessibility, but overlooked discrepancies between customer expectations and service perceptions. By the early 21st century, research expanded to address these gaps, predominantly applying SERVQUAL and SERVPERF. Chang et al. (2008) surveyed 137 South Korean shipping companies, identifying Reliability as the primary driver of satisfaction. Similarly, Shanaki et al. (2012), surveying 216 customers at Shahid Rajaei Port, emphasised Tangibles, Employee Competence, and Accessibility. In Kenya, Riitho (2018) found that Reliability, Speed, and Responsiveness were critical, especially in competitive port environments. In Vietnam, studies by Le et al. (2020) at Cat Lai Port highlighted the prominence of Responsiveness, Assurance, Empathy, and Tangibles. Despite its widespread adoption, SERVQUAL has faced criticisms regarding its applicability to complex service industries, including banking and supply chain management. Within port logistics services, its limitations stem from its inability to incorporate customer expectations (Chang et al., 2008) and its exclusion of managerial and operational factors (Lee et al., 2013).

To overcome these limitations, Thai (2008) introduced the ROPMIS model, which integrates five dimensions: Resources, Outcomes, Processes, Management, and Image & Social Responsibility. Unlike SERVQUAL, ROPMIS accounts for corporate responsibility and environmental management, making it more suitable for maritime transport services. Empirical validations of ROPMIS include studies on container terminals (Tepe, 2015), road transport (Thai et al., 2014), and freight forwarding (Gil-Saura et al., 2018). In port logistics, ROPMIS has proven effective in multiple contexts. Yeo et al. (2015), based on 313 members of the Korea Port Logistics Association, found that Management, Image, and Social Responsibility were highly influential. In Singapore, Thai (2016) emphasised Service Outcomes as the primary driver of customer satisfaction, advocating for green infrastructure investments. In Vietnam, Phan et al. (2021) underscored the importance of Service Outcomes, Image, and Social Responsibility, particularly in relation to cybersecurity and service diversification. However, existing studies require further expansion across diverse geographical contexts and should integrate customer loyalty metrics to enhance generalizability and managerial applicability.

Research on the Relationship Between Port Logistics Service Quality, Customer Satisfaction and Loyalty

Using the SERVQUAL framework and the PLS-SEM method, Cho et al. (2010) analysed 215 customers and found that extrinsic service quality and relationship quality had significant impacts on satisfaction and post-purchase behaviour, whereas intrinsic quality had a lesser effect. The study also revealed that at Incheon Port, only extrinsic quality was crucial for all customer segments, whereas at Shanghai Port, the relative importance of the three dimensions varied depending on customer demographics. Similarly, Lin et al. (2023) applied the SOR model to 810 customers in China, demonstrating that satisfaction was most strongly influenced by Personal Interaction and Service Customisation. Additionally, Chang & Thai (2016) conducted a study at Kaohsiung Port with 104 logistics managers and concluded that port service quality (both hardware and software) had a more substantial impact on customer satisfaction and loyalty than port security quality (personnel security and procedural security). However, these studies are limited by small sample sizes, narrow geographic scope, and a lack of focus on specific service sub-factors and qualitative

moderators, such as cultural or demographic influences, which could refine loyalty predictions (Jang et al., 2013). Further research is needed to explore loyalty through repurchase intentions and positive word-of-mouth for greater generalizability.

Research on Customer Segmentation and INCOTERMS in Port Logistics

Customer segmentation is vital in port logistics, as diverse decision-making roles shape service quality perceptions and loyalty (Vinh & Tra, 2020). Shipping lines, direct port users, prioritise operational efficiency and reliable infrastructure to support fixed routes, often making long-term port commitments (Dulebenets et al., 2021). For instance, Hapag-Lloyd's 2023 acquisition of Jm Baxi's port operations in India illustrates their strategic supply chain investments (Dulebenets et al., 2021). Freight forwarders, as intermediaries, have limited port selection autonomy, following shipping line or shipper directives (Jang et al., 2013). Ports attract forwarders through competitive strategies, such as reduced handling fees and faster cargo processing (Alfares & Ghaithan, 2016).

In Vietnam, INCOTERMS shape port selection for indirect users like import-export firms and manufacturing/service providers. Free on Board (FOB) terms, prevalent in Vietnam, transfer port choice to buyers, limiting exporters' ability to assess service quality, while Cost, Insurance, and Freight (CIF) terms give shippers greater control (Tongzon, 2009; Murphy et al., 2023). Vinh and Tra (2020) divide these users into two groups: (1) large import-export firms with long-term port partnerships, prioritizing cost, route efficiency, and delivery conditions, and open to switching ports if inefficiencies occur; and (2) smaller manufacturing/service firms, reliant on shipping lines, valuing customer support, cost transparency, and problem resolution due to infrequent port interactions. FOB terms reduce exporters' agency, decreasing loyalty, whereas CIF aligns shippers' priorities with direct customers' focus on cost and efficiency. Indirect users emphasise communication and transparency, which drive their loyalty (Nguyen et al., 2024).

Despite their importance, INCOTERMS and customer segmentation are underexplored in port service quality models, particularly in Vietnam's competitive port sector. This study refines the ROPMIS framework to analyse how service quality affects satisfaction and loyalty across business types and INCOTERMS-driven decision-making roles. By incorporating loyalty metrics like repurchase intentions and word-of-mouth, it provides actionable insights to strengthen port competitiveness and foster enduring customer relationships.

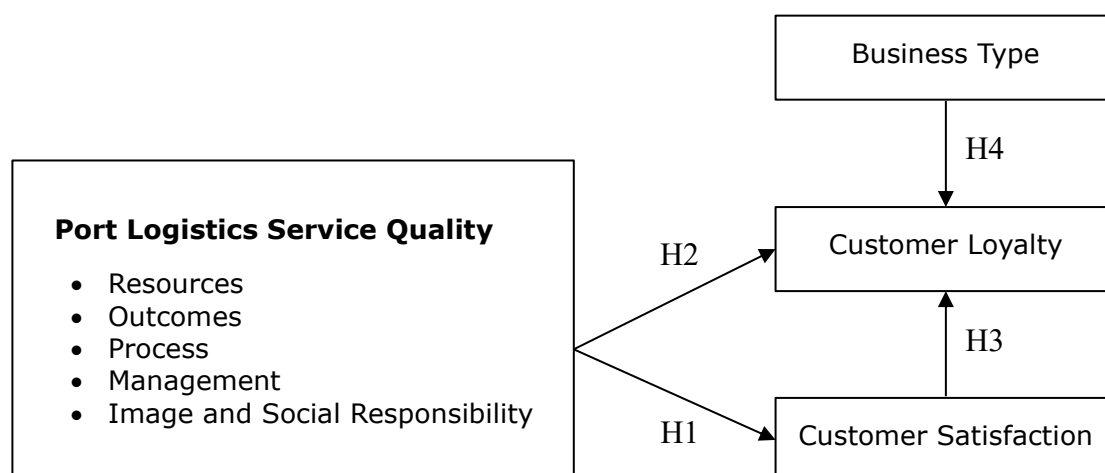
RESEARCH PROBLEM

Existing research on port logistics service quality has contributed substantial theoretical and practical insights; however, several limitations persist concerning generalizability and unresolved issues. Traditional models such as SERVQUAL and SERVPERF fail to encapsulate the full spectrum of service quality determinants, whereas the ROPMIS framework, while more applicable to the maritime sector, requires further refinement. Additionally, international studies predominantly employ quantitative methodologies, lacking qualitative insights and failing to account for demographic heterogeneity across markets. Given the behavioural and psychological variations among customer segments (Cho et al., 2010), a mixed-methods approach is essential for a more comprehensive analysis. Furthermore, research gaps persist in assessing customer loyalty, particularly in measuring repurchase intentions and positive word-of-mouth, necessitating the development of more robust loyalty assessment frameworks. In Vietnam, although studies have validated the SERVQUAL and ROPMIS models, they remain limited in scope and sample size, with insufficient exploration of customer segmentation, relationship quality, and port security.

This study aims to enhance and refine the conceptual framework of port logistics service quality by investigating the impact of service quality determinants on customer satisfaction and loyalty through behavioural indicators such as loyalty intentions, repurchase behaviour, and positive word-of-mouth. Leveraging the ROPMIS framework (Thai, 2008) alongside insights from Chang & Thai (2016), this research establishes a robust theoretical and

methodological foundation, addressing existing empirical gaps and contributing to strategic decision-making in port logistics management.

Figure 1. The conceptual framework of this study



By the previously stated research objective, the conceptual framework is illustrated in Figure 1, and the developed hypotheses are as follows:

Hypothesis Group H1: There is a relationship between port logistics service quality determinants and customer satisfaction.

Hypothesis Group H2: There is a relationship between port logistics service quality determinants and customer loyalty.

Hypothesis Group H3: There is a direct and mediating role of customer satisfaction in the relationship between port logistics service quality determinants and customer loyalty.

Hypothesis H4: There is a relationship between customer business type and loyalty.

RESEARCH METHODOLOGY

This study adopts a primarily quantitative approach, supplemented by qualitative expert interviews to validate the survey instrument, ensuring methodological rigour and alignment with port logistics dynamics at TCTT.

Qualitative Research Method

After developing the preliminary measurement scale, the author conducted expert interviews with three faculty members specialising in Logistics and Supply Chain Management, three senior managers from TCTT port with extensive industry experience, and two mid-level managers from the Operations and Logistics departments of Ocean Network Express (ONE) Vietnam. The primary objective was to validate the accuracy, appropriateness, and clarity of technical terminology and survey wording while ensuring respondents fully comprehended the survey's purpose and focus, thereby minimising redundancy. The selection criterion for item retention or addition was based on consensus from at least five out of eight experts. Ultimately, the experts unanimously agreed to retain the entire measurement scale without modifications, as the 35 observed variables were deemed comprehensive and representative of all relevant factors and dimensions. However, they recommended refining the wording for improved clarity, specificity, and contextual alignment with TCTT port operations.

Table 1. Survey items for survey development

Construct		Measurement item	Source
Port Logistics Service Quality (PLSQ)	Resources (RE)	RE1: TCTT port is consistently equipped with state-of-the-art machinery, equipment, and infrastructure, including container yards, traffic guidance systems in each area, laden and empty container forklifts, and complimentary Wi-Fi access.	Thai (2008), Yeo et al. (2015), Chang & Thai (2016)
		RE2: TCTT port's equipment, machinery, and infrastructure are modern and consistently in optimal working condition.	
		RE3: TCTT port's infrastructure, including terminals, warehouses, distribution centers, and domestic connectivity networks, is well-organized and strategically located to facilitate cargo handling and related procedures.	
		RE4: TCTT port has an efficient tracking and positioning system for cargo shipments.	
		RE5: TCTT port maintains financial stability and possesses strong financial resources.	
	Outcomes (OU)	OU1: TCTT port provides simplified customs clearance services and rapid processing times.	
		OU2: TCTT port ensures accurate and transparent invoicing and documentation.	
		OU3: TCTT port guarantees the security and safety of vessels and cargo.	
		OU4: TCTT port delivers reliable services and has established policies to protect customer data and privacy.	
		OU5: TCTT port ensures service consistency and synchronization across all operations.	
		OU6: TCTT port offers competitive service pricing.	
	Process (PR)	PR1: The personnel across various departments and functional units at TCTT port exhibit professionalism in both attitude and conduct.	
		PR2: TCTT port staff are highly competent, well-versed in customer needs, and responsive to requirements.	

Construct		Measurement item	Source
		PR3: TCTT port's personnel promptly address inquiries and service requests through multiple support channels, including email, hotline, call center, Zalo, and Facebook fan page.	
		PR4: The application of Information and Communication Technology (ICT) in customer service at TCTT port is comprehensive.	
	Management (MA)	MA1: The application of ICT in TCTT port operations and management is comprehensive, including e-port systems, e-invoicing, terminal operating system planning software (TOPX), container data management software (TOPO), the new container management software (TOPOVN), and the RIVER GATE platform for barge operations.	
		MA2: TCTT port demonstrates high operational efficiency in managing and executing activities such as laden/empty container handling, customs inspection, quarantine, fumigation, container scanning, cargo stuffing and stripping, as well as empty container cleaning and repair.	
		MA3: TCTT port management team possesses expertise, knowledge, and strong soft skills, including problem-solving capabilities.	
		MA4: TCTT port actively collects customer feedback to refine and enhance service quality with a customer-centric approach.	
		MA5: TCTT port continuously improves management and operational processes in alignment with customer-oriented strategies.	
	Image and Social Responsibility (IS)	IS1: TCTT port maintains strong collaborative relationships with other ports in the Cai Mep - Thi Vai port cluster and road transport service providers.	
		IS2: TCTT port holds a strong market reputation for reliability.	
		IS3: TCTT port prioritizes occupational safety in all operations.	
		IS4: TCTT port effectively fulfills its corporate social responsibilities towards employees and other	

Construct		Measurement item	Source
		stakeholders.	
		IS5: TCTT port consistently emphasizes and complies with environmental regulations in port operations and management.	
		IS6: TCTT port has an established environmental management system.	
Customer Satisfaction (CS)		CS1: Overall, we are satisfied with TCTT port’s infrastructure, equipment, and facilities.	Anderson et al. (2008), Pantouvakis (2010), Cao & Chen (2011)
		CS2: Overall, we are satisfied with TCTT port’s management team and personnel across various functional departments.	
		CS3: Overall, we are satisfied with the service quality provided by TCTT port.	
Customer Loyalty (CL)		CL1: We are willing to continue our business collaboration with TCTT port in the coming year.	Kim et al. (2001), Al-Adwan et al. (2022)
		CL2: TCTT port remains our top choice for future business activities.	
		CL3: We will recommend TCTT port’s services to our business partners.	

Quantitative Research Method

The survey used a structured questionnaire with clear, concise questions on a 5-point Likert scale, incorporating screening questions to confirm respondents' relevance (e.g., business type: shipping lines, freight forwarders, import-export firms, manufacturing/service providers; INCOTERMS usage: FOB, CIF; and monthly port service interactions). A convenience sampling method was employed due to its efficiency in accessing TCTT's customer base, despite potential bias, which was mitigated by targeting diverse customer segments (Etikan et al., 2016).

Data collection occurred from September to October 2024, targeting 250 TCTT customers who regularly used port logistics services. A multi-channel approach combined in-person surveys at TCTT facilities with online distribution via Google Forms, QR codes, and digital platforms (Email, Zalo, Facebook), ensuring broad reach. This yielded 225 valid responses (90% response rate), sufficient for robust statistical analysis.

For data analysis, the study applied descriptive statistical techniques, PLS-SEM and One-way ANOVA to assess both the measurement and structural models and test the research hypotheses. All quantitative analyses were conducted using SmartPLS 4.0 and SPSS 26.0, ensuring robust statistical validation.

RESULTS AND ANALYSIS

Table 2. Descriptive Statistics

VARIABLES	FREQUENCY	PERCENTAGE
Registered Business Location	225	100.0%
Ho Chi Minh City	135	60.0%
Binh Duong Province	20	8.9%
Dong Nai Province	30	13.3%
Ba Ria - Vung Tau Province	36	16.0%
Others	4	1.8%
Type of Business	225	100.0%
Shipping Line	42	18.7%
Freight Forwarder	62	27.6%
Import-Export Company	101	44.9%
Manufacturing/Service Provider Company	16	7.1%
Others	4	1.8%
Service Usage Frequency	225	100.0%
Less than 3 times	23	10.2%
3 to 5 times	47	20.9%
5 to 8 times	88	39.1%
8 to 10 times	58	25.8%
More than 10 times	9	4.0%

After eliminating three observed variables (RE1, OU5, and IS7) that did not meet the threshold for outer loading coefficients, the author revalidated the model to ensure that all remaining observed variables achieved a loading value of at least 0.7 (Hair et al., 2019). Subsequently, reliability testing, convergent validity, and discriminant validity assessments of the measurement scale were conducted. The results indicated that all constructs exhibited Cronbach's Alpha and Composite Reliability values above the 0.7 threshold (Bagozzi & Yi, 1988), while the Average Variance Extracted (AVE) exceeded 0.5, confirming strong convergent validity and high reliability of the scales. Moreover, the square root of AVE was greater than the correlations between latent variables, and all HTMT ratios were below 0.9, reinforcing the discriminant validity of the constructs. Furthermore, based on

the Inner VIF values, it can be concluded that the model does not suffer from multicollinearity issues (Hair et al., 2019).

Table 3. Evaluate the suitability of the model

	R Square	Adjusted R Square	Q² Predict
CS	0.486	0.474	0.458
CL	0.462	0.447	0.421

Table 3 indicates that the port logistics service quality factors explain 47.4% of the variance in customer satisfaction (CS) and 44.7% of the variance in customer loyalty (TT). Additionally, the Q² values range from 0.25 to 0.5, suggesting that the model demonstrates a moderate to high level of predictive accuracy.

Table 4. Assessment of Path Significance

	Path	Path Coefficient	T-statistics	P Value	Decision
H1a:	RE → CS	0.161	2.910	0.004	Significant
H1b:	OU → CS	0.322	4.647	0.000	Significant
H1c:	PR → CS	0.134	2.337	0.020	Significant
H1d:	MA → CS	0.151	2.471	0.014	Significant
H1e:	IS → CS	0.197	3.440	0.001	Significant
H2a:	RE → CL	0.173	3.651	0.000	Significant
H2b:	OU → CL	0.209	2.883	0.004	Significant
H2c:	PR → CL	0.128	2.042	0.041	Significant
H2d:	MA → CL	0.103	1.965	0.049	Significant
H2e:	IS → CL	0.181	3.120	0.002	Significant

	Path	Path Coefficient	T-statistics	P Value	Decision
H3a:	CS → CL	0.158	2.325	0.020	Significant
H3b:	RE → CS → CL	0.026	1.729	0.084	Not Significant
H3c:	OU → CS → CL	0.051	2.111	0.035	Significant
H3d:	PR → CS → CL	0.021	1.573	0.116	Not Significant
H3e:	MA → CS → CL	0.024	1.613	0.107	Not Significant
H3f:	IS → CS → CL	0.031	1.908	0.056	Not Significant

Table 4 shows that all standardised path coefficients are positive and have p-values smaller than 0.05, confirming that all five components of port logistics service quality positively impact customer satisfaction and loyalty. Analysing the magnitude of the standardised path coefficients, the Outcome factor ($\beta_1 = 0.322$) has the strongest influence on customer satisfaction, followed by Image and Social Responsibility ($\beta_1 = 0.197$), Resources ($\beta_1 = 0.161$), Management ($\beta_1 = 0.151$), and Process ($\beta_1 = 0.134$). Regarding customer loyalty, Outcome ($\beta_2 = 0.209$) remains the most influential factor, followed by Image and Social Responsibility ($\beta_2 = 0.181$) and Resources ($\beta_2 = 0.173$). Process ($\beta_2 = 0.128$) also has a significant impact, while Management ($\beta_2 = 0.103$) has a relatively minor influence on customer loyalty. Moreover, customer satisfaction has a strong effect on loyalty ($\beta_3 = 0.158$), indicating that higher satisfaction directly enhances customer loyalty. The results also confirm that only the indirect relationship $OU \rightarrow CS \rightarrow CL$ is statistically significant. This finding suggests that the Outcome factor indirectly influences customer loyalty with a small effect size ($\beta_3 = 0.051$).

The author also conducted variance difference analysis using ANOVA, Levene's test, and Welch's test. The results indicate that the significance levels of all tests are below 0.005, confirming that customer loyalty is not homogeneous but varies significantly depending on the characteristics of each business type. The Shipping Lines exhibit the highest level of loyalty to the port, followed by Freight Forwarders and Import-Export Companies.

Meanwhile, Manufacturing/Service Provider Companies and other groups demonstrate lower levels of loyalty. Tables 5, 6, 7, and 8 below present the detailed results.

Table 5. Analysis of Variance (ANOVA)

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	56.736	4	14.184	153.883	0.000
Within Groups	20.278	220	0.092		
Total	77.014	224			

Table 6. Test of Homogeneity of Variances

	Levene Statistics	df1	df2	Sig.
Based on Mean	6.548	4	220	0.000
Based on Median	5.560	4	220	0.000
F_CL Based on Median and with adjusted df	5.560	4	185,686	0.000
Based on trimmed mean	9.886	4	220	0.000

Table 7. Robust Tests of Equality of Means

	Statistic ^a	df1	df2	Sig.
Welch	170,553	4	19.554	0.000

Table 8. Descriptive Statistics of Customer Groups Regarding Loyalty

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Min	Max
					Lower Bound	Upper Bound		
1	42	4.3095	0.3157	0.0487	4.2111	4.4079	4.00	5.00
2	62	3.9462	0.2969	0.0377	3.8708	4.0216	2.33	4.00
3	101	3.5215	0.2997	0.0298	3.4623	3.5806	2.33	4.00

4	16	2.5417	0.2064	0.0516	2.4317	2.6516	2.33	3.00
5	4	1.9167	0.6310	0.3155	0.9126	2.9207	1.00	2.33
Total	225	3.6874	0.5864	0.0391	3.6104	3.7644	1.00	5.00

DISCUSSION

The study confirmed 13 out of 17 hypotheses, showing that customer satisfaction and loyalty are positively influenced by five key dimensions of port logistics service quality. However, service quality has a stronger impact on satisfaction than on loyalty, consistent with prior research (Jang et al., 2013; Chang & Thai, 2016). Satisfaction can arise from a single experience, whereas loyalty requires consistent service quality over time.

Among the dimensions, Outcomes and Image & Social Responsibility exert the most influence, followed by Resources, while Management and Processes have relatively lower impacts. These findings align with studies on service quality and satisfaction (Thai, 2016; Phan et al., 2021) and service quality and loyalty (Cho et al., 2010; Le et al., 2020; Lin et al., 2023). However, factor rankings differ from Yeo et al. (2015), likely due to differences in research timeframe and port-specific conditions. Conducted post-COVID-19, this study reflects shifting priorities in port selection, with companies placing greater emphasis on reliability, service speed, and reputation.

The study reaffirms the strong positive correlation between customer satisfaction and loyalty. It underscores that failure to meet customer expectations poses significant challenges to customer retention. Furthermore, the research identifies Outcomes as the only dimension of port logistics service quality that indirectly influences customer loyalty through satisfaction (Hypothesis H3c). This is attributed to its tangible and directly perceivable nature, as it encapsulates critical value propositions, including on-time delivery, cargo security, and cost efficiency. When these expectations are fulfilled, customer satisfaction increases, enhancing loyalty. Conversely, the remaining dimensions primarily serve as foundational service quality determinants - if they fail to meet expectations, they exert a direct negative effect on loyalty by diminishing trust and perceived value, irrespective of satisfaction levels.

Additionally, customer loyalty at TCTT varies significantly across business segments, driven by operational roles and INCOTERMS, necessitating targeted service strategies for key revenue-generating segments - shipping lines, freight forwarders, and import-export companies (over 80% of the customer base) - and manufacturing/service providers (Vinh & Tra, 2020).

Shipping lines, the most loyal segment, prioritise infrastructure, schedule reliability, and cost stability, often under CIF terms, granting port selection control (Dulebenets et al., 2021). TCTT can enhance retention by investing in quay cranes, digital tracking, and berthing support for carriers like Maersk Line and Gemadept (Pels, 1992). With moderate loyalty, freight forwarders act as intermediaries, valuing cost-effective Terminal Handling Charges, speed, and routing efficiency under shipping line directives (Tongzon, 2009; Alfares & Ghaithan, 2016). Competitive pricing and streamlined processes are critical for this segment.

Import-export firms' loyalty varies by INCOTERMS: FOB terms, prevalent in Vietnam, limit entrusted firms' port choice, reducing loyalty, while direct firms using CIF prioritise cost, routing, and reputation, switching ports if congestion occurs (Murphy et al., 2023). TCTT's proximity to industrial zones supports retention, but operational efficiency is key. Manufacturing/service providers, the least loyal due to infrequent, FOB-driven interactions via shipping lines, emphasise transparency, support, and problem resolution (Nguyen et

al., 2024). Improving administrative efficiency and communication can boost their engagement.

To optimise loyalty, TCTT should adopt segment-specific strategies: enhance infrastructure and digitalisation for shipping lines, streamline pricing for freight forwarders, ensure efficiency for import-export firms, and improve transparency for manufacturing/service providers, strengthening competitiveness in Vietnam's port sector.

RECOMMENDATIONS

This paper presents strategic recommendations for managers at Tan Cang - Cai Mep Thi Vai Terminal Co., Ltd. (TCTT) to enhance port logistics service quality across five key dimensions. These initiatives will strengthen the competitiveness of the Cai Mep - Thi Vai port cluster and serve as a reference model for improving customer satisfaction and loyalty across Vietnam's port system.

Enhance Outcomes for Operational Excellence: To address shipping lines' and direct import-export firms' priorities under CIF terms (e.g., schedule reliability, cost efficiency), TCTT should upgrade digital systems for seamless data exchange with shipping lines, ports, and customs, adopting real-time container tracking and digital gate codes, as seen in Singapore's PSA (Dulebenets et al., 2021; Notteboom et al., 2022). Training staff in cargo handling and customer service will improve efficiency and professionalism, particularly for freight forwarders valuing speed (Alfares & Ghaithan, 2016). Optimising barge operations and consolidating containers will reduce congestion, benefiting all segments, especially import-export firms switching ports under FOB terms due to inefficiencies (Murphy et al., 2023).

Strengthen Image & Social Responsibility for Sustainability: To align with global sustainability trends and appeal to all segments, particularly manufacturing/service providers valuing reputation, TCTT should adopt clean energy solutions like shore-to-ship power and LNG supply, following Rotterdam's model (UNCTAD, 2023). Big Data analytics can minimise vessel wait times and energy use, enhancing TCTT's environmental credibility (Thai et al., 2022). These initiatives will boost loyalty among environmentally conscious customers and meet international standards, strengthening TCTT's competitive edge.

Optimise Resources for Infrastructure Efficiency: To support shipping lines' infrastructure needs, TCTT should install smart navigation systems with real-time maps and dedicated lanes for reefer containers, ensuring proper storage for perishable goods (Vinh & Tra, 2020). Expanding power plug-in infrastructure for peak-season demand and promoting domestic barge transport will reduce gate congestion, lowering costs for freight forwarders and import-export firms (Nguyen & Tran, 2023). Regular maintenance of quay cranes and forklifts will ensure operational stability, critical for long-term partnerships.

Streamline Processes for Workforce and Security: TCTT should recruit skilled personnel and provide continuous training in technical expertise, safety, and communication, addressing manufacturing/service providers' emphasis on support and transparency under FOB terms (Nguyen et al., 2024). Strict disciplinary measures against negligence or theft, coupled with enhanced container seal verification and customs coordination, will improve security and credibility, benefiting all segments (Thai, 2016).

Improve Management for Coordination and Multimodal Services: To enhance efficiency for all segments, TCTT should improve cargo volume forecasting and yard allocation through closer coordination with customers, reducing berthing times (Dulebenets et al., 2021). Upgrading E-port functionalities with electronic declarations and real-time updates will streamline operations, particularly for freight forwarders and direct import-export firms (Nguyen & Tran, 2023). Introducing value-added services like cargo inspections and packaging will support manufacturing/service providers, fostering end-to-end logistics solutions and increasing loyalty.

By prioritising these initiatives, TCTT can address segment-specific needs - efficiency for shipping lines, cost for freight forwarders, reliability for import-export firms, and transparency for manufacturing/service providers - ensuring sustained customer loyalty and a competitive edge in Vietnam's port cluster.

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Identifying Supply Chain Resilience through Importance-Performance Analysis from Malaysian Logistics Service Providers

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Abstract

Due to rising disruptions, logistics service providers (LSPs) must be resilient in their supply chains. This study evaluates the resilience of LSPs in Malaysia using Importance-Performance Analysis (IPA), identifies their determinants and strategic priorities. This IPA approach is paired with interview data that has been collected at the same time to add more reasoning and context to the findings. The results showed that an improvement in big data analytics and dynamic adaptation capabilities was significantly required. A strategic resilience plan can be built on current strengths in the use of technology and in customer relationship management. Additionally, research mentions the potential of currently underrated, high-performing, low-importance areas such as openness to innovation and digital transformation, suggesting to better utilise them for future success. This study suggests that the LSPs in Malaysia need to work better in areas that are low-priority and low-performance right now, such as artificial intelligence and sustainability, or risk trailing behind global competition and industry norms.

Keywords: Supply chain resilience, Importance-Performance Analysis (IPA), logistics service providers (LSPs), digital transformation, strategic resource allocation.

Introduction

Supply chain disruptions have been increasingly common because of global pandemics, geopolitical disruptions, natural disasters and technological advancements (Ivanov & Dolgui, 2021; Golan et al., 2020). It hinders the logistics service provider's (LSPs) ability to maintain their operational stability and efficiency (Herold et al, 2024). Recent studies show that such firms are more capable of responding to uncertainties when they proactively prepare for these situations (Scholten et al., 2020; Gunasekaran et al., 2015). Even though there are several resilience frameworks, it is still unclear how LSPs prioritise resilience-building efforts, especially in a developing economy like Malaysia (Zainal, 2018; Al Banna et al, 2023; Hassan et al., 2023). The lack of clarity on how Malaysian LSPs prioritize resilience is significant because their unique economic context, resource constraints, and strategic priorities necessitate tailored resilience strategies to safeguard the nation's supply chain and economy against disruptions (Salim, 2023). It is important to study how LSPs can purposely distribute resources to enhance their resilience capabilities with the increasing complexity of global supply chains (Sumantri et al, 2024).

The Malaysian LSPs are facing increasing challenges in supply chain resilience due to disruptions, regulations and market dynamics (Kilpatrick et al, 2024 ; Barret, 2021; Zainuddin et al, 2022). The resilience capability depends on many determinants such as big data, adaptability, financial stability, sustainability, technology (Bahrami and Shokouhyar, 2022). However, there is a lack of clarity on the prioritisation by LSP leaders on these determinants and their performance in implementation (Menon and Ravi, 2021). Even though the academic literature identifies some important determinants for supply chain resilience, that does not mean that these are what LSP leaders in Malaysia think matter during disruptions (Hanaysha and Alzoubi, 2022; Suryanto et al., 2018). Also, even if some determinants are considered important, LSPs may not do well on them due to financial shortfalls, not enough know-how, or inefficiency (Mahdzan et al., 2020). Similarly, there could also be cases where the LSPs might overinvest in less important areas, which leads to inefficient resource usage (Chaudhry, 2022).

Conducting IPA indicates whether the leaders of LSPs recognise the importance of these determinants and how well they perform in them. By deploying the approach to further identify strategic gap, strength, low priority area as well as potential over-investment. When LSPs understand the gap between what is important and what they do, they can make more intelligent decisions on where to spend money, what needs improving, and where their investment will help improve resilience.

Literature Review

Defining Supply Chain Resilience (SCR) in the Logistics Sector

In context of this study, supply chain resilience (SCR) is defined as the ability of a company to anticipate, prepare, respond to and recover from disruptions at acceptable levels of service and continuity of operations (Tukamuhabwa et al, 2015). It has been defined as the quality to resist a breakdown in a supply chain at lower cost and disruption (Hamidu et al, 2023).

IPA helps firms systematically evaluate and prioritise resilience factors based on how important and how well they perform (Martilla & James, 1977). Previous studies have shown that it is useful for decision-making within the scope of the supply chain, such as quantification on risk (Shen et al., 2023). But not much research has been conducted on the application of IPA to logistics resilience (Neto et al., 2023).

Justification of Variables

To assess supply chain resilience among Malaysian logistics service providers (LSPs), this study incorporates **21 resilience variables** identified from the existing literature. These variables represent key dimensions of resilience, including **technological adoption, financial stability, operational flexibility, and sustainability efforts**. The table below presents the selected resilience variables along with their supporting authors.

Table 1: Resilience Determinants

No.	Resilience Variables	Supporting Authors
A1	Openness to Innovation	Yu et al. (2022); Sabahi and Parast (2020); Gölgeci and Ponomarov, (2015).
A2	Use of Technology	Al-Talib et al. (2020); Alvarenga et al. (2023)
A3	Digital Transformation	Li et al. (2025); Yin & Ran (2022);
A4	Ethics and Value Creation	Fritz (2022); Alonso-Muñoz et al. (2021); Linkov (2020)
A5	Application of Artificial Intelligence	Modgil et al (2022); Beta et al. (2025)
A6	Utilisation of Big Data	Pu et al. (2025); Al-Khatib & Shuhaiber (2022);
A7	Total Quality Management Practices	Albalushi et al. (2023); Metaxas et al. (2019)
A8	Handling of 4V (Volume, Variety, Variation, Visibility)	Cappa et al., (2021); Roy, (2021); Sunmola et al., (2023)
A9	Financial Performance	Juan & Li, (2023); Ruel & El Baz, (2023)
A10	Competitive Advantage (value, rarity, imitability, and organisation)	Mubarik et al. (2022); Nikookar & Yanadori (2022); Onofrei et al. (2020); Aslam et al. (2022)
A11	Dynamic Capability	Stadtfeld and Gruchmann (2024); Kähkönen et al (2023); Müller et al. (2023)
A12	Efficiency, Effectiveness & Environmental Responsibility (Triple E)	Tundys and Wiśniewski (2023); Belhadi et al. (2022); Simão et al. (2022)

A13	Sustainability	Negri et al. (2021); El Korchi (2022); Al-Khatib & Shuhaiber (2022)
A14	Building Customer Trust	Qiao & Wang (2021); Robb et al. (2022)
A15	Climate Change and Finance	Pankratz & Schiller (2024); Zilberman et al. (2022)
A16	Reverse Logistics	Dev et al (2021); Kazançoğlu et al. (2022)
A17	Corporate Social Responsibility	Zhao, J. (2021); Wiengarten et al. (2017)
A18	Humanitarian Logistics	Kovács and Falagara (2021); Sigala Dubey (2019)
A19	Intellectual Capital Management	Mubarik et al. (2022); Najar et al. (2020); Ali et al. (2021); Al-Omoush (2022)
A20	Knowledge Management	Zighan et al. (2024); Mukherjee et al. (2024)
A21	Leadership and Culture	Dey et al. (2024); Metaxas et al. (2019); Howard and Irving, (2021)

Table 2: Resilience Determinants by Definitions

Code	Determinant	Definition	References
A1	Openness to Innovation	Readiness to adopt new ideas, technologies, and business models to enhance adaptability.	Yin (2022); Singh (2024).
A2	Use of Technology	Integrates ICT, digital tools advance analytics to improve communication, coordination, and responsiveness.	Kudrenko (2024); Liu et al. (2023)
A3	Digital Transformation	Fundamental changes that accelerate efficiency and visibility by incorporating advanced digital technologies.	Yuan et al. (2023); Reynolds (2024); Ehrenhuber et al. (2015); Lai (2024)
A4	Ethics and Value Creation	Necessity of aligning business operations with ethical standards and societal values; responsible business practices, transparency, and sustainability to foster long-term stability.	Tan (2023), Elwood (2021)
A5	Application of Artificial Intelligence	Optimises logistics, improves demand forecasting, and inventory management. and strengthens overall resilience.	Nweze (2024); Wei et al. (2023); Bradley-Swanson & Burrell (2020); Aliahmadi et al. (2022)
A6	Utilisation of Big Data	Leverages large data-driven decision-making, risk assessment, and adaptability to market changes.	Xu & Liu (2023); Sari et al. (2023); Bradley-Swanson &

			Burrell (2020);
A7	Total Quality Management (TQM) Practices	Emphasises continuous improvement such as improving efficiency, minimising errors, and optimising processes to maintain efficiency for disruptions mitigation.	Saputra et al., (2023); Shishodia et al., (2021).
A8	Handling of 4V	To adapt to fluctuating demands (Volume), provide diverse service offerings (Variety), manage inconsistencies in demand (Variation), and ensure transparency across the supply chain (Visibility) to keep supply chains flexible and responsive.	Swift et al. (2019); Barata et al., (2022).
A9	Financial Performance	Ability to sustain operations and absorb shocks while sustaining financial health and increasing profitability.	Abeysekara et al., (2019); Rezaei et al., (2022); (Sinaga et al., 2021)
A10	Competitive Advantage	Ability to create superior value consistently and agility in responding to market changes and disruptions	Kokkinou et al. (2023); Dubey et al. (2023)
A11	Dynamic Capability	Reconfigures internal and external competencies, respond effectively to disruptions	Lopes et al. (2022); Zhi et al. (2024).
A12	Efficiency, Effectiveness & Environmental Responsibility (Triple E)	Guarantees resilience by maximising outputs while optimising resources and minimising negative environmental impacts.	Lohmer et al. (2020) and Sharabati (2021)
A13	Sustainability Efforts	Mitigate long-term risks related to environmental issues and resource scarcity in supply chains	Zavala-Alcívar et al. (2020); Paul et al. (2020)
A14	Building Customer Trust	Ensures transparency, strong communication, reliability, and ethical practices stakeholders and customers	Piya et al. (2022)
A15	Addressing Climate Change	Involves financial investments in green supply chain initiatives to improve long-term resilience.	Zainurrafiqi & Gazali (2024)
A16	Reverse Logistics Processes	Manages returns, recycling, and repurposing materials to build sustainable and resilient supply chains.	Juan & Lin (2019)
A17	Corporate Social Responsibility (CSR) Initiatives	Improves the reputation of a firm, build consumer trust and strengthen relationships with suppliers, all of which can help a supply chain resist and recover from disruptions.	Long et al. (2020) and Zhang & Li (2022).
A18	Humanitarian Logistics Efforts	Processes and systems involved in supply chains remain functional and responsive during emergencies such as natural disasters or pandemics.	Ataseven et al. (2017; Aslam et al. (2022).
A19	Intellectual Capital Management	Human, structural, and relational capital, knowledge sharing, optimises decision-making processes, and promotes adaptability among supply chain partners	Halawany & Shehata (2024); ,

			Philsoophian et al., (2021).
A20	Knowledge Management Practices	Systematic ways to capture, share and use knowledge of the organisation for efficiency and innovation to remain resilient	Nikookar & Yanadori, (2021); Ali et al. (2021); Pu et al. (2024).
A21	Leadership and Culture	Supportive leadership and a culture that encourages adaptability, innovation, and collaboration, a proactive mindset across supply chain networks.	Cui et al. (2022; Chowdhury & Quaddus, (2016).

Methodology

Importance-Performance Analysis (IPA) began as a two-dimensional importance-performance grid (Lai & Cheng, 2002) but has now advanced to sophisticated applications in various supply chain contexts. It has been described as a tool to recognise which areas take up too many resources and delivers important perceptions into what they should focus more on (Feng et al., 2014). In logistics, IPA allows a firm to assess performance using a four quadrants matrix that points out the priorities for improvement (Lai & Cheng, 2002). The use of IPA to assess green supply chain practices tackles ambiguity and vagueness in human verdicts (Islam et al., 2018). Another approach takes a comprehensive view combining different IPA methods so as not to allow biased interpretations (Feng et al., 2014). Finally, Geng and Chu's (2012) enhanced IPA for product-service systems is a method for continuously satisfying customer value requirements which is a critical strategy for PSS design. All these studies show that IPA can be useful as a resource allocation and performance evaluation tool in the supply chain management field. The application of IPA has also been adaptable and observed in fields beyond supply chains such as in the healthcare sector (Sibevei et al., 2020) and agriculture (Jafarnejad et al., 2019) by adopting an understanding of key risk factors and performance drivers.

For this study, 22 Malaysian logistics service providers (LSPs) were interviewed and evaluated. These LSPs were selected using a purposive sampling technique to ensure representativeness in terms of company size, logistics specialisation, and geographical distribution, among others. The importance and performance assessment ratings for 21 resilience determinants, helping to assess the factors systematically. The size and selection of the sample depend on the objective of the study. If the objective is to make inferences about a larger population, classical statistical techniques can be employed to determine the necessary minimum sample size (Saunders et al., 2009; Singh and Masuku, 2014; Han, Chong & Li, 2020). Nonetheless, this study may not aim at generalisation but rather at contributing to the theory and method on supply chain resilience such as done before (Manchanayake et al., 2023; Stentoft & Mikkelsen, 2024; Kelley, 2010).

For this study qualitative research that employs interviews and IPA assessment together, often saturation point is reached with less than 20 respondents because the primary focus is not to reach the statistical representativeness but to explore a new phenomenon (Guest et al., 2006; Hagaman & Wutich, 2017; Noman, 2024). However, the literature rarely tests for generalizability in the findings of IPA, and more so, they demand theoretical and methodological contributions of the approach (Azzopardi & Nash, 2013; Oh, 2001; Feng et al., 2014; Mikulić et al., 2016; Sever, 2015). Given the explorative nature of this study with a focus on methodological insight, a sample of 22 LSPs is considered adequate as meaningful analysis and theoretical development of the findings were possible. Also, it follows the standard of existing studies in the field of importance-performance analysis and supply chain resilience (Martilla & James, 1977). Prior studies on the IPA method have

proven to be useful strategically, as the previous findings were useful for effective decision-making (Martilla & James, 1977; Leem & Yoon, 2004; Gu, Yang & Huo, 2020).

Importance-Performance Assessment

The IPA method was first introduced by Martilla and James (1977). Thereafter, it has been utilised in many fields with various applications, including in supply chain management and resilience assessment (Abalo et al., 2007; Obeidat and Beliah, 2024). It allows companies to systematically identify strengths and weaknesses to decide on actions they want to take. A Likert scale (1–5) was used to evaluate each of the 21 resilience determinants. For examples, “How important is this to you? 1 = Not important at all, 5 = Extremely important” and “Performance (1 = Very poor; 5 = Excellent)”. To create the IPA matrix, the subsequent steps were taken based on previous studies (Abalo et al., 2007; Ahmed, 2021). Firstly, find average importance and performance ratings for each factor. Then, set cut-off points (usually the mean scores) for the four quadrants. After that, put every factor in one of the four sections to get priorities to improve.

$$\text{Mean Importance for Variable } A_i = \frac{\text{Sum of all Importance ratings for } A_i}{\text{Number of Participants}}$$

$$\text{Mean Performance for Variable } A_i = \frac{\text{Sum of all Performance ratings for } A_i}{\text{Number of Participants}}$$

The four quadrants of the IPA matrix were defined as follows, based on studies (Keikavoosi-Arani and Moghadasi, 2024). For examples, “High Importance, High Performance” which means key strengths to maintain, “High Importance, Low Performance” which means have critical weaknesses, must improve immediately, “Low Importance, High Performance” which means areas LSPs could be saving on and lastly, “Low Importance, Low Performance” which means areas that have low priority.

Findings

The IPA approach gives a precise and evidence-based strategy to analyse resilience determinants, allowing Malaysian LSPs to allocate their resources according to ready strategic priorities

The following way analysis of these findings can show LSPs that they can strategically use resources to improve resilience.

1. Critical weaknesses (High importance, Low performance)

This quadrant shows the weaknesses that are important to improve the supply chain’s resilience but are underperforming currently making the logistics service providers (LSPs) susceptible. According to participants during the interview, LSPs today realise the importance of dynamic capability and big data utilisation. However, some LSPs are struggling to achieve that due to the limited introduction of technological tools, supply of data, message flow, quality management standardisation, and talent problems among others.

A6 (Use of Big Data): Effective big data utilisation improves route optimisation, inventory management, demand forecasting, and cost control (Gudavalli and Ayyagari, 2022). The low performance indicates by the participants that there are issues in adopting and utilising technology like big data, include the cost of investment, limited resources, and being a traditional company that is slow to adapt to new technology. This makes it difficult to be an early adopter and can result in performance only being at a fair rate. This align with study by Rachinger et al. (2018) saying that businesses have been overly reliant on traditional practices are usually slow to integrate new technologies. However, Hsu et al. (2022) argue that how developing the right abilities for big data analytics can help supply

chains become more resilient. Thus, the investments involved should also be to develop competent human capital to use the technologies effectively and not just financial. Moreover, according to Burawat (2024), firms that are not technology-based are compelled to adapt to customer order preferences and technological advances. Failure to do so may hinder the proactive technological innovation like big data of firms. When technology like big data is used for innovation rather than just seen as a cost burden, this can enhance supply chain effectiveness (Wu, 2024). Leaders play a vital role in this transition where adaptive and transformational leaders can better navigate the complexities of technology usage like big data and build a culture of continuous innovation (Sundowo et al., 2024). However, the participants also mentioned that they are working on to change the mentality of customers and staff to adopt new methods and technologies.

A11 (Dynamic Capability): Dynamic capabilities are defined as a firm's processes that use resources to integrate, build, and reconfigure the internal and external competences of the firm in a manner that addresses rapidly changing environments. The logistics sector is crucial for enhancing dynamic capabilities of firms. For example, many studies demonstrate that logistical capabilities affect a firm's competitive power and performance in dynamic environments Wasik et al. (2023), Çakır et al. (2022), Zhang et al. (2018). Dynamic capability is considered highly important because it refers to the ability of an organisation to adapt to changes and innovate (Ferreira et al., 2021). It is seen as essential for responding quickly to changes in the business environment and contributes to competitive advantage and financial performance (Correia et al., 2021). Being able to adapt and respond faster is becoming increasingly important (Ghosh et al, 2022).

A potential reason mentioned by the participants for performance not being higher in some companies is the challenge of getting existing staff, particularly older generations, to adapt to change, which "still needs to take some time". They also revealed some approaches to improve dynamic capability in LSPs such as preparing through lessons learned, building internal capacity through training and communication, and building external relationships with partners, customers and authorities. Successful companies use dynamic capabilities not only to become more efficient but also to exploit flexibility through continuous improvement and learning such as organisational learning was a significant factor for the development of dynamic capabilities (Chen et al., 2019). Moreover, using different types of effective communication as well as training initiatives that are suited to different ages and comfort levels with change can help ease older employees into new ways of operating (Pozniak & Yurchenko, 2024). Firms that develop dynamic capabilities simulate themselves as an adaptive resilient firm that creates not only develops technology but also develops adaptive resilient human capital (Song et al., 2022). It is important for LSPs to emphasise resource capabilities as well as human factors for better operational performance and strategic positioning over the long term in a competitive scenario.

2. Leverage Strengths (High Importance, High Performance)

This quadrant represents those strengths that help LSPs gain competitive advantages and enhance supply chain resilience.

A2 (Use of Technology) and A7 (Total Quality Management Practices): This shows that LSPs do not reject fully the usage of technologies but still adopt some technologies (like WMS for warehouse management or basic tracking systems). The participants revealed that human element can slow down the effective utilisation of latest technology and data. Technological advances help LSPs to enhance their systems and processes and to improve customer experience, bridging the gap between providers and customers (Rakovska, 2016). It is crucial for logistics firms to have this connection to allow them to respond quickly to customer demands and market fluctuations to ensure that their operations will run smoothly and sustainably despite the changing pressures taking place outside of them (Wieland & Durach, 2021). As according to participants during the interview, by leveraging the power of technology to ease the task, enhance tracking and

visibility, and improve client communication; and taking the approach of being ethical and value-generating, trust and commitment can be built. This is particularly true of the service where on-time delivery is a must. The dedicated teams in charge of quality management practices ensure that standardised service of a high quality is delivered to users, along with safety. Moreover, a good management of operational factors like volume, variety, variation and visibility by using means like GPS will increase revenues and sustainability.

A9 (Financial Performance) and A14 (Building Customer Trust): Strong financial performance enables LSPs to reinvest in innovation and resilience strategies. Financial performance ensures LSPs to reinvest in innovation and resilience strategies which facilitate operational smoothness and enable them to cope with supply chain disruptions effectively. LSPs can meet supply-chain disruptions by developing new technologies and services offered, drawn from existing research and their past experiences, merits to their financial position (Rakovska, 2016). In addition, firms with strong financial performance tend to have a better reputation and higher trust from their customers. Both are factors that contribute to long-term customer loyalty (Sann et al., 2024; Hasdiansa, 2023). The way that financial capabilities and technological investments improve operational resilience can help with building customer trust in LSPs (Sann et al., 2024). LSPs should maintain strong financial practices that would allow further investments ensure long term competitive advantage. Furthermore, financial performance continues to be critical for investment and social spending decision-making as ability to manage customer expectations accurately helps to gain competition and retain business (Agyabeng-Mensah and Tang, 2021).

A19 (Intellectual Capital Management) and A21 (Leadership and Culture): Strong leadership and knowledge-sharing practices foster adaptability and strategic decision-making, helping LSPs navigate disruptions effectively (Mahajan, 2024). Research states that intellectual capital and leadership are key for supporting outstanding operations and resilience in crises (Mubarik et al, 2022). Moreover, strong management of intellectual capital, backed by effective training and sharing of knowledge, enhances employee retention and decision-making capacity (Al-Tit et al, 2022). Finally, effective leaders help create a friendly, open communication which aligns everyone working towards a single business goal (Abdulfatai, 2021).

3. Low Priority (Low Importance, Low Performance)

The factors in this quadrant have low performance but are also not important for supply chain resilience currently. Nonetheless, LSPs should not ignore their potential long-term impact.

A5 (Application of Artificial Intelligence): AI-driven logistics offers automation, predictive analytics, and operational efficiency, yet adoption remains limited due to high costs and implementation barriers (Dhaliwal, 2022). According to research, adoption of AI can improve the efficiency of logistics. The LSPs have been classified as AI as a low priority as they require large investments, and they do not require immediate operationalisation. According to participants during the interview, many LSPs believe implementing artificial intelligence is too expensive and there is not clear linkage to business needs. Thus, most of the implementation is done around documentation and not strategising. Even with a capable AI that has the potential to enhance logistics, LSPs may not use them as they do not want to make technological investments and require comprehensive training for staff to operate them (Malhotra & Kharub, 2024). To address these challenges will be essential for the future of AI in logistics, it is recommended that the industry should educate about the value of AI in logistics. They should facilitate the collaboration of tech providers and logistics companies to develop targeted AI solutions for logistics players (Anwar, 2024; Malhotra & Kharub, 2024). Investing in training and infrastructure which stimulate the

strategic incorporation of AI can help make the logistics processes more efficient and resilient against disruptions experienced in global supply chains (Wang, 2021).

A13 (Sustainability Efforts) and A15 Addressing Climate Change: Many LSPs prioritise cost efficiency over green logistics, limiting investments in carbon footprint reduction and circular supply chain models. Regulatory changes may raise the issue's importance with time. According to current industry surveys which point to cost as one of the biggest barriers to sustainability investment. Furthermore, during disruption times, sustainability initiatives are perceived as long-term investment (Gruchmann et al., 2018). This categorisation likely reflects a difference in perceived immediate operational urgency versus recognised long-term value. And often postponed as LSPs put all their efforts into financial survival, especially when government regulations are not that stringent. In the same way, other operational or financial issues are prioritised before climate change initiatives. As to align with secondary data, Malaysian government regulations related to sustainability in the logistics sector are trying to be more stringent, although they are still not as comprehensive as those of some countries that are already developed. To help the logistics industry become sustainable, the government is looking at the introduction of National Sustainability Reporting Framework (NSRF) and carbon tax (Securities Commission Malaysia, 2025). The Joint Committee on Climate Change, along with financial and capital market players, put Malaysia's regulators on notice of these global ESG initiatives to give awareness of these needs (RAM and MIDA, 2023). By establishing strict regulations, it is possible to create an environment where companies will choose to implement sustainable measures or incur penalties (Angelis et al., 2018).

A16 (Reverse Logistics Processes) and A18 (Humanitarian Logistics Efforts): Reverse logistics is often considered less valuable than forward logistics. It is perceived this way because of the nature of reverse logistics. Reverse logistics is reactive due to returns. Besides, organisations also face issues such as cost and customer collaboration. All these lead organisations to see reverse logistics as supplemental rather than strategic (Orlando et al., 2022; Adebayo, 2022). The operation associated with the industry's reverse logistics is compromised by its high costs and the lack of customer cooperation (Francischetti et al., 2024; Morgan et al., 2018), because there is generally more focus on forward logistics as it directly impacts profits and customer satisfaction (Arroyo et al., 2023). In the same way, humanitarian logistics in stable areas are of lower priority and are carried out upon request, which reflects a reactive approach, and ultimately focuses on immediately implemented relief operations instead of proactive reverse channels (Merdivenci et al., 2023; Paula et al., 2019). In the end, the commonalities between reverse logistics and humanitarian logistics share similar challenges. Thus, organisations are encouraged to intentionally adopt practices that enhance sustainability, efficiency and preparedness. Furthermore, this should be in conjunction with improvement of collaboration, regulatory engagement, and performance measurement (Arroyo et al. 2023; Saeed 2022; Morgan et al. 2018).

4. Potential Over-Investment (Low Importance, High Performance)

This quadrant consists of the areas wherein LSPs are performing good but still putting more resources than required.

A1 (Openness to Innovation) and A3 (Digital Transformation): While digital transformation is beneficial, excessive investment without clear operational benefits can lead to inefficiencies, however this could also be interpreted positively. The high performance in these areas suggests a potential strength within the organisation. It is possible that the foundational aspects of innovation and digital transformation are well-established and functioning effectively. However, according to participants during the interview, the openness to innovation is evident when LSPs experiment with new ideas and invest in technology, even though they may struggle to adapt due to limited budgets and a focus on immediate returns. Moreover, digital transformation is recognised as crucial for

improving efficiency and competitive advantage; however, resource constraints often prevent its full implementation in daily operations, leaving room for improvement. Many scholars criticised the traditional importance-performance analysis (IPA) for various reasons (Feng et al., 2014; Deng & Pei, 2009; Sampson & Showalter, 1999). First, importance often self-reported and does not reflect the true driver of satisfaction. Second, attributes that perform well are undervalued in importance because users take them for granted and this misclassifies them into quadrant. Third, importance-performance are not truly independent. That means, changes in performance will generate changes in perceived importance.

A10 (Competitive Advantage – Value, Rarity, Imitability, and Organisation): Some LSPs may be overemphasising competitive positioning rather than focusing on operational resilience.

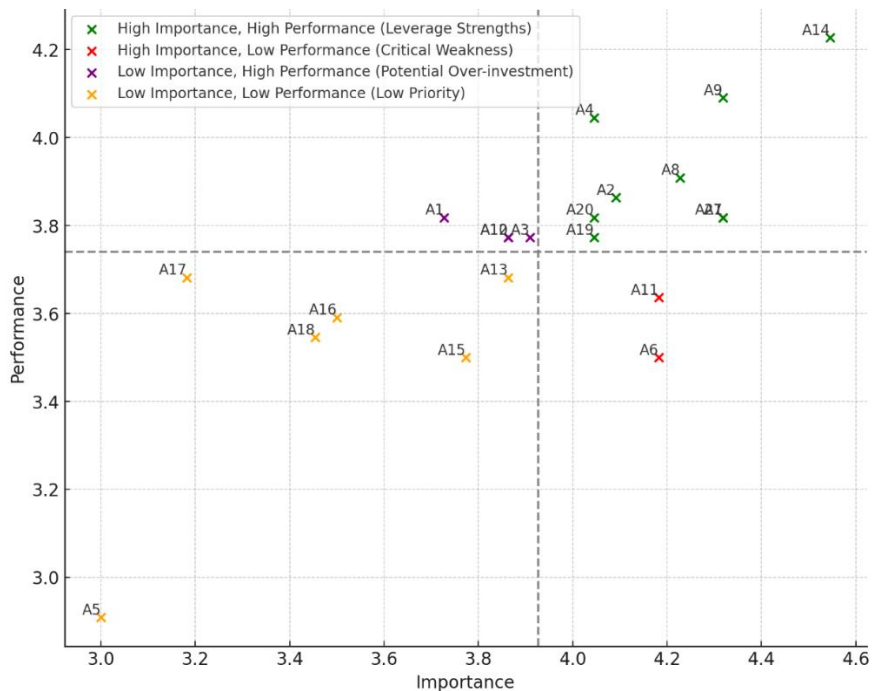
Research suggests striking the right market position and operational efficiency confers better stability over time. Participants recognise the importance of being adaptable and responsive (dynamic capability) but perceive that the organisation currently possesses resources and capabilities that provide a competitive edge (VRIO), even if the underlying dynamic capabilities are not yet fully realised or performing optimally. They may understand the long-term importance of being agile and adaptive but believe the current competitive advantage stems from existing resources/capabilities. The interpretation of "dynamic capability" as an aspirational goal, hence its high importance, while "competitive advantage (VRIO)" might be seen as a current reality, leading to lower perceived importance for further improvement in that specific framework. For example, it indicates that while a framework such as VRIO can clarify a firm's current competitive position, it may not necessarily allow firms to realise the dynamic capabilities needed to maintain that position over time (Knott, 2015). So, even if LSPs possess competitive advantages through existing resources, due to the lack of integration of dynamic capabilities, the competitive advantage may be eroded in changing environments (Kero & Bogale, 2023). This shows how existing asset-based competitive advantages are fundamentally different from adaptive capabilities that are yet not operational.

A12 (Triple E – Efficiency, Effectiveness, and Environmental): Efficient, effective, and environment" are more tangible and specific aspects than sustainability effort. Different stakeholder groups might have varying perceptions of the importance of these factors. The participants may define efficient and effective as aspects of operational and financial elements, generally given higher importance and are a more central focus for performance management compared to the "environment" (sustainability) aspect, primarily due to the fundamental business imperative of profit and the significant cost and sometimes lack of immediate external drivers for environmental initiatives. Consequently, while these areas may receive significant investment, their perceived immediate importance is often low compared to their high-performance outcomes.

Figure 1: Analysis of the Importance-Performance Analysis (IPA) for Determinants A1-A21 in the Context of Supply Chain Resilience LSP in Malaysia.

Potential Over-investment (Low Importance, High Performance) A1 Openness to Innovation A3 Digital Transformation A10 Competitive Advantage (value, rarity, imitability, and organisation) A12 Triple E (Efficiency, Effectiveness, and Environmental)	Leverage Strengths (High Importance, High Performance) A2 Use of Technology A4 Ethics and Value Creation A7 Total Quality Management Practices A8 Handling of 4V (Volume, Variety, Variation, Visibility) A9 Financial Performance A14 Building Customer Trust A19 Intellectual Capital Management A20 Knowledge Management Practices A21 Leadership and Culture
Low Priority (Low Importance, Low Performance) A5 Application of Artificial Intelligence A13 Sustainability Efforts A15 Addressing Climate Change and Finance A16 Reverse Logistics Processes A17 Corporate Social Responsibility Initiatives A18 Humanitarian Logistics Efforts	Critical Weaknesses (High Importance, Low Performance) A6 Utilisation of Big Data A11 Dynamic Capability

Figure 2: Quadrant IPA Analysis



Conclusion

This study examines the factors that contribute to the resilience of Malaysian Logistics Service Providers' supply chains using Importance-Performance Analysis while presenting their priorities, challenges, and strategic gaps. As per the findings, some determinants like technology adoption, financial position, and leadership have high importance and high performance. The dynamic capability and big data utilisation are considered more important than their performance. A shortage of resources, a slow pace of technology adoption, challenges in leveraging data, and limitations within the workforce are to blame. LSPs recognise the benefits of these attributes; nevertheless, they fail to do the needful owing to operational and financial issues.

Moreover, the study identifies determinants that are related to over-investment potential, in terms of investment in digital transformation, openness to innovation and competitive advantage. Investment in the areas excessively may not enhance resilience if not aligned with operational needs. For the past years until now, LSPs neglected determinants like sustainability, reverse logistics, and humanitarian logistics because of their high costs and low regulatory pressure along with not impacting business survival.

By analysing the misalignment between leadership priorities and actual performance, this study provides Malaysian LSPs with actionable insights for enhancing supply chain resilience. LSPs want to enhance supply chain flexibility and efficiency to improve agility and resilience. Most service providers in the sector believe they have weak agile supply chain capacity and relatively good data-driven logistics capacity. The aims and opposition of this study are to extend the analysis of LSPs, which are conditional on supply chain complexity impact. It involves operational capacity and concrete investment.

This paper contributes to theories by showing the gap for perceived importance and actual performance in the Malaysian logistics companies' time horizon when defining "importance". When a participant considers the factors important for long-term resilience, it may not warrant immediate attention and resource allocation. As a result, the actual performance may be lower even though it is recognised as important. The research reveals that while the LSPs consider the long-term importance of advanced technology and data usage, the current performance of the LSPs in this context is not satisfactory because of more operational pressure. The gap between perceived long-term value and current capability provides insights for improving strategy. It can strengthen resilience by linking long-term vision with short-term action in relation to the Malaysian LSP context.

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LOGISTICS CONNECTIVITY

Development of Collaborative Logistics Networks through Social Network Analysis: The Case of the Two-Wheel Sector

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INTRODUCTION

Given the increasing number of actors, Supply Chains (SCs) have become more complex and dynamic (Jain et al., 2019), which creates the need for constant mapping, enabling companies to visualise their suppliers and customers, identify the relationships, flows, and dynamics of networks, and capture the environment in which the SC operates. To this end, Social Network Analysis (SNA), grounded on the principles of network science, has emerged as a promising approach (Kang & Oh, 2023). Another significant trend in contemporary SCs is the growth of logistics outsourcing, projected to reach 13.7 trillion dollars by 2027 (Placek, 2023). In this way, companies can concentrate on their core activities, outsourcing non-core operations to Logistics Service Providers (LSPs), who offer a range of services from basic outsourcing (associated with low value-added activities) to advanced outsourcing, related to SC design and optimisation (Liu et al., 2015).

To foster collaboration between companies, promote cooperation toward a common goal, and establish logistics partnerships, Collaborative Logistics Networks (CLNs) have been established. As Xu et al. (2022) explain, CLNs offer several advantages, including the elimination of information asymmetries, improved resource efficiency, reduced transportation costs, and more effective service provision, leading to higher customer satisfaction and loyalty. CLNs can be promoted by manufacturers, Third-Party Logistics (3PL) providers, or Professional Information Platform Assistance. However, relatively few studies have explored the development of CLNs. Moreover, Yan et al. (2023) mentioned that many studies present logistics networks that significantly differ from real-world scenarios. In addition, the literature lacks studies addressing governance mechanisms, which refer to the rules of exchange between partners and can be contractual, relational, or virtual. According to Ratajczak-Mrozek et al. (2024), governance mechanisms interact dynamically and may depend on contextual factors. Therefore, this study aims to explore the potential of SNA in identifying the roles that LSPs can play in the development of CLNs. To this end, a questionnaire was designed and applied to the Two-Wheel Sector in Portugal. This sector was selected due to its relevance to the Portuguese economy and its predominance of Small and Medium-Sized Enterprises (SMEs), which are considered “*a vibrant and dynamic sector of the world economy*” (Qalati et al., 2021, p.1).

The Two-Wheel Sector is undergoing a deep transformation. Environmental concerns, coupled with incentives for mobility alternatives, such as new cycling infrastructures, in many European cities, contribute towards making electric and conventional bicycles the obvious solution for soft mobility (Statista Research Department, 2025). The signature of the European Declaration on Cycling, in 2024, represented a milestone in promoting cycling and the cycling industry across Europe (CONEBI, 2024).

During the pandemic, there was a surge in bicycle demand, as its use complied with social distancing guidelines. Moreover, difficulties experienced by SCs due to pandemic restrictions led to order fulfilment times of more than one year. In 2023, SCs recovered, however, companies faced an oversupply of new bicycles and components (Statista Research Department, 2025).

According to CONEBI, the Confederation of the European Bicycle Industry, the sector comprises 170.000 direct/indirect jobs, producing 5,1M e-bikes and 11,7M conventional bicycles, generating a 19,3B€ turnover in 2023 (CONEBI, n.d.). From 2019 through 2023, Eurostat presents Portugal as the biggest producer of bicycles in the EU, despite the 24% decrease in overall production in 2023 compared to 2022 (Eurostat, 2024).

The sector also faces technological challenges, with the adoption of electric bicycles (e-bikes). Companies need to adjust their production processes, engage new partners for the electronic components, and deal with the latest regulations regarding transportation and warehousing safety. Nevertheless, there is a growing interest in e-bikes, driven by higher revenue and bike leasing (Mathias Heller, 2024).

This study is structured as follows: the next section outlines the methodology used, followed by the presentation and discussion of the results. Finally, the conclusion is presented, highlighting the main contributions and limitations of the study, along with suggestions for future research.

METHODOLOGY

Following the literature review, a questionnaire was developed, comprising sections on SNA and Logistics Outsourcing. The SNA section included company identification, suppliers/buyers' indication (Laari et al., 2022), and an assessment of interaction frequency, categorised as daily, weekly, bimonthly, or monthly (Carter et al., 2007). The Logistics Outsourcing section contained questions on whether companies outsource their activities, the specification of outsourced activities (Zhu et al., 2017), and the main benefits and barriers associated with outsourcing (Basso et al., 2019; Sandberg, 2007). Each of the questions presented predefined categories, based on the literature, while still allowing respondents to indicate "others".

The questionnaire was initially developed in English and later translated into Portuguese. A pilot version was sent to two experts to ensure content validity, and based on their feedback, some questions were modified.

The *SABI* database was used to identify companies in the Two-Wheel Sector, based on their activity (NACE codes). This database contains information on more than 900,000 companies, providing financial and historical data spanning up to 25 years. Using data from *SABI* and additional information provided by ABIMOTA (the Portuguese National Association of Two-Wheel Industries), 92 companies were identified as operating within the Portuguese Two-Wheel Sector.

Data was collected through the *LimeSurvey* platform, and email invitations were sent to participants. Three reminders (via phone calls and emails) were made during the data collection period (February 9th to May 31st, 2024) to improve the response rate.

RESULTS AND DISCUSSION

Social Network Analysis

The Two-Wheel network includes 89 nodes and 399 ties (**Figure 16**). Nodes represent companies that either responded to the questionnaire or were identified by other respondents. Consequently, out of the initial sample of 92 companies, 89 were included in the network. Ties illustrate the connections between companies. Since companies were asked to identify their suppliers and buyers, the network is directional, as the orientation of the flows and relationships is relevant for its analysis (Adami et al., 2021).

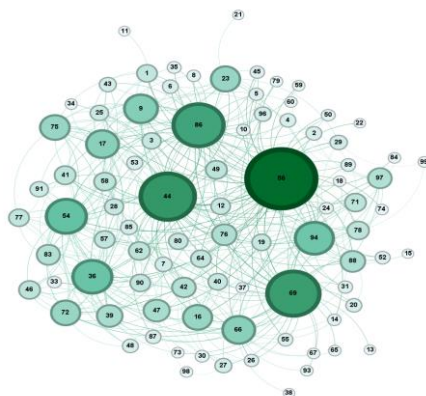


Figure 16. Network of the Portuguese Two-Wheel Sector

Most respondent companies (77%) operate in the secondary sector (development, design and manufacturing). Meanwhile, 21% belong to the tertiary sector (retailers of parts, components, conventional and electric bicycles), and the remaining 2% refer to small companies engaged in part-time craftsmanship activities related to the sector.

Beyond graphical representation, SNA includes additional tools that facilitate a more in-depth network analysis, namely metrics focused on the nodes or the whole network. In the depicted network, node sizes vary according to their Degree of Centrality (DC) – the number of ties connected to each node. In addition to DC, Closeness Centrality (CC) and Betweenness Centrality (BC) are among the most used metrics to assess a node's prominence within the network. At the network level, metrics such as network density, network diameter, and average path length provided valuable insights into the overall structure of the network.

Node-level Metrics

Companies with the highest Degree of Centrality (DC) establish more inbound/outbound ties, resulting in an increased operational load. Company 56, a manufacturer of parts and components, holds the DC in the sector, with 14 suppliers and 39 buyers, resulting in a DC of 53. Company 44, an OEM/ODM, follows with a DC of 40, corresponding to 32 suppliers and 8 buyers. Next, an LSP (company 69) has a DC of 38, referring to the 38 ties established with buyers. Companies 86 and 54, retailers of two-wheeled vehicles and accessories, report DC values of 36 and 27, respectively, with company 86 having 27 suppliers and 9 buyers, and company 54 having 25 suppliers and 2 buyers. Therefore, these nodes must focus on managing their operations more efficiently to ensure the flows they maintain within the network.

Closeness Centrality (CC) measures the average distance from a node to all other nodes within the network. High values of this metric indicate greater autonomy, as the node relies less on direct connections and can access information through indirect ties (Alinaghian et al., 2020). Company 69 presents the highest CC value ($CC = 0,62$), followed by companies 56 ($CC = 0,59$), 17 ($CC = 0,52$) – a bicycle and parts manufacturer -, 40 ($CC = 0,46$) (aluminium and renewable energies), and 90 ($CC = 0,45$) – a manufacturer of saddles and bicycle accessories.

Companies with high Betweenness Centrality (BC) play a crucial role in facilitating the relationship between other companies, as this metric reflects how often a node appears on the shortest path between others in the network. Thus, these companies are essential in ensuring the flows between nodes that, otherwise, would be disconnected or linked via longer paths (Wichmann & Kaufmann, 2016). The highest BC values are observed in companies 86 ($BC = 2216,41$), 56 ($BC = 1779,96$), 12 ($BC = 870,33$) – a manufacturer of carbon bicycle parts -, 75 ($BC = 741,56$) – a manufacturer of parts and components - and 44 ($BC = 718,86$).

Network-level Metrics

Network-level metrics assess the overall structure of the network. Network density is calculated as the ratio between the number of ties present in the network and the number of potential ties. A network density of 1 represents a network where all nodes are connected. From the results of the questionnaire, the network density obtained was 0,051. Since this metric ranges from 0 to 1, this relatively low value suggests weak cohesion and limited connectivity within the sector (Alinaghian et al., 2020). However, networks with higher density tend to exhibit greater complexity, requiring increased coordination efforts and facing higher disruption risks (Adami et al., 2021). Nevertheless, this is not an atypical value, as similar studies focusing on different contexts, such as the automotive industry (Kim et al., 2011), or the agri-food sector (Cai et al., 2020) present low values of network density. Additionally, two-wheeled vehicles are modular products, containing several interchangeable components, made with varied materials (rubber, plastics, metal) (Galvin & Morkel, 2001). In this sense, modularity induces fragmentation, allowing companies to operate independently, thus not promoting collaboration within the network (Chhetri et al., 2022).

The network diameter, which measures the longest distance among the shortest paths between any two nodes, is 7, indicating the maximum number of ties needed to traverse the network. The average path length is 3,224, representing the average path distance between any pair of nodes considered within the network.

The Role of Logistics Service Providers in Promoting Collaborative Logistics Networks

The results from SNA show that company 69 – LSP – exhibits high values for both degree centrality and closeness centrality. Regarding degree centrality, which measures the number of direct connections an actor has with others, LSP is linked to 38 companies. On the one hand, this position provides the LSP with greater visibility within the network, but on the other hand, it also implies a higher operational load (Kim et al., 2011), making the efficient management of operations crucial to ensuring effective flow. Regarding closeness centrality, the LSP holds the highest value for this metric, highlighting its significant influence within the network. Thus, by establishing multiple connections and having a high closeness centrality, the LSP can leverage volumes and assess availability (Prataviera et al., 2023). In this way, the LSP can move beyond its *"initial role as a logistics service provider to offer advanced business and retailing solutions"* (Vlachos & Polichronidou, 2024, p.14). As a result, collaborative solutions, such as CLNs, can be developed by these actors (Xu et al., 2022). In this context, the LSP would play a *transitum* role by promoting solutions to improve operational efficiency. It should also be noted that the LSP can take on the role of orchestrator, as explained by Zacharia et al. (2011), contributing to process standardisation, information sharing, conflict resolution, acquiring external resources, and offering new solutions.

Moreover, the findings indicate that more than 67,44% of companies outsource logistics activities, with transportation being the main service outsourced. To a lesser extent, more advanced logistics activities (logistics information systems integration, e-commerce, in-house inventory management, and inventory management at the LSP's facilities) are also outsourced. This underscores the importance of analysing the role of the LSP and the capabilities it must develop. By examining the relationships established with the LSP, it becomes evident that economies of scale exist (clients of the LSP's clients). As such, the LSP can develop the capability to identify opportunities and threats (detect new customers or alternative reconfigurations for the CLNs), enhance its knowledge management capabilities (interact with other members to determine value-added services for the sector), and improve its innovation capabilities to diversify its service portfolio.

From Social Network Analysis to Collaborative Logistics Networks

SNA enables the representation of the overall network and the ties between the nodes. Furthermore, it is possible to place each node according to its geographical location. According to El Moussaoui (2024), geographical proximity facilitates collaboration and promotes the establishment of logistics proximity networks. In this sense, LSP can expand into new markets within the same geographies, by focusing on the network and prospectively targeting companies not yet directly connected to it.

By considering geographical proximity as well as node-level metrics derived from SNA – following Yan et al. (2023) – two clusters emerged from the Two-Wheel Sector.

Cluster 1 is geographically located in the northern region of the network, comprising 16 companies (**Figure 17**). While most companies work in the production of bicycle parts and components, the cluster also includes packaging solution companies, moulds and machinery manufacturers. Companies that maintain ties within the cluster reported weekly to monthly interaction frequencies. Network metrics for this cluster reveal a density value of 0,033, lower than the overall network density, indicating relatively weak connectivity. The LSP (69) provides outsourcing services to 7 companies within Cluster 1. The outsourced activities mainly consist of transportation (air, road, and sea). The 9 remaining companies may be regarded as prospective clients, with the LSP looking for the opportunity to attain economies of scale, further outsourced activities, and greater connectivity and density within the cluster.

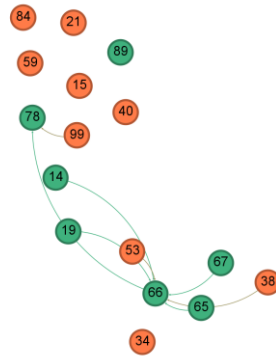


Figure 17. Cluster 1 (● LSP clients; ● Non LSP clients)

Cluster 2, located in the southeast region of the overall network, comprises 20 companies (**Figure 18**). This area exhibits a higher concentration of companies within the sector, meaning Cluster 2 includes many of the central nodes in terms of network metrics. Respondents in this cluster report fortnightly to monthly interaction frequencies. The elevated number of ties within Cluster 2 results in a higher network density value (0,205), exceeding the overall network density of the Two-Wheel Sector.

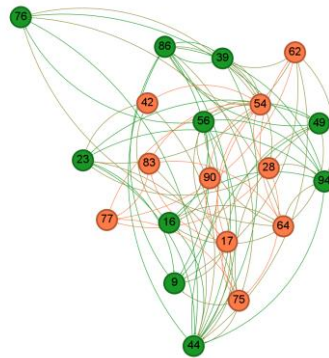


Figure 18. Cluster 2 (● LSP clients; ● Non LSP clients)

Within Cluster 2, 50% of the companies already rely on the LSP (company 69) to outsource their activities, primarily transportation services, customs services, and logistics information systems integration. Additionally, 10 companies in Cluster 2, some of which are central nodes in the overall network, are potential clients for the LSP. By pursuing these market opportunities, the LSP could gain further control of the outsourced activities in the sector, strengthen collaboration through geographical proximity, and improve the sector's overall connectivity.

As Xu et al. (2022) stated that LSPs can play a leading role in establishing CLNs, shifting the focus to the global value of the business, sharing information, and collaborating with all parties involved. By facilitating information sharing between companies, CLNs can reduce asymmetry, integrate logistics resources, and improve their operational efficiency. Information sharing improves inventory management and turnover, thus contributing to a reduction in risk. CLNs have the potential to reduce costs while promoting the long-term and sustainable development of companies. Thus, the LSP, a central node in the Portuguese Two-Wheel Sector network, can promote the establishment of logistics proximity networks, and information sharing, foster collaboration, and increase a sector's connectivity and cohesion.

From the LSP's perspective, collaboration in logistics clusters favours cost reduction, providing access to resources and information not available to others. There are also benefits from geographical proximity, increased market volume, good service quality, and enhanced credibility.

A study conducted by Badraoui et al. (2024) categorised the main challenges faced by companies engaging in collaboration relationships into two categories: differences in joint relationship efforts and differences in trust. Regarding the first, the main issues pointed out were companies' resistance to sharing information, unclear understanding of how the collaboration costs and benefits would be allocated, and a lack of collaboration formalisation. Concerning trust differences, lack of transparency, reluctance to share information, and lack of integrity posed the main difficulties. Lack of integrity was perceived as more penalising for collaboration than lack of abilities. This reinforces the need to apply appropriate governance mechanisms – contractual, relational, or virtual – to establish rules for collaboration between companies.

Thus, the LSP can promote the adoption or adjustment of different mechanisms. As Ratajczak-Mrozek et al. (2024) explain, governance mechanisms interact dynamically and depend on contextual factors. In this sense, the LSP needs to recognise its clients to maintain the predominantly relational aspect of the mechanisms and encourage them to adopt new solutions, such as virtual sharing information platforms. As far as economies of scale are concerned, identifying potential clients is crucial and it is necessary to adjust the governance mechanisms, which should initially be typically contractual and, over time, evolve to a greater level of relational mechanisms.

CONCLUSION

The increasing complexity, sensitivity, and dynamism of SCs have led to a growing need for mapping, allowing actors and their connections to be identified. In this context, SNA has emerged as a powerful tool, as it enables the visual representation of networks, as well as the calculation of analytical metrics.

The SNA results show that the Two-Wheel Sector in Portugal is made up of 89 companies, with 399 ties between them. As a sector of modular products, connectivity is not highly encouraged, which is reflected by the low network density. However, while this is a fact, it also represents an opportunity, as there is potential to strengthen connections between companies, stimulating collaboration, especially through the participation of the LSP. In addition to playing a central role in the Two-Wheel Sector network (with high degree and closeness centrality metrics), the LSP can take on a leading role in developing CLNs. When developed, these networks foster greater collaboration between companies and provide benefits such as reducing information asymmetries, lowering transportation costs, and improving resource efficiency.

Given that more than 60% of companies outsource logistics activities and that the LSP serves 38 of the 89 companies represented in the network, the SNA allows for the identification of economies of scale (clients of clients). Moreover, by using metrics and geographical location, two clusters were designed for the potential implementation of collaborative logistics solutions. In this regard, considering the characteristics of each cluster, the LSP can promote collaboration between companies within each cluster and diversify its service portfolio to offer value-added solutions (for example, a milk-run, which could function as a logistics partnership between multiple companies).

In contrast to other studies emphasising that the logistics networks presented are typically not representative of real-world scenarios, this study, based on primary data, allows for the actual representation of a sector and the design of CLNs based on real-world data, which represents its main contribution. Companies in the Two-Wheel Sector network are mainly SMEs, illustrative of the Portuguese context. The SNA tools used and subsequent analysis regarding logistics collaboration may be replicated to other industrial sectors, or even the same sector, in different locations. As with other studies, there are limitations, namely the inability to capture temporal changes, suggesting that longitudinal studies could be considered for future research.

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Advancing Port Sustainability: Systematic Review of Port Decarbonisation Barriers and Mitigation Strategies

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1. INTRODUCTION

Low carbon operations are essential to reduce emissions and energy consumption, but business responses to climate change remain underdeveloped [1]. The shipping sector is particularly challenging to decarbonise, requiring a multifaceted approach [2]. Ports, as crucial logistic nodes, play a key role in emission reduction, yet their decarbonisation is hindered by complex infrastructure, diverse stakeholders, and reliance on fossil fuels [3], [4]. Research highlights the need for tailored strategies rather than a "one-size-fits-all" approach [5].

Port decarbonisation faces barriers such as technical challenges, regulatory inconsistencies, limited funding, and lack of stakeholder collaboration [4]. Most studies focus on the implementation of specific technologies and measures [6], [7], and there is a limited use of organisational theories in maritime port literature [8]. To address these gaps, this study aims to systematically identify and categorise the barriers to port decarbonisation and present mitigation strategies, thereby providing solutions that can help reduce or overcome the identified barriers. We intend to answer two research questions (RQ):

- RQ1. What are the main barriers to decarbonising maritime ports?
- RQ2. What strategies can address and overcome the barriers to decarbonising maritime ports?

A Systematic Literature Review (SLR) was conducted using the Sociotechnical Systems perspective (STS) as a theoretical lens. This theory allowed us to categorise the identified barriers according to four dimensions: social, technological, organisational, and environmental [9].

The article is structured as follows: Section 1 presents a brief background, the goals of the research, and the research questions that we want to address; Section 2 describes the theoretical background of the study; Section 3 explores the methods employed; Section 4 provides the study's results; Section 5 includes a discussion of the results; and Section 6 concludes the study and offers future research opportunities.

2. THEORETICAL BACKGROUND

2.1. Previous Studies on Port Decarbonisation Barriers

The decarbonisation of maritime ports has been gaining increasing attention over the years. However, the reduction of port emissions still faces various barriers hindering the implementation of decarbonisation measures [10]. Identifying these barriers is challenging due to their interconnections [11], and many studies fail to apply a structured theoretical lens [3]. This leads to arbitrarily categorised barriers, which can miss the opportunity to understand the interconnectedness between them. Among the studies that apply theoretical lenses, the Diffusion of Innovation (DOI) model, in combination with the Implementation Theory, was used to identify determinants of port decarbonisation [10].

Although these lenses provide interesting perspectives, they can overlook external factors to port decarbonisation, limiting their applicability.

Additionally, literature is limited when investigating solutions to port decarbonisation barriers, with only some authors offering suggestions [3], [11]. Most studies that propose mitigation strategies rarely analyse how they interconnect, reducing their practical value for port stakeholders [3]. To overcome the identified gaps, we will review the barriers to maritime port decarbonisation, categorise them through the STS theoretical lens, and propose mitigation strategies to overcome the challenges of decarbonising ports.

2.2. Sociotechnical Systems (STS) Theory

Recent literature on port decarbonisation has called for employing different organisational theories to address conflicts among port decarbonisation issues, like safety, cost, environmental problems, operations, and innovation [8]. The Sociotechnical System (STS) theoretical lens emphasises the synergy between social, technological, organisational, and environmental factors within a system.

The *Social* dimension encompasses the people involved in the organisation, including their knowledge and safety. The *Technological* dimension includes tools, technologies, and physical spaces. The *Organisational* dimension considers how work is designed, comprising aspects such as the rules and the information flow. The *Environmental* dimension refers to all external elements of the organisation that influence technology adoption, such as government policies or regulatory frameworks [9].

Maritime ports could be described as STS since they are complex systems and include several work sub-systems that must work together to manage operations efficiently. This study applies STS theory to categorise barriers, ensuring comprehensive analysis and enabling more effective mitigation strategies.

3. METHODOLOGY

This study employs an SLR to identify the barriers to decarbonising maritime operations, providing insights for future research. SLR represents a rigorous, transparent, and comprehensive approach to analysing, evaluating, and synthesising literature [12].

3.1. Sample articles selection

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) technique guided the literature selection, ensuring reliable and trustworthy findings [13]. Figure 1 presents the several steps of the PRISMA application. We used the Scopus database, one of the largest research databases [1].

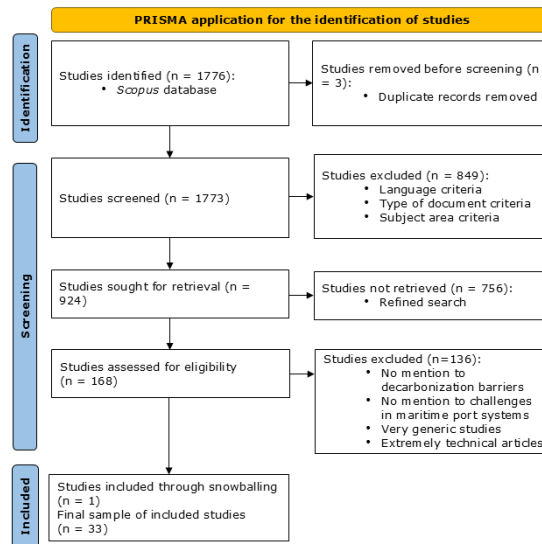


Figure 1: Document selection process, following the PRISMA approach.

The Scopus search identified 1776 articles using determinants (“barrier” OR “driver”) and emission reduction terms (“decarboni*” OR “net-zero”). These keywords were searched for in the papers' titles, abstracts, and keywords. To refine the scope, we included maritime-specific terms (“maritime” OR “marine” OR “shipping” OR “seaport” OR “port” OR “harbor” OR “container”) and applied exclusion criteria (e.g., non-English, non-relevant fields), reducing the sample to 168 articles.

For the final screening round, we conducted an eligibility analysis on the retrieved articles by checking the titles, the abstracts, and the full text when necessary. The articles focused on barriers to decarbonisation or challenges in maritime port systems were selected for the study sample, resulting in 32 articles. Forward and backward snowball was conducted using research citations and references to identify studies relevant to the research topic that weren't obtained in the initial search [12]. This process led to the identification of one additional relevant study [14], resulting in a final sample of 33 articles.

3.2. Qualitative analysis

Two authors independently analysed the 33 selected articles, identifying 25 distinct barriers to port decarbonisation through multiple coding rounds and discussions. For each article, a thorough examination was undertaken, and at least one sentence or paragraph was identified as potentially describing a barrier to decarbonisation. Due to varying terminology across studies, an inductive approach was used to identify barriers based on the meaning rather than the exact wording [3]. Through several rounds of coding and discussion, the authors identified the similarities between the presented concepts, which resulted in the definition of 25 different barriers to port decarbonisation. The identified barriers were then categorised using the STS theoretical lens.

4. FINDINGS

This chapter presents the findings of our investigation and proposes 25 barriers to maritime port decarbonisation. For each barrier, we identify the studies that mention it. This process not only elucidated the focus of each study but also the most prevalent challenges across the selected articles.

4.1. Categorisation through the STS lens

The categorisation of barriers is based on the STS theory [9]. Table 1 presents the categories, assigned barriers, and the number of citations for each barrier.

Category	Barriers	Citations	References
Social	Lack of awareness of environmental priorities	12	[1], [3], [5], [14], [15], [16], [17], [18], [19], [20], [21], [22]
	Limited knowledge, awareness, and expertise	11	[1], [3], [5], [6], [16], [18], [21], [22], [23], [24], [25]
	Resistance to change	9	[2], [3], [14], [18], [21], [22], [26], [27], [28]
	Lack of direct communication	3	[6], [14], [17]
Technology	High costs	18	[1], [2], [3], [5], [6], [14], [16], [19], [21], [22], [25], [28], [29], [30], [31], [32], [33], [34]
	Low technology availability and readiness	18	[1], [2], [3], [5], [7], [14], [15], [16], [18], [19], [20], [21], [22], [32], [33], [34], [35], [36]
	Lack of detailed and reliable data	12	[1], [3], [6], [16], [17], [21], [22], [25], [28], [29], [34], [37]
	Green fuel availability issues	10	[2], [5], [6], [15], [18], [24], [28], [31], [36], [38]
	Infrastructure retrofitting complexity	10	[3], [5], [7], [16], [18], [19], [22], [23], [24], [33]
	Lack of standards for sustainable initiatives	5	[6], [14], [17], [27], [32]
	Long lifespan of ships	2	[29], [36]
Organization	Lack of coordination, collaboration, and cooperation	14	[2], [6], [7], [14], [17], [21], [27], [28], [29], [30], [31], [38], [39], [40]
	Lack of visibility of the whole value chain	10	[2], [5], [6], [7], [14], [18], [19], [30], [36], [40]
	Absence of customised frameworks for decision support	10	[1], [3], [15], [19], [23], [25], [27], [30], [32], [41]
	Reluctance to invest	6	[1], [6], [22], [28], [30], [34]
	Reluctance to share data	6	[3], [6], [17], [19], [27], [34]
	Mismatch between present and future planning	5	[3], [16], [21], [23], [36]
	Conflicting goals in port systems	4	[1], [3], [28], [33]
	Hierarchical decision delays	3	[3], [25], [28]
Environment	Complexity of the industry	16	[1], [3], [5], [6], [14], [15], [16], [23], [25], [27], [30], [31], [36], [37], [38], [39]

	Global policy gaps and instability	16	[1], [3], [5], [15], [19], [21], [22], [23], [24], [25], [27], [28], [29], [30], [31], [37]
	Uncertainties about policies and technologies	13	[1], [2], [3], [6], [16], [23], [25], [28], [29], [30], [31], [35], [36]
	Lack of funding and incentives	12	[1], [2], [3], [5], [16], [21], [22], [28], [29], [30], [32], [33]
	Lack of government support	11	[1], [3], [5], [15], [19], [21], [22], [25], [28], [30], [39]
	Shipping industry growth	4	[20], [21], [22], [37]

Table 1: Port Decarbonisation Barriers and Categories.

4.1.1. Social Barriers

The *lack of awareness of environmental priorities* and the existing *limited knowledge, awareness, and experience* on decarbonisation highlight gaps in critical aspects of the social dimension. The *resistance to change* results from the individuals' inertia and skepticism about implementing new solutions in organisations, such as ship owners and port operators [28]. Similarly, the *lack of direct communication* suggests difficulties in fostering collaboration, trust, and shared responsibility.

4.1.2. Technological Barriers

High costs and *low technology availability* highlight the difficulties in obtaining and implementing advanced solutions. The *lack of detailed and reliable data* impedes effective and data-based decision-making. This could hinder the adoption of new technical measures with low market maturity due to the lack of transparent and realistic estimates of costs and reliable performance data [29]. *Green fuel availability issues, infrastructure retrofitting complexity, and standardisation gaps in the integration of sustainable initiatives* reflect the difficulties in adapting existing technologies and spaces to meet sustainability goals. The *long lifespan of ships* demonstrates how the longevity of technological elements may delay the adoption of new, sustainable technologies.

4.1.3. Organisational Barriers

The *lack of coordination, collaboration, and cooperation* reflects issues with communication and teamwork. *Diminished value chain visibility* and *reluctance to share data* hinder information flow and transparency. The *absence of customised frameworks for decision support* and *mismatches between present and future planning* point to gaps in strategic implementation and task planning. *Reluctance to invest* has been identified in the limited willingness to pay for green alternatives [6]. *Conflicting goals in port systems* and *hierarchical decision delays* demonstrate how organisational culture, structure, and policies can result in inefficiencies and misalignments.

4.1.4. Environmental Barriers

The *complexity of the industry* and the *shipping sector growth* create challenges in aligning practices with evolving sustainability demands. *Global policy gaps and instability* highlight the impact of inconsistent regulatory frameworks. *Uncertainties about policies and technologies* are largely associated with doubts about the technologies that will be favoured in future marketplaces [2]. The *lack of funding, incentives, and government support* underscores the difficulty of securing external resources to stimulate research and adopt sustainable solutions.

4.2. Mitigation Strategies

By rereading the literature selected through the SLR and consulting further literature, we have identified 6 main categories of mitigation strategies to reduce the impact of port decarbonisation barriers: *policy instruments*, *financial incentives and disincentives*, *management tools*, *capacity-building*, *research and development*, and *collaboration and communication*.

The *policy instruments* category includes strategies such as tax exemptions and subsidies, regulations that standardise emissions reporting, alternative fuel infrastructure, and sustainability performance. A targeted policy mix, such as compliance with rules or sectoral agreements, can be harnessed to overcome decarbonisation barriers [42]. Compared to other stakeholders, legislative and regulatory entities are mainly responsible for policy instrument strategies [11]. The *financial incentives and disincentives* strategies focus on using subsidies, penalties, and funding mechanisms to foster or enforce decarbonisation and the use of new technologies and practices [43]. These mitigation strategies include subsidies for adopting low-carbon technologies, funding alternative fuels, and financial rewards for early retirement or modernisation of outdated vessels. However, countries lacking carbon pricing, emission trading schemes, or other mechanisms that support clean energy development are unattractive for investors [25]. Disincentives, such as penalties for unsustainable practices, could support compliance with decarbonisation targets.

Management tools include voluntary agreements, strategic plans, monitoring, and reporting, among others [3]. This category is concerned with enhancing internal procedures, improving decision-making, and developing tools for tracking and monitoring port operations. For example, for shipping companies, participating in voluntary programs by joining a green shipping network could promote emissions reduction and the adoption of new zero-emission technologies or fuels [41]. The *capacity-building* category focuses on information dissemination and the development of skills, expertise, and awareness among stakeholders, specifically managers, employers, and employees [11]. This category includes strategies such as capacity-building programs, awareness campaigns on sustainability, and initiatives to increase knowledge sharing. The role of staff and crew involvement in continuous training for the achievement of energy-efficiency goals has been identified as very important in the context of short sea shipping [32].

The *research and development (R&D)* category includes strategies for developing, implementing, and improving technological solutions and infrastructures. These strategies seek to mitigate risks and improve the cost-effectiveness of low-carbon technologies. R&D strategies also focus on more digitally based activities, such as investing in digital infrastructure, real-time communication systems, or advanced data processing techniques [11]. The *collaboration and communication* category focuses on developing strong partnerships and encouraging stakeholder dialogue to achieve common sustainability goals [11]. Therefore, it includes strategies like fostering cross-industry knowledge sharing, exchanging data, and encouraging regular stakeholder meetings and workshops to map and monitor the value chain.

In summary, each port will experience port decarbonisation barriers differently, which will require its own mix of mitigation strategies depending on factors such as dimensions (i.e., small vs large ports), the existence of potential partners (e.g., recurrent shipping routes), location (e.g., developed vs developing country), and the mix of decarbonisation measures.

5. DISCUSSION

As highlighted earlier, the literature on port decarbonisation barriers and mitigation strategies primarily focuses on identification, missing the opportunity to explore interconnections between them. We aim to bridge this gap by examining how specific barriers can be addressed through targeted strategies. *Figure 2* offers a structured approach for port stakeholders, enabling a more effective transition toward decarbonisation.

To address *social* barriers, efforts should be made to *build capacity* and increase *collaboration and communication* between the different actors. Doing so could increase environmental awareness or reduce resistance to change. Overcoming *technological* barriers will require *policy instruments, R&D, collaboration, and communication* strategies. Given their strong economic dependency, *financial incentives and disincentives* also play a key role in mitigating barriers such as *high costs, low technology availability and readiness, and green fuel availability issues*.

	Social			Technological			Organizational						Environmental									
	Lack of awareness of environmental priorities Limited knowledge, awareness, and expertise Resistance to change Lack of direct communication High costs			Low technology availability and readiness Lack of detailed and reliable data Green fuel availability issues Infrastructure retrofitting complexity Lack of standards for sustainable initiatives Long lifespan of ships Lack of coordination, collaboration, and cooperation (3Cs) Diminished visibility of the whole value chain Absence of customised frameworks for decision support Reluctance to invest Reluctance to share data Mismatch between present and future planning Conflicting goals in port systems Hierarchical decision delays Complexity of the Industry Global policy gaps and instability Lack of funding and incentives Uncertainties on policies, technologies, and next steps Lack of government support Shipping Industry Growth																		
Policy Instruments				x	x		x	x			x							x	x	x	x	x
Financial Incentives/disincentives				x	x		x			x	x								x			
Management tools			x			x			x		x	x	x	x	x	x	x			x		
Capacity Building	x	x	x	x							x			x	x							
R&D				x	x	x	x	x	x	x		x	x	x							x	x
Collaboration and Communication	x	x	x	x		x	x	x	x	x	x	x	x	x		x	x	x			x	x

Figure 2: Mapping of Port Decarbonisation Barriers and Mitigation Strategies.

The organisational category comprises the highest number of barriers, thereby requiring a diverse mix of strategies. *Management tools, collaboration, and communication* are essential for addressing the complex organisational context of ports, while a *capacity-building* strategy will help support knowledge-sharing and informed decision-making. Due to the shipping industry's growing needs, environmental barriers may be the most difficult to overcome. Thus, a mitigation strategy that focuses on *policy instruments* and combines regulation, investment, and innovation is essential for long-term sustainability.

6. CONCLUSIONS

This study has explored the barriers influencing the decarbonisation of maritime ports and their corresponding mitigation strategies. Through the SLR, it was possible to identify 25 key barriers that were later categorised through the STS lens. While previous research has primarily focused on identifying these barriers, our analysis provides a deeper understanding of how different mitigation strategies can be leveraged to overcome specific challenges. Through our study, we aimed to provide a structured approach for port authorities and policymakers to implement targeted decarbonisation strategies.

This study presents limitations in selecting articles for the SLR, which could result in authors' bias and affect the study's findings (e.g., articles were exclusively sourced from Scopus and were only English-published articles and reviews, leaving aside grey literature). We recommend that future research try to validate the proposed barriers through empirical methodologies, like surveys or expert interview-based case studies. The interrelationship between the barriers is also highlighted, and methodologies such as Interpretive Structural Modelling can help clarify how various barriers influence each other. We also propose that specific case studies of ports that have successfully implemented decarbonisation measures should be explored, providing tangible examples and a list of best practices for overcoming these barriers. Greenhouse Gas (GHG) accounting helps identify areas for reduction and assess mitigation efforts. Future studies should use life cycle assessments (LCA) to pinpoint port operations that contribute the most to emissions across all scopes.

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HUMANITARIAN LOGISTICS

The Distribution Logistics of Covid-19 Vaccines in Germany: A Case Study

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ABSTRACT

Purpose of this paper:

The global rollout of COVID-19 vaccines has been one of the most significant public health measures in modern history. The logistics systems of the vaccination campaigns were key to both their effectiveness and efficiency. This paper examines the logistical framework conditions of the German COVID-19 vaccination campaign and analyses vaccine distribution in ultra-cold supply chains in order to contribute to a better understanding of the design of challenging logistics systems in the field of tension between public and private actors.

Design/methodology/approach:

We use a case study approach to look at the COVID-19 vaccination campaign in Germany where the federal structure gives the 16 federal states (the units of analysis in the case study) a decision-making authority in health-related issues that was also reflected in the various logistics systems that were implemented for the campaign. Primary data was obtained through in-depth interviews and enriched with secondary data from newspapers and other sources. The cases were analysed through the theory lens of the collaborative governance framework.

Findings:

Federalism leads to braking effects where a rapid, coordinated and technically excellent response would be required. Although the vaccination campaign was an overall success, some logistical processes lacked GDP (Good Distribution Practice) approval, so the start was a bit bumpy. The opportunity to develop standard procedures for similar situations in the future was not properly utilised, reducing preparedness to a level below what was possible.

Value:

This case study is one of the few empirical works that deal with the logistical systems and processes behind vaccination campaigns. In particular, it sheds light on the interplay between public and private actors in a federal government structure.

Research limitations/implications:

Primary data could only be obtained from four of the 16 federal states. This is mainly due to the fact that dealing with the COVID-19 pandemic in Germany is still an open issue and an unparalleled political minefield.

Practical implications:

The research shows that standardised, GDP-approved and configurable logistics processes together with a strategic inventory of equipment, infrastructure and consumables are key elements to be prepared for similar situations in the future.

INTRODUCTION

The global rollout of COVID-19 vaccines has been one of the most significant public health measures in modern history. With the rapid spread of the pandemic across the globe, the world faced the dual challenge of developing effective vaccines and ensuring their timely

distribution. Germany, one of the largest and most industrialised countries in Europe, presented a unique case study for the logistics of vaccine delivery due to its decentralised healthcare system and reliance on federal-state coordination.

The vaccination campaign in Germany began at the end of 2020 amid unprecedented logistical and organisational challenges. The federal government, in cooperation with the 16 federal states, had to deal with complex supply chain issues, including suitable storage systems and handling processes for temperature-sensitive vaccines. Added to this was the fluctuating supply of vaccines, public hesitation and the need to adapt to new scientific data on storage conditions and the shelf life of vaccines.

This paper examines the logistical framework of the German COVID-19 vaccination campaign. We use the framework of collaborative governance (Ansell and Gash, 2008) as a theoretical basis, as it focuses on partnerships and cooperation between government agencies, the private sector and civil society in the management of large-scale projects. The federal environment in Germany, where 16 logistics systems for the vaccination campaign have been implemented, led to the research question of what is needed to establish effective and efficient logistics systems for a vaccination campaign. The strengths and weaknesses of the German approach are discussed, along with lessons learned that may be useful for future vaccination campaigns. By examining the interplay between policy, infrastructure and actors, this study aims to contribute to the growing body of knowledge on logistics and pandemic preparedness in a broader context.

LITERATURE REVIEW

The COVID-19 pandemic has challenged scientists, pharmacists, politicians, doctors, nurses and many other professionals in different ways. As different as they may be, they all, with the exception of those opposed to vaccination, had one common interest: getting their vaccine doses as early as possible. After the first COVID-19 vaccines were approved for general use, the focus shifted to mass production and distribution. Setting up a large-scale distribution system for the COVID-19 vaccines was a unique challenge unlike any other campaign in history, as the vaccines had to be distributed worldwide and in each country to local vaccination centres and mobile vaccination teams under time pressure and strict temperature controls.

Based on general comments on logistics in one-off large-scale projects, this section specifically examines the literature on COVID-19 vaccine distribution and related areas such as cold chain management.

To understand the challenges of COVID-19 vaccine logistics, it is important to first examine established supply chain models. Supply chain management has a long tradition of suggesting appropriate supply chain approaches for specific product categories, starting with Fisher's (1997) distinction between functional and innovative products. In this context, COVID-19 vaccines are primarily innovative products that require a responsive supply chain "at all costs" due to their uncertain demand and supply. However, as the situation stabilised, parts of the supply chain adopted efficient strategies leading to a hybrid supply chain model (Selldin and Olhager, 2007; Harris et al., 2010). Cavinato (2002) suggests a more granular approach with 16 supply chain models, including one for projects. To cope with the complex scope of large-scale projects, Lovallo et al. (2023) propose a method which gathers information from similar projects to forecast the plan for a new project, taking into account both similarities and dissimilarities between the projects.

Emergency logistics for natural and man-made disasters is an important example of one-off projects of significant scale and impact (Sheu, 2007). The need for effective logistics planning and operations management is paramount in such scenarios, as the challenges are inherently complex and require a different approach than in general business logistics (Jiang et al., 2012; Jiang and Yuan, 2019). Sheu's (2007) definition of emergency logistics as *"the process of planning, managing and controlling the efficient flows of relief, information, and services from the points of origin to the points of destination to meet the*

urgent needs of the affected people under emergency conditions” makes it clear that both the specific design of the logistics system and its more routine implementation are important components of the project. Based on a strategic plan, the supply chain needs to adapt continuously to new information as it becomes available (Sheu, 2007; Jiang et al., 2012; Jiang and Yuan, 2019).

The phase models for emergency logistics are very similar. Kovács and Spens (2007) propose three phases: preparation, immediate response and reconstruction, while FEMA (2019) adds mitigation (i.e. actions aimed at preventing the occurrence of a disaster or reducing its impact from the outset) as the first phase. Preparedness is a key advantage as it enables quick, cooperative and efficient responses (Sabbaghtorkan et al., 2020). The ability to make appropriate decisions, collaborate effectively with multiple parties and adapt to appropriate logistics models is crucial to cope with overwhelming demands and uncertainties (Jiang et al., 2012). Effective emergency logistics requires collaboration between different companies and humanitarian organisations (Nurmala et al., 2017). The success of such projects depends on coordination and collaboration between public, private and various stakeholders (Breitbarth et al., 2021). Although the COVID-19 vaccine distribution campaign differs from disaster management due to the longer period of time available to set up the logistics system, the aspects of preparation and coordination and collaboration between different stakeholders can be utilised.

The actors involved in vaccine production through to deployment include research institutes, government, private and non-profit organisations at local, national and international levels (Torshizi et al., 2024). Strong coordination between these actors plays a critical role in planning a reliable supply chain (Alam et al., 2021; Forman et al., 2021; Wouters et al., 2021).

The distribution of COVID-19 vaccines required overcoming unique needs and challenges, especially in terms of storage and transportation requirements. Stakeholders involved in pharmaceutical products, including COVID-19 vaccines, must adhere to good manufacturing practices (GMP), good storage practices (GSP) and good distribution practices (GDP) (Lin et al., 2023).

During the pandemic, various companies around the world have developed COVID-19 vaccines, including Pfizer/BioNTech, AstraZeneca and Moderna. Pharmaceutical companies need to produce sufficient quantities and maintain the supply chain to ensure effective distribution of the vaccine around the world (Alam et al., 2021; Forman et al., 2021; Torshizi et al., 2024). In addition, other medical (e.g. syringes) and non-medical products (e.g. transportation boxes) and services (e.g. websites to manage vaccination appointments) are required for a successful vaccination campaign (Forman et al., 2021).

Each vaccine has its specific needs and requirements for storage and temperature control (Khodaei et al., 2022; Sun et al., 2022). The temperature range of -70°C to 8°C, limited shelf life and time pressure make the supply chain for COVID-19 vaccines more challenging and different from the usual vaccine supply chains (Burgos et al., 2021; Georgiadis and Georgiadis, 2021; Khodaei et al., 2022; Sun et al., 2022). This required maintaining and monitoring the cold chain during transportation, storage and handling from the production sites to the points of consumption to avoid spoilage of the vaccine doses (Burgos et al., 2021; Forman et al., 2021; Georgiadis and Georgiadis, 2021; Lin et al., 2023; Ali and Khan 2023). Important decisions had to be made at various stages, including the location of central and regional hubs, vaccination centres, means of transport, infrastructure and equipment (Georgiadis and Georgiadis, 2021). As vaccination centres were usually equipped with regular refrigerators only, proper organisation and coordination was essential (Georgiadis and Georgiadis, 2021).

METHODOLOGY

We use a case study approach to analyse the distribution logistics of COVID-19 vaccines in Germany. Germany was chosen as the context for the case study as it offers access to first-hand information and thus a high density of information can be expected (Flyvbjerg, 2006). Germany can be considered well developed in terms of logistics, which means that the case study will highlight specific problems of COVID-19 vaccine distribution that are not affected by basic logistical problems, which increases the validity of the results. Furthermore, the federal structure of the country represents an additional layer of complexity that makes Germany an extreme case in terms of coordination and cooperation (Gammelgaard, 2017).

Technically, we follow an embedded single case design with the 16 federal states as embedded units of analysis (Yin, 2018, p. 48). In practice, we were limited to a much smaller number of units, as some federal states or actors in charge of vaccine distribution at the state level were not available for in-depth interviews. The most likely reason is that the assessment of the government's actions during the COVID-19 pandemic has not yet been officially started and will only begin, if at all, when a new federal government takes office after the national elections at the end of February 2025 (Tagesschau, 2025). However, we managed to obtain information from three federal states. The interviewees were involved in the vaccination campaign in A (a larger federal state from the western part of Germany), B (a larger federal state from the eastern part of Germany), C (a smaller state from the western part of Germany), and D (a city state). While the logistics service providers answered for A and B, for C and D it was the state authorities. In the case analysis, the information is labelled accordingly with [A], [B], [C], and [D].

The framework for cooperative governance by Ansell and Gash (2008) forms the theoretical basis for the case analysis. To date, this framework has been little used in logistics research, for example, with regard to the implementation and enforcement of levies in an Indonesian city (Hermansyah et al., 2024) and the institutional design of collaborative arrangements related to urban freight transportation (Fossheim and Andersen, 2022; Cheng et al., 2025). Ansell and Gash's (2008) collaborative governance framework is particularly well suited for our purpose because of the complex, multi-stakeholder environment in which public health agencies, federal and state governments, logistics providers, healthcare institutions, and pharmaceutical companies had to coordinate under urgent and uncertain conditions. The framework's emphasis on stakeholder involvement, trust building, shared understanding, and joint decision making provides a structured lens to evaluate how the decentralised German government system managed intergovernmental coordination and public-private collaboration.

The framework comprises four variables: Starting Conditions, Institutional Design, Facilitative Leadership, and Collaborative Process (**Fig. 1**).

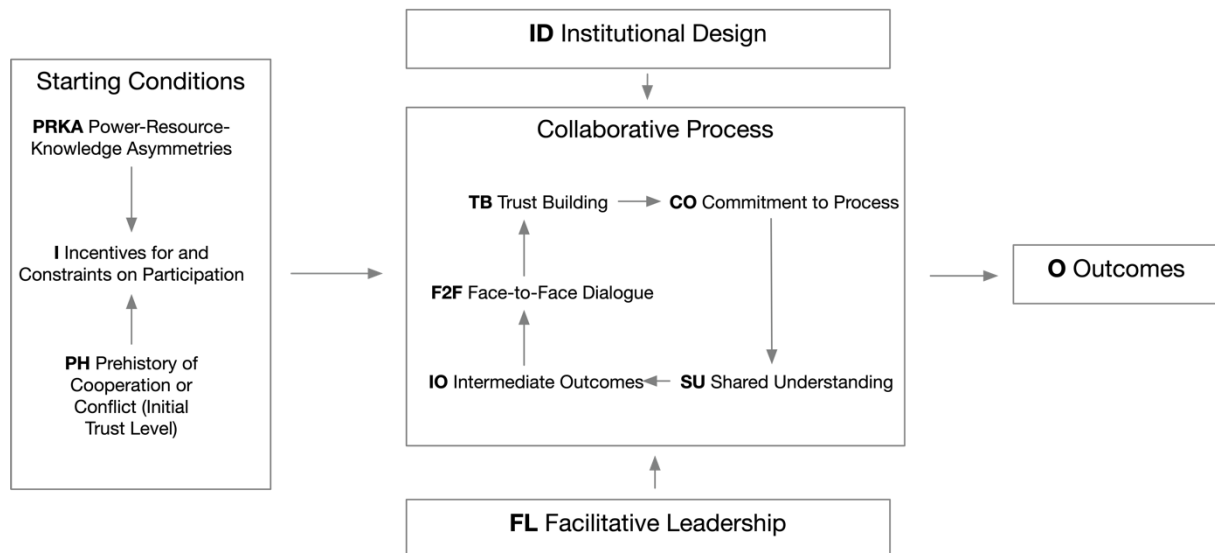


Fig. 1: Collaborative governance framework (Ansell and Gash, 2008)

The **starting conditions** can either facilitate or discourage cooperation. **Facilitative leadership** brings and holds stakeholders together while steering them through the **collaborative process**, an iterative process with frequent feedback loops. **Institutional design** defines the basic protocols and rules for collaboration.

The primary data comes from in-depth online interviews (Zoom meetings) for A, B and D (which were recorded with the consent of the interviewees) and from a written statement for C. Secondary data was collected from a range of sources, including official statistics, newspapers and the internet.

CASE ANALYSIS AND FINDINGS

The case analysis goes from the big picture to the details. It starts with the political framework (i.e. the federal structure of Germany) and then, based on the logistical needs for the various COVID-19 vaccines, analyses the logistics systems set up at federal and state level.

Political Framework

The COVID-19 vaccination in Germany began on 26 December 2020. By 8 April 2023, around 76.4% of the population had received a basic vaccination and 62.6% had also received at least one booster vaccination. Despite intensive public advertising campaigns, almost a quarter of the population has not taken up their vaccination doses (BMG, 2023). While the supply of vaccines lagged behind demand at the beginning of the campaign, this situation changed, leaving a significant stockpile. By the end of 2024, 213 million vaccine doses had to be scrapped (Kelber, 2023; Westendarp, 2024) because they had reached the end of their shelf life or were no longer considered effective against the current COVID-19 strains. These numbers cannot simply be explained by unpredictable demand or forecasting errors. Rather, panic buying and hoarding seems to have occurred (Kelber, 2023).

The European Union negotiated with the vaccine manufacturers, ordered and allocated supply quotas on the basis of the demand figures reported by the Member States. In Germany, the demand figures were aggregated from the demand reported by each federal state. The sixteen federal states are responsible for inpatient care and the public health service, which also includes the prevention and control of communicable diseases (BMG, 2016).

Germany's federal structure explains why no nationwide logistics system was set up for the vaccination campaign. Instead, the federal government and the 16 federal states have set up a federal logistics system (to receive and store the contingents supplied by the vaccine manufacturers), which is based in its design and infrastructure on the system implemented in one federal state by a cold chain service provider [A] and 16 state logistics systems (to organize the regional storage and distribution of vaccines to the points of use).

Initially, the fight against the pandemic was coordinated by a crisis team, which was actually the usual working group approach of the federal government and all the federal states for everything that concerns the federal states and the federal level. It was not considered effective and efficient due to differing views on priorities and cooperation [C]. Just under a year after the start of the vaccination campaign, at the end of November 2021, a more specific and centralized approach was chosen: A new crisis team was set up in the Federal Chancellery, headed by Carsten Breuer, a general in the German Armed Forces who is considered a logistics expert with extensive experience in crisis management (Tagesschau, 2021). This approach, although it came very late [B], was more effective and changed the spirit and pace of federal cooperation and is considered mandatory for any similar situation from the outset [B, C]. A centralised approach, where vaccine vials are allocated to states instead of states ordering them, would have avoided the frequent rescheduling of vaccination appointments because orders were not fully dispatched [B]. Information was generally not shared between states [B], but some neighbouring states helped each other with vaccines [C].

In each federal state, the respective health ministry was responsible for the vaccination campaign. The usual administrative and decision-making structure was retained, but supplemented by an advisory group with experts from various fields. The functions of these advisory groups were dissolved as soon as the vaccination campaign became the responsibility of the medical practices [C, D].

The service providers tasked with setting up and operating the logistics systems for the vaccination campaign not only had to deal with the authorities at state level but also had to take into account the targets set by the federal government. The dual objectives led to confusion and were not helpful. While the advice of cold chain experts was readily accepted by experts at state level, it often went nowhere at federal level [A]. Another dilemma existed between the service providers responsible for logistics and the organisations responsible for administering the vaccine, which worked in parallel. Any problems that arose had to be brought to the attention of the government, as only the government had the right to issue instructions [B].

Logistical Needs for the COVID-19 Vaccines

Although four vaccines were available when the vaccination campaign gained momentum in Germany, the Pfizer-BioNTech vaccine accounted for more than 70% of all doses administered in Germany (Statista, 2024). The Moderna vaccine was a distant second, while the Astra Zeneca and Johnson&Johnson vaccines were only used to a limited extent. The case analysis therefore focuses on the Pfizer-BioNTech and Moderna vaccines, especially since the other vaccines did not pose any other major logistical challenges.

Against the background of the European Union's rules on good distribution practice (Directive 2001/83/EC in conjunction with Guidelines 2013/C 343/01), which apply to all medicinal products marketed in the EU, manufacturers define the specific logistical requirements for vaccines. The Pfizer-BioNTech vaccine is packaged in cartons containing 195 vials and must be stored ultra-cold at $-75^{\circ}\text{C} \pm 15^{\circ}\text{C}$. The original shelf life under these conditions was six months. Any transfer of cartons between ultra-cold storage facilities must be completed in less than five minutes at an ambient temperature below 25°C . For single vial picking, cartons must be transferred from the ultra-cold storage facility to a standard cold storage facility ($2^{\circ}\text{C} \dots 8^{\circ}\text{C}$) within five minutes at an ambient temperature below 25°C . The time stamp of this transfer must be noted on the carton and on any qualified package containing partial quantities as it marks the start of the 120-hour shelf

life, of which a maximum of 12 hours is allowed for transportation in qualified transport boxes. The transport boxes are equipped with temperature loggers and at each interface in the distribution chain it must be checked whether the temperature range of 2°C ... 8°C has been maintained and the vials are still within their shelf life. In the event of a violation, the contents of the transport box must be quarantined and withdrawn from further distribution (NN 2021a). The Moderna vaccine must be stored at -25°C ... -15°C for up to seven months. The logistical infrastructure and equipment used for frozen food meets this requirement. After transfer to a cold store at 2°C ... 8°C, the shelf life is 30 days. Low-vibration transportation must be possible. The requirements for temperature monitoring and documentation are the same as for the Pfizer-BioNTech vaccine (NN 2021b).

Vaccine-specific transportation and storage requirements changed during the vaccination campaign. The record-breaking speed of vaccine development also meant that these requirements were initially more theoretical in nature (e.g. the vials must be transported without vibration, which cannot be achieved [B]). One service provider designed its own thermoformed insert that can be used to hold the individual vials in a GDP-approved standard box) or on the safe side, as they were often based on theoretical calculations rather than practical testing (e.g. the shelf life of Pfizer-BioNTech's vaccine was extended as more data became available) [A].

The most commonly used vaccine in Germany was the most difficult, as it has to be stored and transported ultra-cold, which requires non-standardized logistical infrastructure and equipment. Two process variants are possible for the Pfizer-BioNTech vaccine: (1) ultra-cold distribution of whole cartons (195 vials) to the point of use [C] and (2) transfer to a cold storage facility (e.g. a refrigerated container converted into a "walk-in refrigerator" for which a GDP certificate has been obtained) and the picking of partial quantities in regional distribution centers and distribution of these quantities to the point of use [A]. Some service providers tried to pick individual vials at -70 °C using devices such as grill tongs but found this method to be ineffective [A]. The first option requires ultra-cold storage facilities at the point of use but offers more flexibility for vaccination as it makes a larger quantity of supplies available at the point of use. The second option allows the critical infrastructure and equipment for ultracold storage to be concentrated in the regional distribution centres, while the limited shelf life of vials in cold storage places a burden on the process of scheduling vaccination appointments. Both options were implemented in Germany, but mainly the second option was used.

When Pfizer-BioNTech's vaccine went through the approval process, it turned out that ultra-cold storage was the most important logistical requirement. Every country that had contracts for this vaccine urgently needed ultra-cold storage facilities, i.e. (1) container-sized freezer units, (2) cabinet-sized freezer units and (3) special insulated transport boxes filled with dry ice. While the freezers were used to store Pfizer-BioNTech's vaccine in Germany at both the federal and state levels, the special transport boxes were used to maintain ultra-cold storage during transportation. Once the vaccine was removed from the ultra-cold storage facility, insulated transport boxes and temperature-controlled refrigerators at the point of use ensured the 2°C ... 8°C cold storage.

At the beginning of the vaccination campaign, it was difficult to get hold of all the ultra-cold storage units [A, B]. The service providers of the federal states did not join forces to procure this critical equipment but worked independently of each other. Ilyushin cargo planes were chartered to transport the containers from Asia to Germany, paying large sums of money to expedite the delivery [A]. Dry ice was also in short supply in summer 2021 (Rinke, 2021), as it is a by-product of the production of ammonium for fertilizers, cannot be stored for more than two days and is also in high demand in other industries (e.g. in the production of carbonated drinks or as a freezing agent in the food industry).

Logistics Service Providers

The federal states commissioned service providers with the logistics of the vaccination campaign without knowing the logistical scope and challenge of the vaccination campaign,

as the situation was completely new [A] and the existing state structures were not suitable to cope with the logistical challenges [B]. The commissioning came late, in October/November 2020 [A, B], and, from that perspective, the logistics system set up for the COVID-19 vaccine logistics can be considered an "*Olympus of speed and professionalism*" [A].

The selection of service providers was very diverse and ranged from global logistics service providers with many years of experience in the cold chain to regional logistics service providers specializing in pharmaceutical logistics to providers with a less obvious connection to cold chain logistics, e.g. a federal association of the German Red Cross (with references to the logistical support of the 2015 refugee crisis and the operation of a blood transfusion service) and a consumer protection organization. Regionality (in line with federalism) and trust coming from previous cooperation (e.g. in the storage of PPE masks [A] or the logistical support during the 2015 refugee crisis [B]) were decisive factors in the selection of the service provider, much more than experience with ultra-cold chains [A].

The scope of the contract was also different. While some federal states made turn-key contracts [A, B], others left part of the supply (e.g. consumables like swabs or syringes) to the vaccination centres. Some federal states also asked the service providers to set-up the web-based services and call centres to register for and schedule vaccinations [B].

The cold chain and pharmaceutical specialists among the logistics service providers were aware of the GDP requirements and were at least partially able to use infrastructures and procedures that had passed a general GDP audit. One of the logistics service providers subjected the logistics system developed specifically for COVID-19 vaccines to a GDP audit [A]. Other service providers went their own way and dispensed with a formal GDP audit.

For the service providers, working with the government as a client was a particular challenge, as the decision-making structures are different and even involved distributed responsibilities with stakeholders who were not aware of the GDP requirements. When the selection of cold chain equipment was left to the logistics experts and the government only dealt with the purchase of this equipment, this risk was under control. However, taking responsibility beyond one's own expertise can lead to serious problems. In Bavaria, for example, the Ministry of Health provided the transport boxes for the 2 °C ... 8 °C "last mile" of the vaccine distribution chain. It turned out that these boxes were intended for use in outdoor recreational activities and did not have a GDP certificate. The permissible temperature range could not be maintained for many shipments, meaning that hundreds of vaccine doses had to be scrapped at the start of the campaign due to a system error (NN 2021c). Even without a GDP certificate, tests would have shown whether the transport boxes could maintain the required temperature range [B]. In a more professional logistics system, only 30 vaccine vials had to be scrapped within two years, in all cases due to individual carelessness unavoidable on this scale [A].

As speed in implementing the logistics systems for the vaccines was key to the success of the vaccination campaign, a professional understanding of the GDP requirements was of great importance. The most important part was the risk assessment against the general GDP and the specific vaccine requirements with the aim of understanding the sources of risk and controlling them rather than eliminating them completely [A]. Governments set targets, such as individual vials having to be delivered to points of consumption, without understanding the logistical consequences [A].

Governments were able to expand their logistical competence if they succeeded in combining a clear will to "get the project done" and a willingness to learn with intensive cooperation with the service provider. The success of the logistics system depended on the close cooperation of all those involved [A, C]. This success is seen as a good starting point for any other similar task in the future [C]. Some continuously shared the insights gained during the project [A], while others fear that the most important insights remained at the individual level [B]. A "lessons learned" session at the dissolution of the task force structure presented a handbook to share findings and help in a similar situation in the future [D].

CONCLUSION AND OUTLOOK

In this section, we integrate the findings from the case analysis into the collaborative governance framework (**Fig. 2**), also referring to Kovács and Spens' (2007) three phases of emergency logistics (preparation, immediate response and reconstruction). The **institutional design** is framed by the federal structure of Germany. This basic concept will continue to apply to any similar crisis in the future, as it is enshrined in the German constitution. However, the emergency response would benefit from a clear task force structure and the involvement of logistics service providers from the outset.

The COVID-19 vaccination campaign has shown that the starting conditions were not optimal because Germany, like other countries, was not well prepared for the challenge. In the immediate response phase, which included the design of logistics systems, one of the main problems was that in the division of tasks between state administrations and logistics service providers, logistical decisions were not always made by the experts, but by those who formally considered themselves responsible. For the vaccination campaign, it was advantageous that the federal states commissioned the service providers on the basis of trust based on previous experience. However, it would have been better to forego regionality in favour of expertise, especially with regard to GDP. After the pandemic, the federal and state governments should discuss the requirements for LSPs in order to increase readiness.

During the COVID-19 vaccination campaign, facilitative leadership was improved by the appointment of a clear leader of the task force, albeit late. The success and positive response to this decision suggests that Germany should strategically train leaders for such positions.

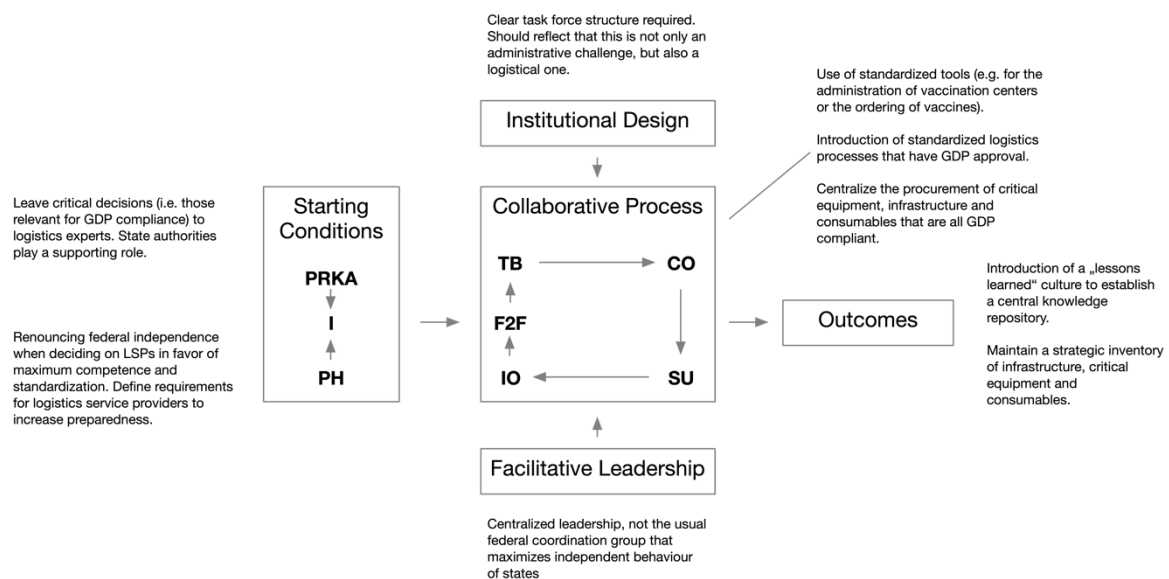


Fig. 2: Learnings from the case analysis

Although the **collaborative process** generally worked, it showed weaknesses in GDP compliance and standardisation. Work was often duplicated across states (e.g. vaccine administration websites), to the point of competition in the procurement of essential equipment. There was limited learning from each other during the campaign, leaving some states reliant on procedures that were not GDP approved. A more centralised approach aimed at standardised logistics processes would have been advantageous.

One important **outcome** is the need for a culture of lessons learned. This opportunity was missed, with a few exceptions in individual states. The state authorities and their LSPs should make up for this if they can reach the key people involved. It is also clear that the critical equipment, especially the ultra-cold temperature freezer units, must form the basis of a strategic inventory, which must also include the basic infrastructure (GDP-compliant warehouses) and a basic stock of consumables.

Schwarzendahl et al.'s (2022) models show that rapid intervention, including vaccination, is key to breaking the wave of future pandemics, so good preparation is essential. Future research in the field of logistics should aim to define standardised, configurable logistics processes for vaccination campaigns.

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