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A systematic literature review of halal transportation in logistics studies

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Keywords: halal transportation, halal supply chain, cross contamination, halal logistics.

Abstract: This article examines how halal transportation supports the integrity of material and information flows in the halal supply chain by systematically reviewing the international scientific literature indexed in the Scopus database. The study addresses the fragmented knowledge of halal logistics transportation, particularly regarding contamination risks, logistical constraints, lead times, and infrastructure quality, which hinder the design of robust halal logistics systems. Using a Systematic Literature Review (SLR) approach guided by the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) framework, 13 relevant articles were selected from an initial set of 28 publications. The findings show that research on halal transportation is still limited and concentrated in a few countries, with Malaysia as the main contributor, and that four critical challenges dominate the discussion: the risk of cross-contamination along logistics flows, the limited availability of halal-certified transport alternatives, delays in delivery time, and inadequate transport infrastructure. In scientific terms, this article offers a structured synthesis of these challenges from a logistics perspective and clarifies how halal transportation influences the performance of supply chain flows. In practical and pedagogical terms, the study provides guidance for logistics managers, policymakers, and educators in designing logistics networks, infrastructure, and learning materials that better support the implementation of halal transportation.

1 Introduction

In the era of increasingly advanced globalization, the number of people seeking halal products has grown dramatically. Along with increased purchasing power supported by Islamic finance [1] and recognition of the importance of selecting items that adhere to Islamic principles, Muslim consumers are increasingly inclined to seek Halal products [2,3]. Not only does this desire for halal comprise food, but it also encompasses a wide range of other items that adhere to the rules of sharia. In response to this need, the concept of halal logistics emerged as an essential component of supply chain management [4,5].

Islam recorded an annual growth rate of 1.5%, making it the fastest-growing religion in the world. It is estimated that by 2030, the Muslim population will reach 26.4% of the total projected global population of 8.3 billion people [6]. This expansion has substantial repercussions across a variety of industries, including the halal industry and halal logistics. Within this framework, halal logistics transportation is of utmost importance in order to ensure that halal products are supplied efficiently and securely from producers to customers [7]. Halal logistics not only includes the storage and transportation of goods but also ensures that the entire process meets strict sharia standards. With increasing awareness among Muslim consumers of the halal status of products, the need for a logistics system that ensures product integrity and halal status is becoming urgent.

In Indonesia, the implementation of halal integrity is an obligation regulated by government regulations. The rule mandates segregation of halal product operations by location, slaughter site, methodology, storage, packaging, distribution, sale, and presentation of non-halal items. This rule mandates that, to preserve the integrity of halal logistics, halal items must not be stored in the same containers or trucks as non-halal products to prevent cross-contamination [8].

In the absence of halal logistics, it is impossible to ensure that consumers receive trustworthy halal items. What is surprising, however, is that a significant number of halal food manufacturers remain reluctant to include halal transportation services in their operations [2]. Halal value creation in logistics refers to the innovative ability of halal-based logistics service providers to offer products or services that comply with halal standards [9].

Despite extensive research on halal logistics, there remains a significant knowledge gap regarding the difficulties and opportunities logistics service providers encounter when adopting halal transportation systems. Findings from several studies indicate an immediate need to construct suitable infrastructure and raise awareness among various stakeholders of the significance of halal certification in the context of logistical operations [10]. Additionally, clear regulations and government support are necessary to encourage the adoption of halal logistics practices in the private sector.

Despite the growing body of research on halal logistics, there remains a significant gap in understanding how halal transportation specifically affects logistics flows, risk management, and the performance of halal supply chains. Existing studies tend to focus on partial aspects, such as certification, consumer behaviour, or isolated case studies, and thus do not provide a comprehensive overview of the main logistical problems encountered in halal transportation. This article seeks to address that gap by conducting a Systematic Literature Review (SLR) of studies on halal logistics transportation indexed in the Scopus database, with two main objectives: first, to clearly identify and classify the key logistical challenges in halal transportation, namely the risk of cross-contamination, the limited availability of halal transport alternatives, delivery time issues, and the quality of transport infrastructure; and second, to explain what is new in terms of logistics theory, supply chain management practice, and pedagogy derived from these findings. In doing so, this study contributes to the logistics and halal supply chain literature by providing an integrated scientific synthesis and by formulating practical implications for the design and management of halal transportation systems.

2 Literature review

The bibliometric study revealed that the development of halal supply chain research is relatively new but has continued to develop in the last decade [11]. During the course of the investigation, it was discovered that, out of a total of 104 articles on the halal supply chain taken from the Scopus database for the years 2008-2018, more than 60% were published between 2015 and 2018. This research also identifies four main themes in halal supply chain research, namely Halal Foundation, Implementation, Preparing and Processing, and Concept Development. It is interesting to note that the research focuses more on the final product (the Halal Foundation) and, at the very least, analyzes the preparations and procedures involved in various activities along the halal supply chain [11].

In another bibliometric research study, a bibliometric technique was used to analyze literature publications associated with Halal Supply Chain Management (HSCM) [12]. The analysis included 149 articles retrieved from the Scopus and Web of Science databases and covered the period from 2011 to 2021. The analysis reveals that HSCM's research can be grouped into five main groups: Halal Food Industry, Halal Logistics Challenges and Opportunities, Halal Food Integrity Assurance, Halal Logistics Integrity Assurance, and Halal Logistics Performance. The findings of this study represent a major addition to the knowledge base on the growth of Halal Supply Chain Management research and the identification of future research prospects, notably in the service industry, which remains underexplored.

Halal transportation is an essential element of halal logistics, designed to preserve the integrity of halal products throughout the supply chain. Research demonstrates that manufacturers' adoption of halal transportation is minimal, with several constraints, such as complexity, elevated costs, and the restricted availability of halal transportation service providers, posing considerable challenges [13]. Additionally, physically separating halal and non-halal items during transportation is a crucial step in preventing cross-contamination, which is a significant risk in halal logistics [14]. In 2017, an event occurred in which halal meat and pork were mixed in the same container. This occurrence highlighted the significance of halal transportation [15]. In addition, halal transportation is an essential component of the halal tourism business, as it enables the fulfillment of the transportation requirements of Muslim visitors in terms of transportation [16].

Research by [17] proposes a framework for assessing risks in halal logistics. Nonetheless, it fails to properly gather and analyze the current material to present a thorough overview of the issues encountered in halal transportation. Their research used qualitative analytical approaches, such as interviews and surveys, to ascertain the factors influencing firms' preparedness to implement halal logistics. This work seeks to address this gap by conducting a systematic literature review, enabling a more thorough identification and categorization of halal transportation concerns.

In this study, the method used to conduct a systematic literature review of halal logistics transportation studies differs significantly from previous studies [18]. This study aimed to explore the factors influencing the adoption of halal logistics. This study focuses on collecting and synthesizing data from various literature sources to identify risks associated with halal logistics transportation.

In addition, the SLR approach used in this study also distinguishes it from previous studies, which are often limited to specific geographic contexts or industry sectors. As a result, this study not only gives fresh perspectives on the dangers associated with halal transportation, but it also provides direction for practitioners and other researchers who are interested in comprehending the intricacies of halal logistics in a variety of settings.

3 Methodology

To conduct an in-depth investigation of halal logistics transportation, the approach used in this study is a Systematic Literature Review (SLR). This topic has never been explored before through a systematic literature review. Using the Scopus database as the primary source, the systematic literature review (SLR) method was chosen because it provides a systematic, structured framework for collecting, evaluating, and synthesizing information from relevant literature, thereby producing an in-depth understanding and generating new findings in the field of halal transportation logistics.

By using the Systematic Literature Review (SLR), the research can provide a comprehensive overview of the state of the art in the field of halal transportation logistics, as well as identify existing research gaps for future development [19]. In this study, the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) diagram was used as a framework to manage and evaluate the literature [20] systematically. This diagram serves as a structured guide that assists researchers in carrying out a series of stages, from the initial identification of the literature through screening to the selection of final articles that meet the quality standards for analysis in this study. Researchers ensured that only high-quality, relevant papers were included in this systematic review by using the PRISMA methodology, which structured and made the selection process more transparent [21].

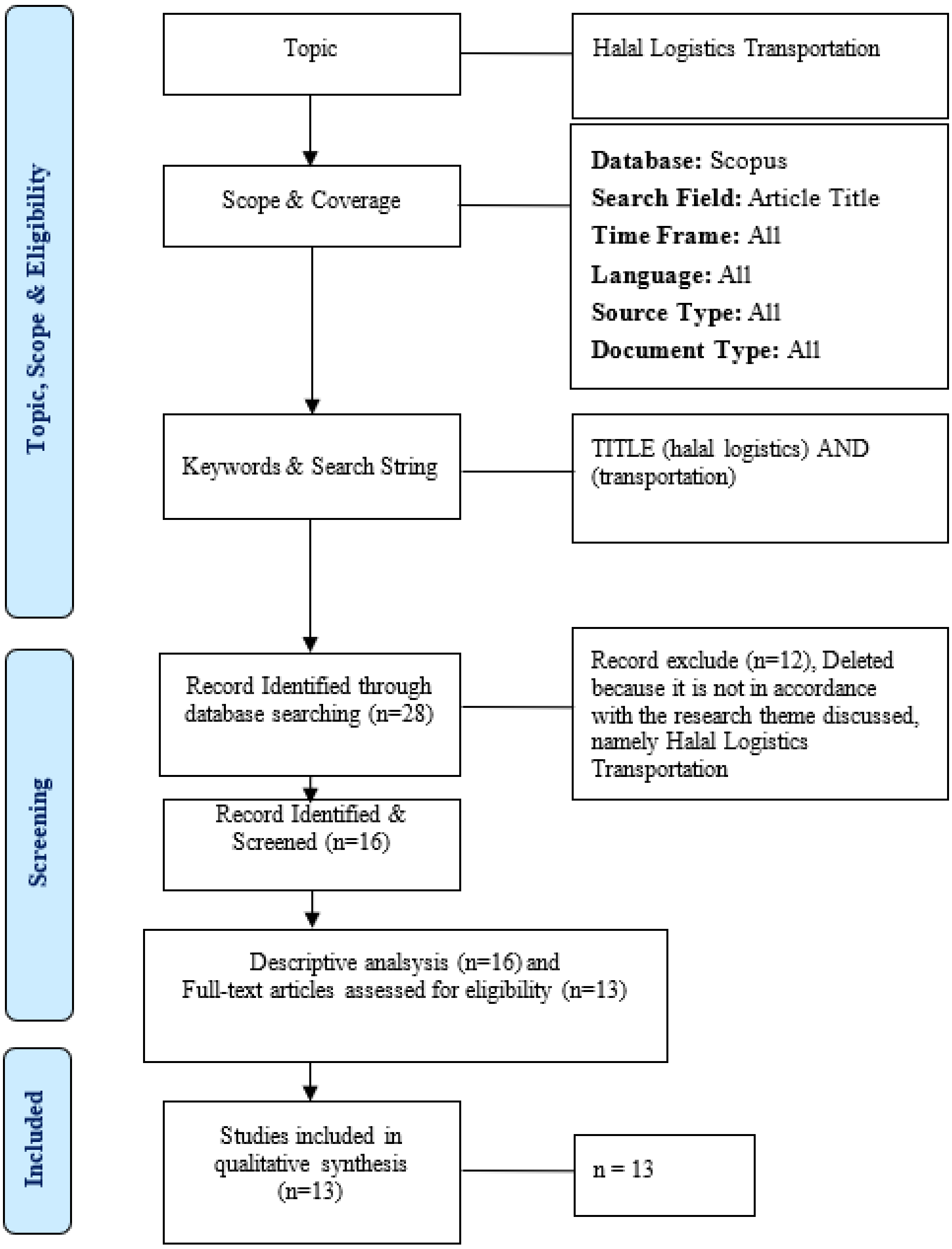

Figure 1 The flow diagram of the search technique

This study processed documents through a series of systematic, detailed selection stages, using primary data obtained directly from the Scopus database. The research flow is illustrated in Figure 1. The research process begins with determining the focus of the topic to be studied, followed by an in-depth evaluation of the selected articles. The selection of articles is carefully made, with content suitability and relevance to the analyzed topic in mind. The literature search in this study was conducted using the following keywords: "TITLE-ABS-KEY (Halal logistics) AND (Transportation)" in the Scopus database. The initial search results, as of October 19, 2024, yielded 28 articles, which were then subjected to two screening stages. The first stage involved content-relevance analysis, resulting in 16 articles that fit the research topic. Furthermore, in the second stage, a screening was conducted based on the availability of full-text articles, which ultimately resulted in 13 articles that became the primary sources in this systematic literature review.

In addition, the relatively small number of articles included in this review reflects the limited body of research on halal logistics, particularly studies with a specific focus on halal transportation. This condition arises not from a narrow selection process alone but from the scarcity of empirical and conceptual works that explicitly address halal transport within the broader halal logistics system. Even with this limitation, transportation is treated in this study as a crucial element of halal logistics, so the available articles were retained and examined in depth to capture, classify, and interpret the key logistics issues related to halal transport flows as comprehensively as possible.

4 Results and discussion

4.1 Publications regarding halal logistics transportation by year

The "Total Publication" graph in *Figure* 2 shows the trend of publications on halal transportation, logistics, and supply chains from 2012 to 2024. At the beginning of the period, the number of publications was relatively low, with only one publication in 2012. An increase was observed in 2014, with two publications, but it declined again in 2016. A significant increase began in 2019, reaching its peak in 2022 with these five publications. However, this number has again decreased to three publications in 2023. This trend reflects fluctuating interest and attention to this topic among academics and researchers, suggesting that despite the increase in awareness and research, there is still instability in the number of annual publications.

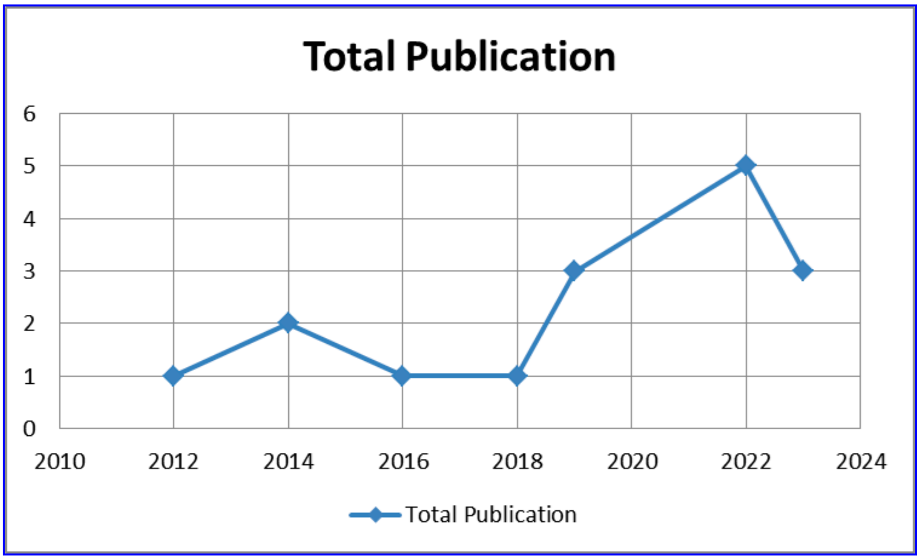

Figure 2 Publication trends by year

4.2 Publications by subject area

Table 1 presents an analysis of the research subject area on halal logistics transportation, showing that the field of Business, Management, and Accounting dominates with 12 publications, accounting for 40% of the total publications. This data highlights the importance of the managerial aspect in developing a halal logistics system. Computer Science accounted for five publications (16.67%), emphasizing the role of technology in logistics process optimization. The fields of Decision Sciences and Economics, Econometrics, and Finance each have four publications (13.33%), indicating a focus on decision analysis and economic aspects. Other fields, such as Arts and Humanities, Chemistry, Engineering, Materials Science, Mathematics, and Social Sciences, each accounted for one publication (3.33%), indicating that although the contribution was small, a multidisciplinary approach was still needed to enrich research in these areas.

Table 1 Publications by subject area

Subject Area	Total Publication	Percentage
Business, Management, and Accounting	12	40.00%
Computer Science	5	16.67%
Decision Science	4	13.33%
Economics, Econometrics, and Finance	4	13.33%
Arts and Humanities	1	3.33%
Chemistry	1	3.33%

4.3 Publications by country

According to Table 2, Malaysia is the nation that has made the most significant contribution to halal transportation, logistics, and supply chain. The country has produced 14 publications, accounting for 58.33% of the total. This result suggests that Malaysia has significant attention and development in the sector, likely driven by government policies that support the halal industry and by adequate infrastructure. Despite having the largest Muslim population in the world, Indonesia accounts for only two publications, or 8.33%. This phenomenon may reflect challenges in implementing a more structured halal logistics system or a lack of documented research compared to Malaysia. Other countries, such as India, Jordan, the Netherlands, Oman, Saudi Arabia, and Singapore, each contributed one publication (4.17%). This data shows that, despite global interest in halal logistics, its implementation remains limited to a few regions. The participation of non-Muslim nations, such as the Netherlands, illustrates the potential for a globally appealing halal industry. This data indicates that, despite global recognition of the significance of halal logistics, considerable disparities in research and development exist among nations. Malaysia has the potential to serve as a paradigm for other nations in establishing an efficient halal logistics framework.

Table 2 Publications by country

Country	Total Publication	Percentage
Malaysia	14	58.33%
Indonesia	2	8.33%
India	1	4.17%
Jordan	1	4.17%
Netherlands	1	4.17%
Oman	1	4.17%
Saudi Arabia	1	4.17%
Singapore	1	4.17%

4.4 Publications based on journal source titles

Table 3 of the analysis of journal sources concerning Transportation Halal Logistics indicates that the Journal of Islamic Marketing is the predominant source, accounting for 25% of publications, followed by Halal Logistics and Supply Chain Management Recent Trends and Issues and the International Journal of Supply Chain Management, each at 19%, underscoring the significance of halal logistics management. Other publications, such as the International Journal of Innovation, Creativity, and Change and the Journal of Global Operations and Strategic Sourcing, offer novel insights despite their limited contributions (6%). This research demonstrates the substantial advancement and importance of halal logistics in response to global concerns.

Table 3 Top 5 publications based on journal source titles

Source Titles	Total Publication	Percentage
Journal of Islamic Marketing	4	25%
Halal Logistics and Supply Chain Management: Recent Trends and Issues	3	19%
International Journal of Supply Chain Management	3	19%
International Journal of Innovation, Creativity, and Change	1	6%
Journal of Global Operations and Strategic Sourcing	1	6%

4.5 Publications based on citation performance

Table 4 of the citation performance analysis in the study on Halal Logistics reveals that the article "Principles in Halal Supply Chain Management" dominates with 190 citations (66% of the total), indicating the significant influence of this topic in the academic literature. The study on "Halal Transportation Adoption Among Food Manufacturers in Malaysia" received 30 citations (10%), reflecting the growing concern about the adoption of halal practices in the food sector. Other articles, such as "Halal Logistics: Practices, Integration and Performance of Logistics Service Providers" and "Factors Behind Third-Party Logistics Providers' Readiness Towards Halal Logistics," have 24 (8%) and 20 citations (7%), respectively, highlighting the importance of logistics service providers' practices and readiness. Overall, this data demonstrates the evolution of halal logistics and supply chain research, with a focus on best practices and the integration of technology to enhance industry performance.

Table 4 Top 3 publications based on citation performance

Article Titles	Total Citation	Percentage
Principles in Halal Supply Chain Management	190	66%
Halal transportation adoption among food manufacturers in Malaysia: the moderated model of technology, organization, and environment (TOE) framework	30	10%
Halal Logistics: practices, integration, and performance of logistics service providers	24	8%

4.6 Publications by the university

The analysis in Table 5 on Halal Logistics Transportation, based on university data, indicates that Universiti Sains Malaysia, Universiti Kuala Lumpur, and Universiti Malaysia Terengganu each published 3 papers (17%), highlighting the substantial contributions of these institutions to halal research. Simultaneously, Universiti Kebangsaan Malaysia, Universiti Teknologi Malaysia, and Universiti Putra Malaysia each own two publications (11%), demonstrating their engagement in this domain, but with lesser contributions. Furthermore, entities such as the Malaysian Institute of Economic Research, the National Space Agency, and Universiti Teknologi MARA each produced one paper (6%), suggesting that research on halal logistics extends beyond universities to encompass diverse institutions. Overall, this data illustrates the extensive collaboration among various educational and research institutions in Malaysia in developing knowledge and practices related to halal logistics.

Table 5 Publications by university

Affiliation	Total Publications	Percentage
Universiti Sains Malaysia	3	17%
University of Kuala Lumpur	3	17%
Universiti Malaysia Terengganu	3	17%
National University of Malaysia	2	11%
Universiti Teknologi Malaysia	2	11%
Universiti Putra Malaysia	2	11%
Malaysian Institute of Economic Research	1	6%

4.7 Tree map analysis in halal logistics transportation research

The analysis in the image below is a tree map, also commonly referred to by this name, which is a data visualization technique [22]. The NVivo application is a data visualization tool that helps in mapping and analyzing the relationships between concepts, themes, or categories in textual data. Using the NVivo application, key concepts can be identified and analyzed using a tree map, which facilitates classification of terms by frequency of appearance (Table 6), with more frequently occurring terms displayed in larger columns. In Figure 3, the five terms with the large columns are visible, indicating a high level of importance or interest based on their frequency of occurrence relative to the research theme. The five terms with the enormous columns are "halal," "logistics," "supply," "transportation," and "chain."

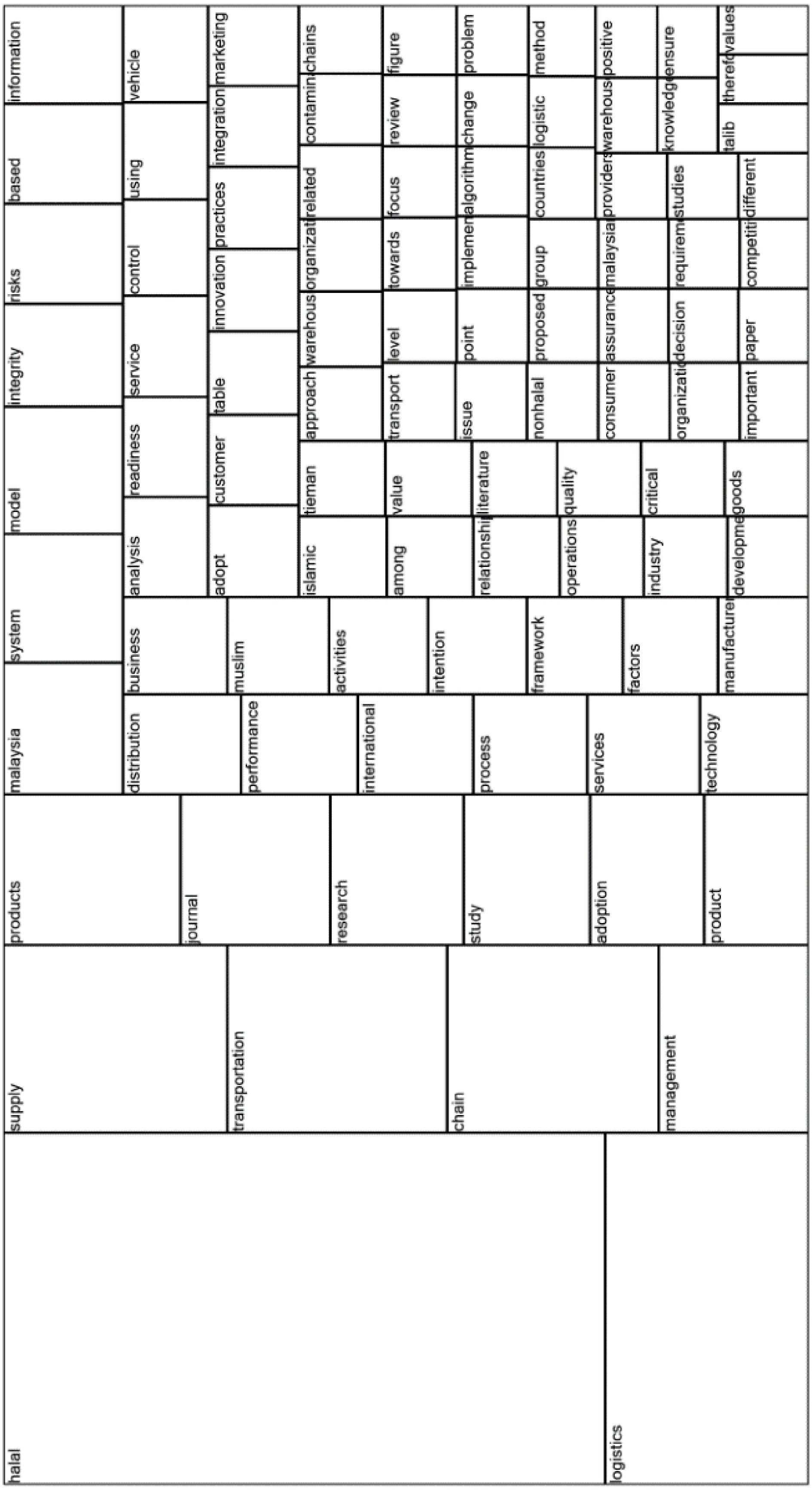

Figure 3 Tree map

Table 6 Classification of research themes on halal logistics transportation

Aspects of the Synthesis of research on halal logistics transportation	Key points	Source
Potential contamination during transportation	• Contamination • Significant risk • Halal logistics • Cross-contamination	[2,9,15,23,24]
Lack of Halal Transportation Alternatives	• Transportation alternatives • Halal products • Halal-certified transportation • Limited availability • Supply chain	[2,8,13,25]
Lead Time	• Distribution Time Management • Delivery Timeliness	[9,17,25]
Quality of Transportation Infrastructure	• Road quality • Risk of failure • Shipping requirements • Halal product quality • Infrastructure impact	[8,14,17,25,26,27]

4.8 Classification of research themes on halal logistics transportation

4.8.1 Risk of contamination during transportation

In order to adhere to the fundamental concept of halal transportation, it is necessary to maintain a physical distinction between halal and non-halal items throughout the transit process [24]. The risk of cross-contamination arises when halal products come into contact with non-halal items or substances that do not comply with halal guidelines during transit. Consequently, the distribution of halal items must be conducted independently to ensure and safeguard the product's halal integrity [15]. This separation must be carried out thoroughly throughout the logistics chain, from the shipping terminal through storage in the warehouse to the product reaching the customer's hands [9].

The maintenance of a product's halal status from the beginning of the production process through to the point of consumption is the feature of halal products that customers consider most significant. When it comes to the expansion of the halal food business worldwide, the role of the halal logistics system is an essential component in ensuring its success. Due to the possibility of cross-contamination throughout the packing process, it is vital to implement more stringent monitoring in order to examine essential items that may be contaminated with unlawful, filthy, or dangerous chemicals. Cleaning the container regularly is also required in order to eliminate any and all signs of past shipments with a status that was either non-halal or uncertain. This cleaning mechanism helps ensure the product's halal status is preserved (Ngah, Thurasamy et al., 2022).

Because of the nature of halal goods, whose halal status cannot be validated after consumption, halal food manufacturers are required to establish trust with their suppliers and rely on the integrity of their suppliers in order to provide raw materials that are in accordance with Sharia standards. It is thus necessary for the entire supply chain to comply with the standards and halal regulations established [23].

4.8.2 Lack of halal transportation alternatives

The availability of halal-certified transportation service providers remains limited, particularly in rural areas, creating a significant challenge for producers to ensure compliance with halal standards throughout the supply chain [25].

Additionally, the high costs of halal certification for vehicles and transportation facilities pose a significant barrier to logistics providers seeking in provide halal standards-compliant services [18]. As a result, only a small percentage of manufacturers use halal transportation services, even though these services are important to maintain the quality and halal status of products during delivery.

The adoption of halal transportation is also affected by the lack of awareness and support from halal goods manufacturers. For example, only 15% of manufacturers use halal transportation services due to service providers' limitations and a lack of understanding of the benefits (Ngah, Thurasamy et al., 2022). Therefore, collaboration is needed between governments, logistics providers, and industry players to increase the number of halal transportation alternatives available to support the growth of the global halal ecosystem

4.8.3 Lead time

Delivery time, or lead time, is an important aspect of halal logistics that affects operational efficiency and customer satisfaction. In the context of halal logistics, inappropriate delivery times can compromise the product's halal integrity, as delays increase the risk of contamination or damage during transportation [9].

In addition, the quality of roads and transportation infrastructure also contributes to the risk of delivery delays. Poor road conditions in certain areas can delay delivery times, thereby impacting the quality of halal products being transported [17]. To overcome these risks, a more effective route-planning process and information system are needed to ensure on-time delivery while adhering to halal principles. Therefore, optimizing logistics networks and leveraging GPS-based tracking technology are crucial solutions to improve delivery efficiency in halal logistics [25].

4.8.4 Quality of transportation infrastructure

The quality of transportation infrastructure is one of the important factors that affect the successful implementation of halal logistics. Poor infrastructure, particularly in rural areas, often poses a significant obstacle to ensuring the timely delivery of halal products and maintaining their quality during transportation [17]. Inadequate road conditions can increase the risk of failing to meet delivery requirements and compromise product quality, ultimately jeopardizing the halal integrity of the product [14].

The lack of adequate transportation infrastructure, including poor road conditions and limited logistics facilities, can hinder the efficient distribution of halal products. This condition leads an longer delivery times and an increased risk of contamination during transportation [26]. Additionally, the limitations of transportation infrastructure affect the availability of halal-certified transportation services. The limited number of halal-certified vehicles poses challenges for logistics providers in meeting demand for specialized halal products. This limitation often forces manufacturers to share vehicles with non-halal products, thereby increasing the risk of halal integrity violations [8]. Limited transportation infrastructure also hinders overall adoption of halal logistics, particularly in developing countries where supporting infrastructure, such as roads and logistics terminals, is inadequate [25]. To address this problem, some studies recommend developing technology-based transportation systems, such as GPS tracking and geofence algorithms [27].

4.9 Further discussion on contribution and future research suggestions

This study presents a systematic literature review of halal logistics transportation and identifies four main interrelated challenges in implementing halal transportation systems. This study offers an analytical synthesis of how the main challenges in halal transportation jointly affect logistics performance and supply chain flows [17,28,29]. The four central issues—contamination risk, limited halal transport alternatives, delivery time constraints, and inadequate transport infrastructure—are treated as mutually reinforcing bottlenecks that reduce the reliability, traceability, and efficiency of halal logistics networks [30,31]. The contribution of this article lies in structuring these problems into an integrated perspective on logistics risks and management implications, rather than only restating individual findings from prior studies on halal food logistics and halal supply chain risk [28,32]. The synthesis presented here indicates, for example, that the lack of halal-certified transport options not only creates compliance challenges but also amplifies lead-time variability and the probability of cross-contamination along transportation and storage nodes [17,29,33]. By indicating which elements are directly drawn from previous research and which reflect our interpretation of their combined effects on logistics flows, the discussion aims to provide additional scientific value to researchers and more actionable insights to managers and policymakers who design and manage halal transport systems [34-36].

The risk of contamination during transportation is a significant concern because the physical separation between halal and non-halal products remains difficult to implement consistently, especially during transportation and storage in warehouses. Additionally, the availability of halal-certified transportation service providers remains limited, with only 15% of manufacturers utilizing halal transportation services [2]. This condition is exacerbated by poor infrastructure quality and delivery time issues that can increase the risk of contamination and product damage during transportation [26]

The subsequent research can focus on several important aspects of halal logistics transportation development. First, the development of an integrated technology system combining GPS tracking and geofence algorithms to monitor halal status during transportation. Second, a study on an efficient model for halal transportation infrastructure development, particularly in rural areas, includes a feasibility analysis of constructing a specialized terminal for halal products. Third, research on harmonizing halal transportation standards and regulations across regions to facilitate the growth of the global halal ecosystem, as well as on the economic and operational impacts of implementing halal transportation systems at various industrial scales, is warranted.

This article positions halal transportation as a specific yet illustrative case within the broader field of logistics, particularly in relation to traceability, contamination risk management, transport quality control, and supply chain resilience. Beyond summarizing prior studies, the paper contributes to logistics theory by organizing the diverse findings into a coherent set of four interrelated logistics risk domains—contamination risk, scarcity of certified transport alternatives, lead time instability, and infrastructure limitations—and by explaining how these domains jointly affect the reliability and integrity of logistics flows in value chains that must comply with stringent product requirements. On the practical side, the article derives implications for logistics managers and policymakers by outlining how integrated monitoring technologies, cleaner and segregated transport configurations, and targeted infrastructure improvements can be used to manage these risks more proactively, not only in halal transportation but also in other logistics contexts where product integrity, chain-of-custody, and regulatory compliance are critical. In this way, the study's originality lies in translating fragmented evidence on halal transportation into a more universal logistics perspective relevant to designing traceable, contamination-aware, and resilient supply chains in both Muslim-majority and non-Muslim markets.

5 Conclusions

This article explores how halal transportation supports the integrity of logistics flows in halal supply chains by systematically reviewing international scientific literature indexed in the Scopus database. The study addresses the still-limited, fragmented research base on halal logistics transportation and responds by critically comparing the available evidence rather than merely summarizing it. Using a Systematic Literature Review (SLR) approach guided by the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) framework, 13 relevant articles were selected from an initial set of 28 publications. Publication trends indicate fluctuating growth from 2010 to 2024, with a peak of 5 publications in 2022, followed by a decrease to 3 publications in 2023. The thematic analysis revealed that Business, Management, and Accounting dominated with 40% of publications, Malaysia was the most significant contributor with 58.33% of publications, the Journal of Islamic Marketing was the primary source with 25% of publications, and the article "Principles in Halal Supply Chain Management" was the most cited with 190 citations. This study makes a significant contribution in identifying four main challenges in the implementation of halal transportation: the risk of contamination during transportation, limitations of halal transportation alternatives, delivery time issues, and the quality of transportation infrastructure. These findings underscore the complexity and interconnectivity of various factors that influence the successful implementation of halal transportation systems. For future development, investment in integrated technology, such as GPS tracking and geofence algorithms, is necessary for halal status monitoring, the development of adequate transportation infrastructure, especially in rural areas, and the harmonization of standards and regulations across regions. At the academic level, further research is needed on the economic and operational impacts of implementing halal transportation systems on various industrial scales, as well as studies on models for developing efficient halal transportation infrastructure.

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ESG perception and green logistics adoption: the mediating role of brand image and trust in emerging markets

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Keywords: sustainable supply chain, green logistics, ESG and sustainable consumer behavior, generation Z, green marketing.
Abstract: Despite the growing adoption of Environmental, Social, and Governance (ESG) criteria in corporate strategy, a significant gap exists in understanding how consumer perceptions of ESG translate into the adoption of tangible green logistics services. This study investigates how ESG factors influence consumer willingness to pay for green logistics such as sustainable transport, optimized material flow and eco-friendly packaging in an emerging market context. Grounded in the Theory of Planned Behavior, the model examines the mediating roles of green brand image, green trust, and green purchase intention in shaping sustainable logistics consumption. A structured online survey was administered to 350 young consumers belong to Generation Z, and data were analyzed using PLS-SEM. Structural model results reveal that green marketing and CSR significantly enhance green purchase intention, while greenwashing undermines trust. All hypothesized relationships were statistically significant. This research provides a novel, validated model linking perceived ESG performance to consumer willingness to pay for green logistics. It offers practical insights for supply chain managers on leveraging transparent ESG practices to build brand trust and drive adoption of sustainable logistics solutions.

1 Introduction

In the context of rapid global economic expansion, sustainability has become a pivotal issue in policymaking and corporate strategies, particularly in industries with considerable environmental consequences such as logistics and transportation, which manage the core material and information flows of the economy [1]. Initially intended to evaluate corporate governance, ESG initiatives have transformed to play a crucial role in shaping brand identity and influencing consumer purchasing decisions [1].

Despite this importance, a significant research gap persists. There is limited empirical comprehension of how ESG-aligned practices concretely impact consumers' willingness to adopt and pay for environmentally responsible logistics services such as sustainable transport, optimized supply chains, and green warehousing. While concepts like green marketing [2-5] and green trust [6] are recognized, the specific mechanisms linking ESG perception, brand image, trust, and the adoption of green logistics solutions remain under-examined, especially in emerging markets.

To address this gap, the present study aims to investigate the factors influencing Green Logistics Consumption Willingness, understood as the intention to support environmentally friendly logistics services through active participation and payment. The primary contribution of this work is an empirically validated framework connecting intangible ESG perceptions to tangible consumer willingness to pay for green logistics.

This issue is particularly salient among Gen Z, a powerful demographic characterized by its robust environmental values [2,3]. In Vietnam, specifically Ho Chi Minh City the nation's economic hub these concerns are amplified by challenges like pollution and traffic congestion, highlighting the need for private sector commitment in logistics and supply chain management. Utilizing the Theory of Planned Behavior, this study provides insights for firms managing sustainable supply chains by merging ESG alignment with behavioral intentions.

2 Literature review and hypothesis development

2.1 Green logistics and willingness for green logistic consumption

Green logistics represents an integrated strategic response to the growing environmental concerns within the logistics and supply chain sectors. It encompasses a wide range of environmentally responsible practices across transportation, packaging, warehousing, and product return systems. This concept aligns with the definition of green logistics consumption, which involves a comprehensive set of practices that aim to reduce emissions, optimize energy usage, and promote circularity in packaging and materials across supply chain operations. Research [7-11] emphasize that the objective of green logistics is not only to protect the environment but also to enhance social equity and economic efficiency throughout logistics networks. As logistics operations increasingly embrace sustainable development principles, the adoption of innovations such as electric vehicles, energy-efficient routing, and resource recycling contributes to reduced material waste, carbon emissions, and overall environmental impact. According to research [1], these initiatives also play a critical role in supporting circular economic models and in fostering responsible resource management within supply chains.

The concept of willingness for green logistics consumption refers to the extent to which consumers are ready to accept higher costs in exchange for environmentally sustainable delivery or supply chain solutions. This willingness reflects a growing preference for services that are consistent with environmental and ethical values. A global survey by PwC in 2024 revealed that consumers, on average, are willing to pay an additional 9.7 percent for green products and services, underscoring the tangible economic potential of green consumerism. This trend illustrates how ethical and environmental priorities are becoming more prominent in shaping modern consumption choices, particularly among younger generations.

Several psychological and perceptual factors contribute to this willingness. Study of Kwak et al. (2020) found that perceived environmental benefits and the perceived value of sustainability are among the most influential drivers behind the willingness to pay for green logistics. In addition, consumer trust in service providers plays a pivotal role [12]. When brands communicate clear and credible commitments to environmental, social, and governance principles, this fosters green trust and strengthens purchase intention. On the other hand, deceptive greenwashing practices that misrepresent environmental efforts can significantly erode trust and reduce the likelihood of consumer engagement [13]. Recent reports from PMC indicate that Vietnam's Gen Z exhibits stronger eco-conscious preferences than previous generations. However, most documented behaviors remain focused on sectors such as fashion and personal care, with limited exploration of logistics services.

This identifies a critical research gap. Existing studies tend to focus on Western or Latin American contexts, with minimal evidence from emerging Asian cities. Furthermore, few studies have comprehensively examined how ESG signals, such as genuine green marketing, corporate social responsibility, and greenwashing, interact within a behavioral framework like the Theory of Planned Behavior to influence sustainable logistics choices among Gen Z consumers. While these studies establish a link between values and willingness to pay, they often fail to deconstruct how specific corporate ESG signals (marketing, CSR, greenwashing) interact to form the trust and brand image necessary to motivate adoption of complex services like green logistics. This study synthesizes these disconnected streams to address this gap.

2.2 Environmental, social and governance

ESG represents a set of three core criteria widely applied to assess the sustainability performance of businesses. The three components, namely environmental responsibility, social engagement, and governance practices have emerged as crucial metrics for evaluating long-term corporate value. The concept of ESG was first presented in the 2003 report entitled Who Cares Wins, which received support from the United Nations. This report underscored the importance of embedding sustainability into business strategies to foster responsible growth. Emerging from the broader context of corporate social responsibility, ESG has evolved into a widely accepted framework that signals a shift from prioritizing short-term profits toward a comprehensive consideration of societal and environmental impacts [14]. In the current business landscape, ESG factors are not only regarded as compliance obligations but also as strategic levers for enhancing corporate reputation and attracting long-term investment. Studies in the United States reveal a clear generational pattern in consumer behavior, with younger cohorts, particularly Gen Z, demonstrating a readiness to support sustainable brands. Approximately 66 percent of this group are willing to pay a premium for environmentally certified products, while 75 percent believe that companies should actively contribute to social welfare rather than focusing solely on profit generation.

Each component within the ESG framework plays a distinct role in advancing corporate sustainability. The environmental dimension concerns how organizations manage their interactions with the natural environment, including reducing greenhouse gas emissions, minimizing waste, conserving energy, protecting biodiversity, and implementing broader ecological protection measures. These practices have become increasingly influential in shaping consumer attitudes, particularly among Gen Z, who display a strong preference for environmentally responsible brands [2]. The social dimension addresses how companies manage relationships with stakeholders such as employees, customers, partners, and communities, covering aspects like fair labor conditions, employee well-being, data privacy, product safety, and community investment [9]. Firms that uphold transparency, diversity, fairness, and ethical conduct tend to be evaluated more favorably by Gen Z, who are also quick to disengage from brands that violate labor ethics or human rights. The governance dimension focuses on internal management structures, adherence to legal standards, transparency in reporting, protection of intellectual property, and effective risk management. Generation Z consumers not only expect sustainable products but also demand verifiable proof of corporate commitment, often rejecting companies involved in scandals such as corruption or tax evasion.

While prior studies have extensively discussed the positive relationship between ESG performance and consumer support, particularly in green product contexts, there remains a gap in understanding how each ESG dimension individually and interactively shapes Gen Z's willingness to pay for green logistics services. Existing literature tends to treat ESG as a unified construct, overlooking potential variations in how environmental, social, and governance factors influence consumer perceptions and purchase intentions. However, much of the literature treats ESG as a unified construct, or focuses on its impact on green products, not on green services like logistics. This gap provides the foundation for the next section, which develops specific hypotheses to test the differentiated impacts of ESG components on Gen Z's behavioral responses in the context of green logistics.

2.3 Hypothesis development

Green marketing behavior refers to environmentally responsible business practices aimed at reducing environmental harm while creating long-term value for both companies and consumers. From a theoretical perspective, green marketing includes actions such as minimizing non-renewable resource usage, reducing pollution, and promoting sustainable product lifecycles [15]. When companies implement genuine green marketing strategies and establish environmentally friendly brand images, they can increase consumer loyalty and purchasing intention [16,17]. On the other hand, superficial or insincere green marketing efforts may cause skepticism among consumers, thereby reducing their intention to purchase green products. Similar trends have been observed in Vietnam, where eco-labeling and transparent supply chain communication have been shown to strengthen purchase intention in green markets [18]. Therefore, it is proposed that effective green marketing behavior enhances consumers' willingness to adopt environmentally friendly consumption.

H1. Green marketing behavior positively influences green product consumption intention.

In response to growing environmental awareness and global sustainability trends, firms have increasingly turned to CSR initiatives to build brand equity. Green brand image, reflecting a brand's environmental responsibility, has become an intangible asset that fosters consumer trust and differentiation in the marketplace. Prior studies have demonstrated that CSR enhances the public perception of a company and strengthens its association with sustainable values [19,20]. This relationship is mirrored in Vietnam, where CSR-linked environmental programs in sectors such as food and beverage have been shown to improve brand recognition and consumer [21]. When consumers perceive that a company genuinely engages in socially responsible behavior, including environmental stewardship, they are more likely to view its brand as credible and eco-conscious. This alignment leads to a stronger green brand image and a deeper emotional connection between the consumer and the brand.

H2. Corporate social responsibility (CSR) positively influences green brand image.

Greenwashing refers to deceptive practices where companies exaggerate or fabricate their environmental efforts to appeal to eco-conscious consumers. These actions can damage both corporate reputation and consumer trust [22] In today's saturated green market, ambiguous or unverified environmental claims create confusion and skepticism among consumers. As shown in studies by [21] greenwashing increases perceived risk and reduces consumer confidence in environmental commitments. The more consumers recognize greenwashing tactics, the less they trust green messages and products, ultimately diminishing their green trust. Therefore, reducing greenwashing is essential for maintaining authentic relationships with consumers who value sustainability.

H3. Greenwashing negatively influences green trust.

Consumers' perception of a brand as environmentally responsible has a significant impact on their trust in the brand. A positive green brand image not only reduces perceived risks but also enhances consumer confidence and likelihood of purchase [23,24]. According to branding theories, when a brand consistently aligns with environmental values that consumers care about, it builds a trustworthy image. This trust becomes especially important in green markets, where consumers rely on brand credibility to validate eco-friendly claims [25] A strong green brand image signals to consumers that the company is committed to sustainability, which fosters deeper green trust.

H4. Green brand image positively influences green trust.

Green trust, defined as the belief in a brand's environmental commitments, plays a crucial role in shaping consumer intentions and behavior toward sustainable products. Studies have shown that consumers who trust eco-labels or green claims are more likely to engage in organic or green consumption [26,27]. When consumers trust a brand's environmental efforts, they perceive lower risk and complexity in purchasing green products, which facilitates behavioral engagement [28,29]. Trust enables consumers to accept uncertainty and believe that the product will meet their expectations, increasing the likelihood of trial and long-term use. Hence, stronger green trust translates into higher intention to consume green products.

H5. Green trust positively influences green product consumption intention.

Drawing upon the Theory of Planned Behavior, which frames behavior as shaped by attitudes, subjective norms, and perceived behavioral control, several studies have emphasized the predictive power of intention in driving green behaviors. While intention does not always translate directly into action, it remains a critical antecedent to behavior, especially in environmentally conscious consumption. In the context of green logistics, intention can be reframed as the willingness to pay for sustainable logistics services, encompassing eco-friendly transport, optimized supply chains, and reduced emissions. Prior research [10,13,30] supports the notion that consumers with strong pro-environmental intentions are more likely to invest in green logistics solutions when they perceive environmental and personal benefits. Accordingly, this study hypothesizes that stronger green logistics intention is positively associated with higher willingness to pay, forming the basis for sustainable adoption and market expansion of such services.

H6. Green consumption intention positively influences green logistic consumption willingness.

The resulting framework captures both cognitive and affective evaluations mediating the ESG intention link and introduces an extended TPB path from green intention to logistics consumption presented in the figure 1. This model provides an integrative lens to understand how firms' sustainability related actions and missteps shape consumer behavior within the context of sustainable logistics. This is consistent with Vietnamese market reports showing that urban consumers with strong green intentions are increasingly willing to pay premiums for sustainable delivery options.

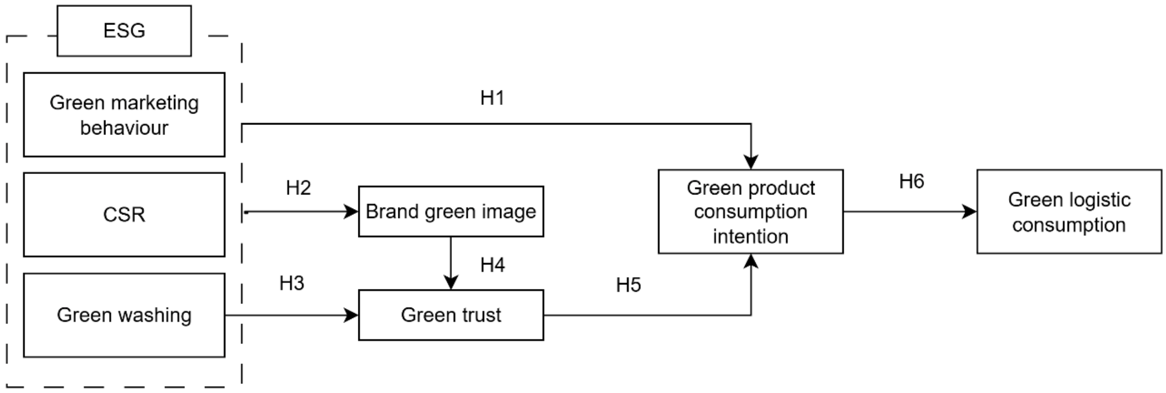

Figure 1 Research model

3 Methodology

3.1 Research design and model

To examine the factors influencing consumers' willingness for green logistics services consumption (GLC), this study develops a conceptual framework grounded in the Theory of Planned Behavior and integrates relevant constructs such as green marketing behavior, corporate social responsibility, greenwashing, green brand image, and green trust. The research adopts a quantitative approach, operationalized through a structured questionnaire survey targeting Gen Z consumers who have experienced e-commerce delivery services in urban Vietnam. This demographic was selected due to their increasing environmental consciousness and substantial influence on future consumption patterns. Drawing from validated scales in prior studies, the survey items were refined and contextualized to fit the logistics service domain. A pilot test was conducted with 30 participants to ensure content clarity and reliability prior to full deployment. The selection of PLS-SEM was based on this study's primary objective of prediction and the model's complexity, including multiple mediators. This approach is robust for complex predictive models and is not constrained by the strict data normality assumptions required by covariance-based SEM.

The measurement model includes seven latent variables: green marketing behavior, corporate social responsibility, greenwashing, green brand image, green trust, green consumption intention, and willingness to pay for green logistics services. Each construction is measured using multi-item Likert-type scales adapted from existing literature. Data was collected via an online survey platform, employing a purposive sampling strategy to reach respondents who are both familiar with sustainable products and have experience with logistics services. A total of 350 valid responses were obtained and analyzed using structural equation modelling (SEM) to validate the proposed model and test the hypothesized relationships. The model aims to empirically explore how psychological and perceptual variables influence consumers' consumption willingness in the context of sustainable logistics, thereby offering insights into how green behavioral intentions translate into economic actions. In the second phase, a quantitative method was applied to test the proposed model using data from 350 Gen Z respondents in Ho Chi Minh City. A convenience sampling approach targeted university students with experience in green consumption. Surveys were distributed both online and offline. SPSS was used for descriptive statistics and bias checks, while Smart PLS 4 assessed reliability, validity, and structural relationships through PLS-SEM and bootstrapping. Key metrics included Cronbach's Alpha, CR, AVE, and R^2. Harman's single-factor test was employed to address common method bias. The findings empirically validated the influence of ESG factors, green image, and green trust on green product intention and green logistics consumption.

3.2 Data collection

This research utilized a two-phase data collection methodology to investigate the willingness of Generation Z in Vietnam to pay for green logistics services. The first qualitative phase revealed the ESG-related factors that affect the consumption of green products. A systematic questionnaire was subsequently created and disseminated utilizing a convenience sampling approach, selected for its ease of access and effectiveness [31]. The survey targeted both undergraduate and graduate students attending universities in Ho Chi Minh City, including the University of Finance – Marketing, the University of Economics Ho Chi Minh City, FPT University, RMIT, and others. This location was chosen because of its significant population of Gen Z consumers and their considerable engagement with sustainability initiatives.

Data were collected both online (via Google Forms) and offline, utilizing social media platforms such as Facebook and Zalo for broader reach. A total of 30 observed variables was assessed utilizing a 5-point Likert scale, grounded in validated constructs from existing ESG and green logistics literature. In accordance with [32], a minimum of 150 responses was necessary; however, the study sought to gather 350 responses to enhance statistical reliability. The questionnaire was reviewed by experts and pilot-tested for clarity and validity before official distribution with a data collection period spanned from March to April 2025.

Table 1 Sample characteristics

Category	Frequency	Percent	Valid Percent	Cumulative Percent
Gender				
Male	167	47.7	47.7	47.7
Female	183	52.3	52.3	100.0
Total	350	100.0	100.0	
Age group				
Under 18	82	23.4	23.4	23.4
18–22	144	41.1	41.1	64.6
23–28	124	35.4	35.4	100.0
Total	350	100.0	100.0	
Education Level				
High School Diploma (12/12)	64	18.3	18.3	18.3
College/University Degree	282	80.6	80.6	98.9
Postgraduate	4	1.1	1.1	100.0
Total	350	100.0	100.0	

4 Result and discussion

4.1 Outer model and scale validation

Figure 2 presents the outer loadings of the observed variables, confirming their reliability and contribution to the respective constructions. All items exceeded the recommended threshold (>0.7), indicating strong indicator reliability. CSR-related items ranged from 0.833 to 0.886, with CSR3 and CSR4 showing the highest contributions. Green brand image (GBI) indicators ranged from 0.828 to 0.887, with GBI1 as the strongest. Green consumption intention (GI) items showed high loadings from 0.823 to 0.911, particularly GI4. Green marketing behavior (GMB) loadings ranged from 0.833 to 0.878, with GMB4 leading. Green trust (GT) items also demonstrated strong values (0.841–0.899), while greenwashing (GW) variables were the most robust (0.882–0.938), with GW4 being the highest. These results confirm the strong convergent validity and internal consistency of all constructs in the research model.

From out loading model in Figure 2, the evaluation of the quality of observed variables in the research model through the outer loadings of each construct. These values indicate the degree of contribution of each observed variable to its corresponding latent construct. The results show that all outer loadings exceed the recommended threshold of 0.70, confirming that the measurement items demonstrate strong reliability and are suitable for further analysis.

For the CSR construct, outer loadings range from 0.833 to 0.886, reflecting a high level of contribution from the measurement items. CSR3 (0.886) and CSR4 (0.877) record the highest values, indicating that these items play the most critical role in measuring CSR within the context of this study. Regarding Green Brand Image, outer loadings fall between 0.828 and 0.887, with GBI1 achieving the highest loading (0.887), suggesting its substantial influence on shaping consumers' perception of a green brand.

For the Green Consumption Intention, the outer loadings vary from 0.823 to 0.911, with GI4 reaching the highest value (0.911). This implies that this item strongly captures the essence of consumers' willingness to adopt green logistics services. In the case of Green Marketing Behavior, the outer loadings are between 0.833 and 0.878, with GMB4 recording the highest score (0.878), indicating its strong impact on consumers' perception of green marketing initiatives.

The Green Trust construct also demonstrates robust item contributions, with outer loadings ranging from 0.841 to 0.899, reflecting the significant role of these variables in shaping trust toward green products and services. Finally, Greenwashing shows the highest overall loadings among all constructs, ranging from 0.882 to 0.938. Notably, GW4 reaches 0.938, indicating that it is a particularly influential indicator in assessing consumer perceptions of greenwashing practices.

Overall, the consistently high outer loading values across all constructs confirm that the measurement model has strong indicator reliability, ensuring the conceptual soundness and empirical robustness of the study. This provides a solid foundation for subsequent analyses, including the assessment of internal consistency, convergent validity, and discriminant validity in the following sections.

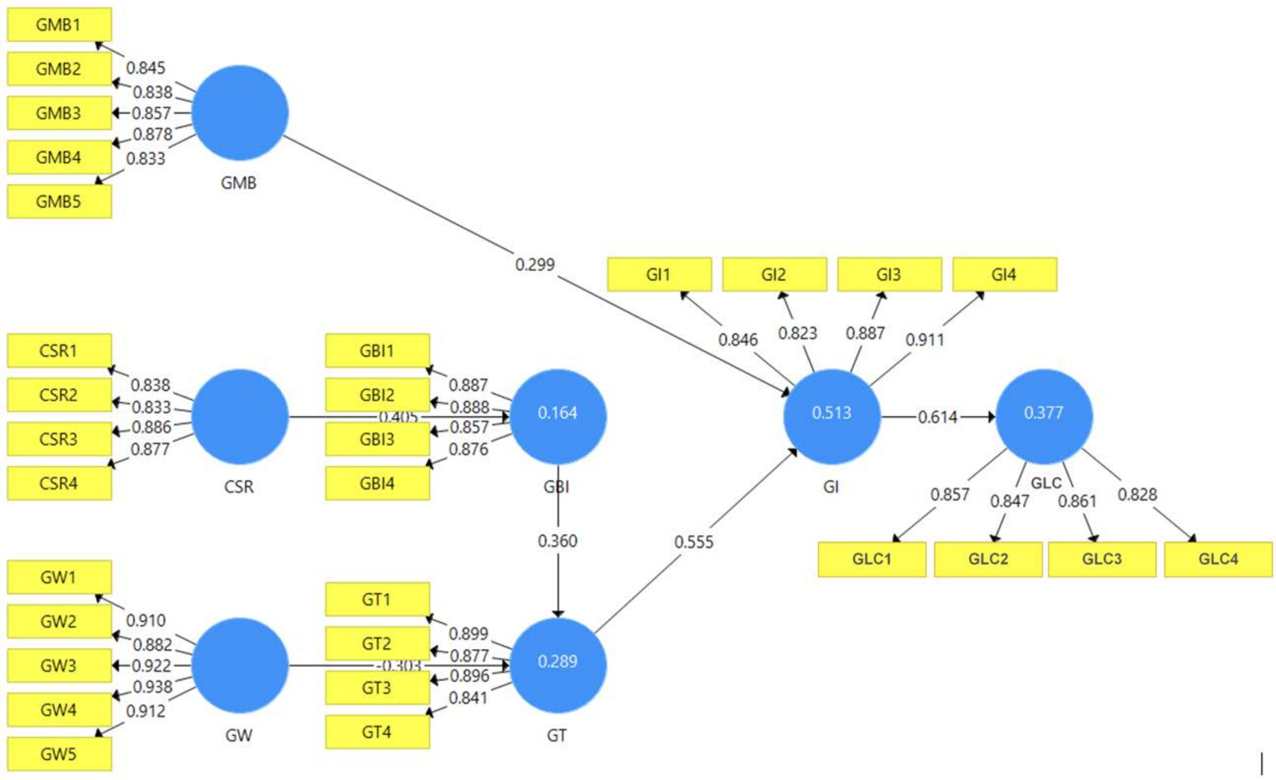

Figure 2 Research quantitative model

Besides, Table 2 demonstrates the internal consistency and convergent validity of all constructs using Cronbach's Alpha, Composite Reliability (CR), and Average Variance Extracted (AVE). All values exceed the recommended thresholds (Alpha > 0.70, CR > 0.70, AVE > 0.50), indicating that the measurement model has strong reliability and convergent validity. Among them, greenwashing shows the highest reliability (Alpha = 0.950, CR = 0.962, AVE = 0.833), while other constructs such as green trust, green marketing behavior, and green brand image also report high scores, confirming the robustness of the measurement items.

Table 2 Reliability analysis and convergent validity

	Cronbach's Alpha	**rho_A**	**Composite Reliability**	**Average Variance Extracted (AVE)**
CSR	0.882	0.888	0.918	0.738
GLC	0.870	0.872	0.911	0.720
GBI	0.901	0.908	0.930	0.770
GI	0.890	0.891	0.924	0.752
GMB	0.904	0.906	0.929	0.723
GT	0.901	0.902	0.931	0.771
GW	0.950	0.956	0.962	0.833

Moreover, table 3 presents the discriminant validity using the Fornell-Larcker criterion. The square roots of AVE (diagonal values) are higher than the correlations among constructs (off-diagonal), confirming that each construct is distinct from the others. For instance, the square root of AVE for GI is 0.867, which is higher than its correlations with other constructs, such as GT (0.659) and GMB (0.492). This supports the discriminant validity of the model, showing that each latent variable captures unique aspects of the green logistics and consumer behavior framework.

Table 3 Discriminant validity (Fornell-Larcker Criterion)

	CSR	GLC	GBI	GI	GMB	GT	GW
CSR	0.859						
GLC	0.344	0.848					
GBCI	0.405	0.414	0.877				
GI	0.557	0.614	0.693	0.867			
GMB	0.297	0.243	0.401	0.492	0.850		
GT	0.447	0.368	0.454	0.659	0.348	0.878	
GW	-0.367	-0.328	-0.312	-0.538	-0.349	-0.415	0.913

The study then assessed discriminant validity through the Heterotrait-Monotrait ratio of correlations (HTMT) as in Table 4, which present a robust criterion for evaluating the extent to which constructs in the model are distinct from one another. The results indicate that the HTMT values for all construct pairs range from 0.273 to 0.771, which are well below the 0.85 cut-off. This finding provides evidence of clear discriminant validity among the constructs in the research model. Besides, the HTMT value between CSR and GLC is 0.392, suggesting a satisfactory degree of distinction between these two constructs. Similarly, the highest HTMT value observed is between GI and GBI at 0.771. While this value is relatively high compared to other construct pairs, it remains below the critical threshold, indicating that these constructs are related yet still conceptually and empirically distinct.

Table 4 Discriminant validity (Heterotrait-Monotrait Ratio)

	CSR	GLC	GBI	GI	GMB	GT	GW
CSR							
GLC	0.392						
GBCI	0.447	0.463					
GI	0.626	0.698	0.771				
GMB	0.331	0.273	0.444	0.547			
GT	0.499	0.414	0.501	0.735	0.386		
GW	0.396	0.357	0.329	0.580	0.373	0.445	

4.2 Inner structural model evaluation

According to figure 3, the direct relationships among variables in the research model, including values for Original Sample (O), Sample Mean (M), Standard Deviation (STDEV), T Statistics, and P Values. All T Statistics exceed the 1.96 threshold, and all P Values are below 0.05, confirming the statistical significance of the relationships. Notably, GT strongly influences green intention GI with the highest T Statistic of 11.427. CSR has a moderate yet significant effect on green brand-consumer identification GBI (O = 0.405, T = 8.391), while GBI positively impacts GT (O = 0.360, T = 6.575). Green intention significantly affects willingness for GLC (O = 0.614, T = 10.388), and green marketing behavior GMB has a smaller yet meaningful influence on GI (O = 0.299, T = 6.648). Additionally, GW shows a negative impact on GT (O = -0.303, T = 6.438), indicating that greenwashing undermines consumer trust. Overall, all paths are statistically robust and practically meaningful, reinforcing the validity and reliability of the research model.

The research findings confirm that the measurement model demonstrates strong reliability, convergent validity, and discriminant validity across all constructions, ensuring the robustness of the research framework. These results provide a solid foundation for interpreting the structural relationships among variables in the next stage. With validated measures, the study is well-positioned to explore theoretical contributions, particularly in advancing understanding of how ESG-related factors influence consumer behavior and decision-making in the context of green logistics.

Building on this measurement confirmation, the structural model results provide insights into the relationships among constructs (Table 5). All direct effects are significant, with GT having the strongest influence on GI (O = 0.555, T = 11.427). CSR positively affects GBI (O = 0.405, T = 8.391), which in turn strengthens GT (O = 0.360, T = 6.575). GI strongly drives GLC (O = 0.614, T = 10.388), while GMB also supports GI (O = 0.299, T = 6.648). In contrast, GW exerts a significant negative impact on GT (O = –0.303, T = 6.438). Indirect effects reinforce these dynamics. GT influences GLC through GI (O = 0.341, T = 7.529), GMB affects GLC via GI (O = 0.184, T = 5.508), and multi-step mediation paths such as CSR → GBI → GT → GI → GLC (O = 0.050, T = 3.534) highlight the layered nature of the relationships. Conversely, GW reduces GLC indirectly through its negative effects on GT and GI, as seen in GW → GT → GI → GLC (O = –0.103, T = 4.497). Together, these findings confirm that enhancing GT, GI, and GBI strengthens GLC, while GW emerges as a critical barrier to be mitigated.

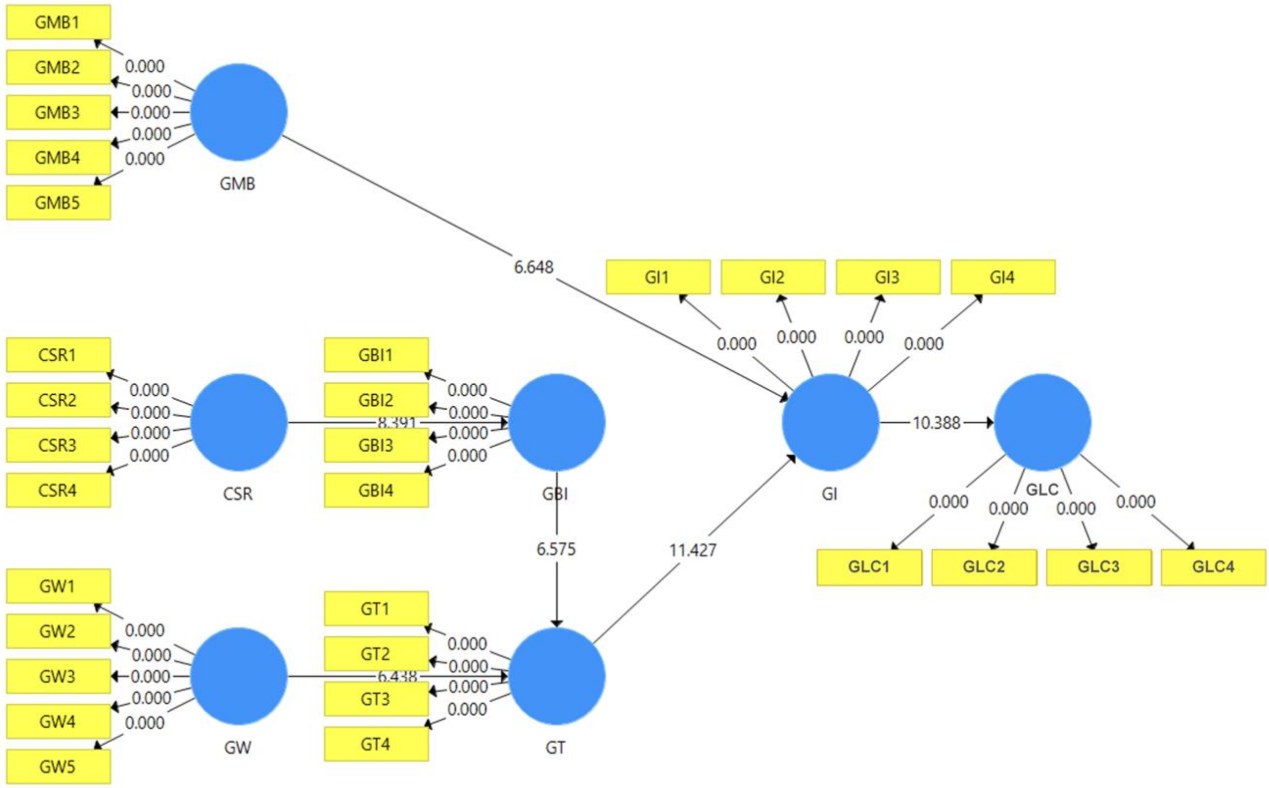

Figure 3 A framework of the inner model result

With measurement validity established, the structural model provides deeper insight into the dynamics among constructs. GT emerges as the most powerful driver of GI, reinforcing the idea that trust in green products is a critical precondition for purchasing intentions. CSR contributes meaningfully to GBI, which in turn enhances GT, indicating a sequential pathway from corporate responsibility to brand perception to trust. GI is the strongest direct driver of GLC, showing that intentions translate effectively into willingness to engage with green logistics services. GMB also supports GI, suggesting that marketing actions can stimulate intention, while GW acts in the opposite direction, eroding trust and, indirectly, the willingness to adopt green logistics.

Table 5 Confirmation of direct and indirect relationship between factors

	Original Sample (O)	Sample Mean (M)	Standard Deviation (STDEV)	T Statistics (|O/STDEV|)	P Values
Direct relationship					
CSR -> GBI	0.405	0.409	0.048	8.391	0.000
GBI -> GT	0.360	0.359	0.055	6.575	0.000
GI -> GLC	0.614	0.615	0.059	10.388	0.000
GMB -> GI	0.299	0.301	0.045	6.648	0.000
GT -> GI	0.555	0.555	0.049	11.427	0.000
GW -> GT	-0.303	-0.305	0.047	6.438	0.000
Indirect relationship					
GMB -> GI -> GLC	0.184	0.186	0.033	5.508	0.000
GBI -> GT -> GI -> GLC	0.123	0.123	0.028	4.433	0.000
CSR -> GBI -> GT -> GI -> GLC	0.050	0.051	0.014	3.534	0.000
GT -> GI -> GLC	0.341	0.342	0.045	7.529	0.000
GW -> GT -> GI -> GLC	-0.103	-0.104	0.023	4.497	0.000
GBI -> GT -> GI	0.200	0.201	0.041	4.839	0.000
CSR -> GBI -> GT -> GI	0.081	0.082	0.021	3.809	0.000
GW -> GT -> GI	-0.168	-0.169	0.032	5.319	0.000
CSR -> GBI -> GT	0.146	0.148	0.032	4.563	0.000

The mediation analysis further clarifies these interactions, revealing how constructs influence each other through layered pathways. Notably, positive mediations strengthen the impact of CSR and GMB, whereas GW transmits a negative influence through trust and intention.

4.3 Implications

4.3.1 Theoretical implications

By empirically validating the relationships among CSR, green marketing behavior, green brand image, trust, study advances theoretical understanding of sustainable consumption by empirically examining the interplay among CSR, green marketing behavior, green brand image, trust, greenwashing, and willingness to pay in a unified framework. While prior studies have tended to investigate these constructs in isolation [6,33], the findings reveal their combined effects in shaping Gen Z's willingness to pay for green logistics services. CSR and green marketing behavior strengthen brand image and trust, whereas greenwashing diminishes them, extending the TPB by demonstrating that perceptions of corporate ESG conduct influence not only intention but also price-related behavioral outcomes.

The results further confirm and extend the mediating roles of green brand image and trust identified in earlier literature, showing their relevance in service-based sustainability contexts. In line with signaling theory and brand credibility frameworks, authentic ESG initiatives enhance trust through credible brand signaling, with trust emerging as the most influential driver of willingness to pay. This reinforces prior sustainability marketing findings while adding new evidence on trust as a critical mechanism linking ESG strategies to consumer behavior among digitally native, socially conscious cohorts. This finding extends the work of Kwak et al. (2020), by demonstrating that trust is not just a general antecedent, but the critical mechanism mediating the path from ESG perception to willingness to pay specifically for logistics services.

A generational perspective strengthens the contribution of this work. Gen Z's heightened ESG sensitivity and skepticism toward greenwashing indicate that conventional persuasion models may require adaptation to account for active ethical evaluation and values-driven decision-making.

Finally, the study contributes to the limited body of ESG research in emerging economies by contextualizing findings in Vietnam, where environmental awareness intersects with economic development. The positive relationship between green consumption intention and willingness to pay supports the extension of TPB to contexts involving service trade-offs and premium pricing, while highlighting the need for ESG theories to incorporate localized socio-cultural and regulatory conditions.

4.3.2 Managerial implications

Building on these theoretical insights, the findings offer several actionable directions for practitioners in the green logistics sector. First, the positive effects of CSR and green marketing suggest firms should invest in transparent, verifiable ESG initiatives. For logistics firms, this means moving beyond annual reports to create transparent dashboards showing real-time data on carbon emissions per delivery, the percentage of sustainable packaging materials used, and ethical labor practices in their warehouses and transport flow. Given Gen Z's high sensitivity to authenticity, communication must emphasize concrete actions to avoid perceptions of greenwashing.

Second, as green brand image and trust are pivotal in translating ESG efforts into willingness to pay, managers should prioritize brand-building strategies that integrate sustainability into core value propositions rather than treating it as an add-on. This includes leveraging credible third-party certifications, transparent supply chain disclosures, and ongoing consumer engagement to reinforce brand credibility.

Third, the generational differences identified indicate that marketing strategies should be tailored to the digital-native preferences of Gen Z, employing interactive platforms, social media storytelling, and participatory campaigns that invite consumer co-creation of sustainability narratives. Such approaches can strengthen emotional bonds and foster long-term loyalty.

Finally, in emerging markets such as Vietnam, where environmental awareness is growing alongside economic development, logistics firms should design green service offerings that balance sustainability with cost-effectiveness. Policies such as tiered pricing for green options, government-backed incentives, and partnerships with NGOs can help lower adoption barriers and broaden market appeal. Aligning these practices with local socio-cultural values will not only meet regulatory expectations but also enhance competitive advantage in a rapidly evolving sustainability landscape.

5 Conclusion

5.1 Findings

This study examined the factors influencing Gen Z's willingness to use green logistics services in Ho Chi Minh City by validating a conceptual model grounded in ESG dimensions and the Theory of Planned Behavior. By emphasizing key mediators such as green brand image and consumer trust, the study offers a clearer understanding of the underlying mechanisms through which ESG strategies shape actual consumer readiness. This comprehensive framework provides a strategic basis for logistics firms to synchronize their sustainability efforts with changing market demands and the value preferences of environmentally aware consumers in fast-urbanizing economies.

In contrast, greenwashing behavior undermines consumer trust and weakens the effectiveness of green communication strategies. The study contributes to the logistics literature by connecting ESG constructs with behavioral intention models, providing a more cohesive view of the factors that drive consumer engagement with sustainable logistics services. By identifying green brand image and trust as critical mediators, the research clarifies how ESG initiatives affect Gen Z's readiness to embrace green logistics.

While the empirical focus is Vietnam, the findings have broader implications for other emerging markets, especially in Central and Eastern Europe, where digital-native consumers are increasingly sustainability-conscious and expect authentic corporate ESG practices. The insights derived from this context may inform policymakers and logistics providers in comparable economies facing similar urbanization pressures and demographic shifts.

Practically, the findings suggest that logistics providers should focus on transparency, social responsibility, and active engagement with ESG principles to build customer trust and promote sustainable brand equity. It is essential to raise awareness and foster behavioral readiness among Gen Z consumers to support the green transition in urban logistics systems. As cities like Ho Chi Minh City and counterparts in the CE/SEE region pursue sustainable development objectives, encouraging young consumers to endorse green logistics emerges as a strategic necessity –for both environmental outcomes and competitive positioning.

5.1 Limitations and future work

Several constraints of this study should be acknowledged to guide future investigations. The study primarily relied on the theory of planned behavior and existing conceptual frameworks to examine the willingness of Generation Z in Ho Chi Minh City to adopt green logistics services. This focus may have neglected other contextual elements such as cultural norms, political factors, emotional conditions, or social influences that could affect consumer behavior.

Subsequent studies should integrate these elements. A concrete future study, for example, could test the moderating effect of perceived logistics infrastructure quality on the relationship between green intention and willingness to pay. Furthermore, the reliance on convenience sampling and a relatively limited sample size of 350 participants, restricted to those who are accessible digitally, may limit the generalizability of the results. Subsequent studies should employ probability-based sampling techniques and target more diverse demographic groups to enhance representativeness and practical relevance.

Additionally, the geographic focus of the study was limited to Ho Chi Minh City and was conducted over a brief period, which may not adequately reflect regional or temporal differences in the adoption of green logistics. Future research should move beyond intention-based surveys. A concrete next step would be a longitudinal study or a field experiment A/B testing different green delivery options on an e-commerce platform to measure actual adoption behavior, not just willingness.

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Sustainability of warehouse process by SWP model with orientation on cost reduction and growth performance

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Keywords: costs, improvement, performance, quality, warehouse process.
Abstract: Warehouse management is based on improving productivity while reducing costs, improving quality, lead times, workforce availability, health, safety, and environmental effects. The warehousing costs create key factors for the efficiency of the warehouse process, too, in the food industry. The main goal of the research was to optimize costs in the warehouse process of the food company and improve the efficiency of the warehouse process. We stated the hypotheses oriented towards improving the quality of the warehouse process, which can decrease warehousing costs and increase the warehouse process's efficiency. The results of the research confirmed the hypothesis. Hypothesis H1: Improving the quality of the warehouse process decreases warehousing costs. This hypothesis was confirmed because warehousing costs decreased by 8341€ in the year 2025 and by 1070€ in the year 2024. H2: Improving the quality of the warehouse process influences the efficiency of the process. Ineffective processes - meat, fruit, vegetables, pallet warehouses became effective processes. The corrective measures brought benefits such as financial sources, efficiency, the layout of the warehouse, the JIT system, and cost reduction to the warehouse process in the food company. The suggestion of corrective measures can be used as a SWP model for smart warehouse processes in food companies.

1 Introduction

The sustainability of the supply logistics process is based on 5 pillars, such as costs, time, quality, price, and suppliers. Those pillars are key factors for growth performance and improvement of the supply process. In the frame of research, we deal with stocks in the selected firm. The storage stocks create company assets and represent liquid resources that can be converted quickly to financial resources. Liquidity is one pillar of business sustainability. The cash form represents the liquidity of the company and the source for buying new storage stocks. This is the reason for warehouse process management. It is necessary to monitor and optimize the stocks. Monitoring of stocks relates to the digitization and visualization of the logistics chain. Digitalization of the logistics chain plays an important role in monitoring the value of the stocks in warehouses, and visualization is the framework of the Industry 4.0 approach for mapping the state of stocks in the warehouse in amounts. The main goal of the research was to optimize stocks of the reason to bind financial resources and cost optimization in the warehouse process of the food company. We stated two hypotheses: Hypothesis H1: Improving the quality of the warehouse process decreases warehousing costs. Hypothesis H2: Improving the quality of the warehouse process influences the efficiency of the process. Based on the determination of corrective measures, we plan to change the supply process in the food company and reduce storage costs. The main instrument for improving warehouse processes is automation, including the use of robots and modern technologies such as conveyor belts for material handling. That approach is creating conditions for improvement and optimization.

2 Literature review

Warehouse management is based on improving productivity in all logistic processes connected with supply. Baruffaldi, G. et al. (2020) state that reducing costs, improving quality, lead times from customers, workforce availability, health and safety, and effects on the environment are priority factors for effective logistic processes and the basis for logistic sustainability [1]. Logistics sustainability focuses on efficient flows from the supplier to the customer, and it depends on internal logistics, transport tim,e and costs [2]. Mensah el. al. (2021) said that the logistic sustainability is standing on the priority green logistics management practices are a significant driver of organizational performance, such as environmental sustainability, social sustainability, and business performance [3]. Nantee el. al.. (2021) said that logistics sustainability focuses on automated warehousing systems. on the economic, environmental, and social dimensions of sustainability performance of those systems [4]. Larson et. al. (2021) said that logistics sustainability is connected with logistics performance. Logistics performance is a driver of economic activity and success; it is also a contributor to environmental degradation in the form of harmful emissions [5]. Jayarathna et. al. (2023) said that logistics sustainability depends on transforming toward a circular economy is a viable strategy for achieving sustainable logistics systems [6]. Fernando et. al. (2023) said that logistics sustainability is connected with a circular economy-based reverse logistics that emphasises the effect of reverse logistics on sustainable resource commitment and financial performance [7]. Gupta et. al. (2022) said that logistics sustainability of the circular economy is oriented on service quality that influences the performance of supply chains [8]. Kádárová, J. et al. (2015) state that the supply and warehouse process is important to know. Reaction to the risks and investigating the conditions of crises of deficit of stocks is the basis for effective supply and warehouse management [9]. There are three basic flows (Figure 1) in the supply-customer chain, material, information, and financial, which ensures logistical sustainability [10]. Automation and digitization are the driving forces of the Industrial Revolution 4.0. which relates to the increased need for modern warehouses. To cope with huge product flows, modern innovations (such as IoT) should be used more extensively to manage these processes. The Internet of Things (IoT) is a technology designed to process large amounts of data with maximum efficiency in real time [11]. The base of each logistic process in the industry companies is the economic principle. Economic categories such as material costs, production costs, transport costs, warehousing costs, and operational costs are important for the supply and warehouse process and their optimization. In this area, an important place stands for cost controlling [12].

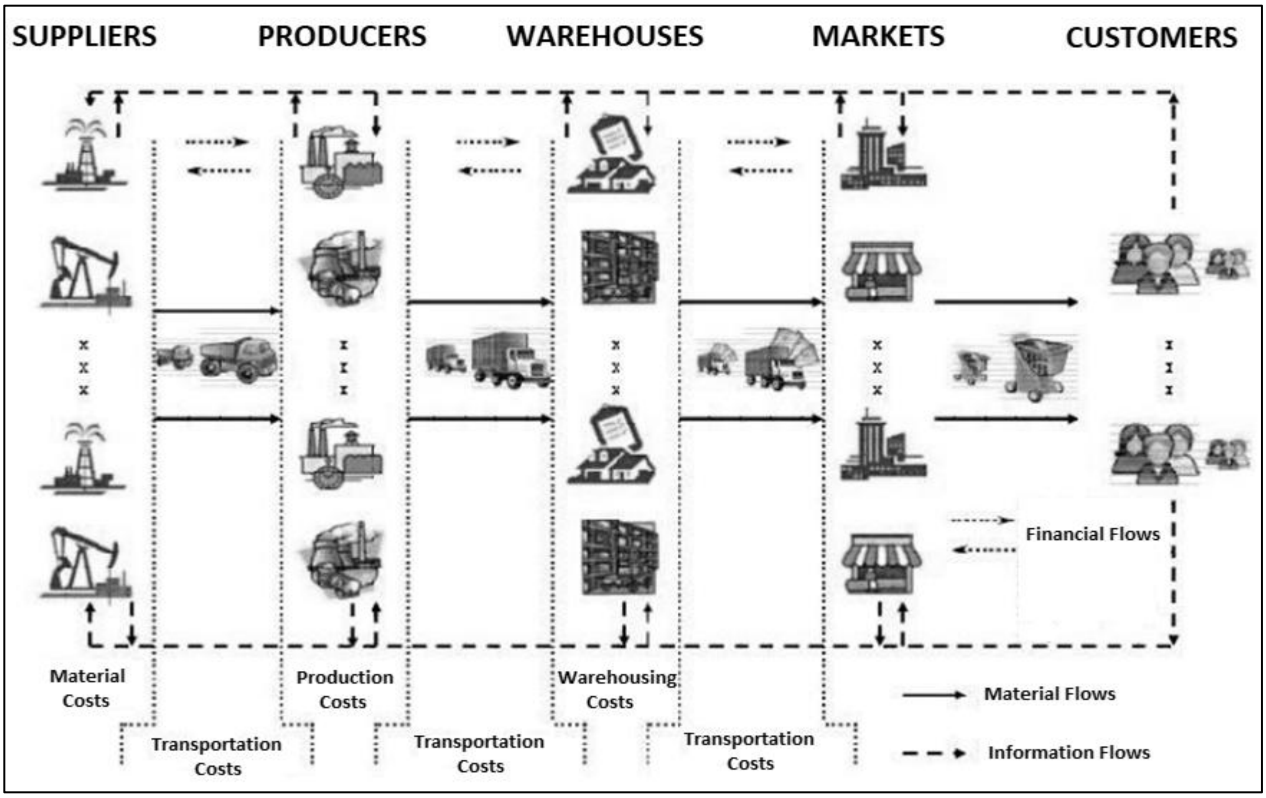

Figure 1 Basic logistic flows [4]

Potkány. M. et al. (2024) commented on the barriers to the implementation of business controlling in practice and the advantages of the collection of data and their processing [13]. Kádárová et al. (2015) commented on the BSC approach, which creates a customer and internal process perspective through the warehouse process. This approach is important for the performance strategy and progress of the supply process [9]. Kumar, S. et al. (2021) created a multi-warehouse inventory model that creates the base for the improvement of the warehouse process. The performance of stocks and other indicators for the performance of the warehouse process create the base for improvement and economic growth of the process by indicators such as efficiency [14]. The business sustainability presented by Mosteanu et al. (2020) means that all management tasks heavily depend on successful integration between the supply chain and logistics [15]. The theme of the future is the integration of sustainable supply chain management and logistics applications in the logistics chain. Van Geest et al. (2020) commented that smart warehousing aims to design the reference architecture. The intelligence model was presented using feature diagrams that show the common and variant features of smart warehouses [16].

Maheshwari, P. et al. (2023) presented that warehouses are a vital link in the supply chain and the pillars of Industry 4.0. The main pillars of Industry 4.0 are optimization, digitalization, automatization, and customization. It is the goal idea for create an instrument for the proactive and modern warehouse process [17]. A warehouse is a place where multiple activities are carried out, depending on the warehouse function. Saderova et al. (2021) present that the warehouse process holds an irreplaceable position in the supply chain. Their methodology for designing the warehouse system is based on five phases: Identification, Process design, System analysis, Synthesis of the logistical system, and Process evaluation. This methodology is a suitable tool for decision-making in the field of selection and design of the warehouse system for various areas [18]. Marasová, D. et al. (2018) overviewed warehouse optimization orientated to the technical structure of the warehouse, standard operational and organizational frame of warehousing, coordinating and controlling systems for warehouse operations, and typical operations in the warehouse [19]. Van Geest et al. (2021) commented that smart warehouses aim to increase the overall service quality, productivity, and efficiency of the warehouse while minimizing costs and failures. It was identified that the key subdomains where smart warehouse technology has been adopted are receiving the order, storing and shelve management, order picking, and order shipping [20]. Prasetyawan et al (2020) obtained that the spatial and temporal optimization for smart warehouses relates to fast turnover. With the development of commerce, the same day is provided delivery [21]. Millstein, M.A. et al. (2022) state that the market is implementing unmanned smart warehouses to improve logistics efficiency and cost reduction in the warehouse [22]. Pinto et al (2020) solved the problem with the warehouse locations for goods distribution. They found that the minimum distance is cost-efficient, and a short time is the optimal time [23].

Marziali, M. et al. (2021) presented the new storage assignment policy. They reduced transport time for order picking by benchmarking, toward the implementation of corrective and preventive solutions [24]. Živičnjak et al. (2022) said that warehouse management is becoming an increasingly important task and responsibility for employers whose goal is to maximize the profitability of the whole business which is orientated to economic indicators and performance key indicators [25]. Verma, A. et al. (2023) presented that the warehouse process can use target costing calculation for material stocks based on demand. This effective form decreases the costs of stocks [26]. Csikósová et.al. (2021) commented that financial performance is part of the evaluation of companies' results, and it contains indicators of the warehouse process. The important indicators are the number of stocks, the price of stocks, the time of delivery, quality of stocks [12]. Khan, M. G. et al. (2022) created the multi-warehouse model. This model was oriented on total cost, total investment, and total delivery time. This model enables retailers to obtain more profit by maintaining a multi-warehouse model with fewer inventory holding costs [27]. Kordos et al. (2020) said a large share of operating costs related to product storage relates to the preparation of the expedition. Based on many studies, it has been established that about 60% of warehouse operation costs are the costs of picking up goods when completing orders. They confirmed that minimizing the order picking times reduces the costs in storage [28].

Sert et. al. (2020) commented on the complexity of providing timely and cost-effective distribution of finished goods to customers makes effective operational coordination difficult. The effectiveness of the logistic processes is crucial for customer service and sustainable business [29]. For logistics planning are important the external factors. The most significant is the growing number of customers, varied geographical locations, the uncertainty of orders, and extreme competitive pressure to reduce inventory costs. Millstein et al. (2022) said a new form of distribution - Omni-channel distribution integrates stores and warehouses to fulfil online and store demand. Results document increasing benefits from optimizing the number, locations, and capacities of omnichannel warehouses as the demand increases. The results showed that the profit of different omnichannel designs is shown to depends strongly on the product category and the percentage of demand that is online [22]. Marasová et al. (2018) said that quality is becoming the key decision-making factor for customers when choosing from several products, services, etc. Competitive pressures on the market lead to increasing the quality of the transport services connected with the warehouse process [19]. Transport services possess specific features, as compared to tangible products (goods collection and delivery, claims, means of transport availability, transportation time, and service reliability). In the frame of optimization of the supply and warehouse process are important strategic innovations and use of the quantitative mathematic models of the operational research and managerial methods. Pinto, J. et al. (2020) commented that cost controlling is a road for cost optimization and smart warehouse processes [23]. The main part of managing organizations of all sizes and types because modern information technologies allow access to many data and give managers the possibility to quickly respond to changes in the business environment.

3 Methodology

The research was carried out in a food company in Slovakia in Europe, the purpose of which was to streamline the warehouse process, focused on cost optimization and stocks. The main goal was to create a new innovative model for logistic sustainability for various types of industry and services. The research was carried out from the year 2023 to the year 2025. At this time, the warehouse process was monitored. We suggested corrective measures for the warehouse process in the food company in the year 2023 that were realized in the supply process in the selected company in the following years, 2024, 2025. The suggested corrective measures were a change of warehouse layout, higher turnover of food stocks, a change of transport routes to the customer, a JIT system, reducing damaged stock (waste), stock transfer system. Monitoring of the warehouse process creates the base for the analysis of the coefficient of efficiency.

In the frame of the research were specified two hypotheses:

Hypothesis H1: Improving the quality of the warehouse process decreases warehousing costs.

Hypothesis H2: Improving the quality of the warehouse process influences the efficiency of the process.

The data collection was realized by the accounting system named SAP – for financial accounting with the module of warehouse process and inventory in the food company at account number "501" in financial accounting. The costs for the year 2023 are processed in Table 1. All those costs are accepted by law. The high costs are in the meat warehouse, pallet warehouse and vegetable warehouse. Than we analysed all the types of warehouses.

Table 1 Warehousing costs in year 2023

Type of warehouse	2023
	Costs (€)
aluminum packaging	20 874
vegetable warehouse	50 450
meat warehouse	98 750
fruit warehouse	50 120
cans warehouse	20 590
cardboard warehouse	9 875
pallet warehouse	50 230
spice warehouse	40 560

Source: internal documents of SAP system

The main research algorithm focused on managerial methods applied in the analytical part of the study. These fundamental managerial techniques formed the basis for optimizing warehousing costs and provided insights into improving warehouse processes. Pareto analysis was employed in the economic domain. In the field of quality management, it is considered one of the most effective tools, illustrating that 20% of the causes are responsible for 80% of poor quality. This method enables the identification of key factors contributing to a problem, distinguishing them from less significant ones, and guiding efforts toward the most impactful areas for improvement.

Pareto analysis was realized in steps:
1. to rank the causes from the largest to the smallest value,
2. to determine the percentage of causes based on the formula (1),
3. to determine the cumulative structure of causes, based on the formula (2),
4. to prepare graph and Lorentz curve.

$$\text{Structure: } S\ (\%)\ \frac{Xi}{SUM\ Xi} * 100(\%) \tag{1}$$

$$\text{Cumulative structure: } CS\ (\%) = \sum X_t + X_{t+1} \tag{2}$$

where: (S) structure, (CS) cumulative structure, (X) costs, (t) time.

Based on the Pareto analysis, categories were defined by ABC method based on the costs in the warehouse process through the ABC category classification (Table 2).

Table 2 Category of stocks by ABC method

Category of stocks	Cumulative structure (%)
A category	<80%
B category	<95%
C category	>95%

Source: Kádárová, J. et al., 2015

Category A includes costs that account for less than 80% of the cumulative structure. These costs are critical, as they significantly affect the quality of warehouse processes and inventory. It is essential to address and reduce these costs.

Category B covers costs that fall below 98% of the cumulative structure. These represent a smaller portion of expenses that can still be optimized.

Category C consists of costs exceeding 98% of the cumulative structure. These are negligible and do not pose a threat to inventory quality or warehouse operations.

An important managerial method used in the research is the process efficiency method. The efficiency of the process was monitored using an efficiency indicator formula (3) and its threshold evaluation (Table 3), assessed after the implementation of corrective measures.

$$\textbf{Coefficient of effectiveness: } Ke = X_{(1)}/X_{(0)} \quad (3)$$

where: (X) costs, (t) time (1) real time, (0) previous time.

Based on the limit evaluation of the process efficiency, we can find out the efficiency of the process.

Table 3 Limited valuation of the selected process

Effective process	Ke<1
Ineffective process	Ke>1

The process coefficient (Ke) can be expressed in terms of any measurable economic parameters within the accounting system for a given process. The process coefficient can be expressed through the quantities of production, documentation, number of revisions performed, number of quality objectives met, results achieved in customer and employee satisfaction, number of projects completed within the agreed deadline, number of employees in the monitored period, number of employees meeting the level of education, number of confirmed purchase contracts, number of orders, meeting order deadlines, meeting the project period based on customer requirements, meeting financial indicators and quality indicators, number of complaints and rejections, etc. When calculating the coefficient process, we determine its efficiency, which considers the fulfillment of planned values and expresses deviations of actual values from planned values.

4 Results

In the current global market environment, the food company has decided to optimize its stocks and reduce warehousing costs. This logistics chain has eight warehouses (meat storage, fruit storage, vegetable storage, spice warehouse, storage of cans, aluminum packaging, cardboard warehouse, and pallet warehouse), which are essential parts of production and distribution. In the warehouses, some stocks tie up the company's financial resources, and on the other hand, these stocks can deteriorate, reducing the quality of stocks through continuous storage.

A large amount of stored inventory represents high storage costs for the food company, and overall, the company does not have enough liquid funds (cash) because they are tied up in inventory. The total value of stocks in warehouses represents 341 449 € in the year 2023. In the research, we analyzed warehouses according to the warehousing costs.

We used Pareto analysis (Table 4) for the determination of the critical type of warehousing costs. As part of the Pareto analysis, we determined the amount of the inventory in the individual warehouses in ascending order (from 98 750 € to 9 875 €). We determined indicators such as the structure and the cumulative structure by Formula (1) and Formula (2). Based on the structure indicator, we can conclude that the highest costs are in the meat warehouse, fruit warehouse, vegetable warehouse, and pallet warehouse. Those warehouses contain items with high-value - costs. Meat, fruit, and vegetable items are risk items from reason durability, freshness, and deterioration quickly. The reason for their optimization is the tie of financial sources, which is a problem for selected food companies in cash management. Cash is an important current asset for business. The cash balance is the most unproductive asset of an organization. However, it is important because it is used to pay liabilities.

Table 4 Pareto analysis of warehousing costs in year 2023

Costs (€) in the warehouses	**2023**	**2023**	**2023**
	Valuation (€)	**Structure S (%)**	**Cumulative structure CS (%)**
meat warehouse	98 750	29	29
fruit warehouse	50 120	15	44
vegetable warehouse	50 450	15	58
pallet warehouse	50 230	15	73
spice warehouse	40 560	12	85
cans warehouse	20 590	6	91
warehouse of aluminium packaging	20 874	6	97
cardboard warehouse	9 875	3	100

Source: own source

We have determined the results of stock levels in individual warehouses based on the Lorenz curve in Pareto analysis (Figure 2), which states that 20% of stocks (items in warehouses) represent 80% of the costs of the warehouse process. This Lorencz curve specifies the critical type of inventory in the warehouses. The problem warehouses are on the rules 80/20 - meat, vegetable, fruit, and pallet warehouses.

This method is very easy for the classification of a critical type of inventory in the warehouses, and it provides possibilities for how to stop the warehouse problem for the enterprises. Pareto analysis have advantages such as Pareto analysis can be used to pinpoint the factors that are having an outsize impact on an organization, for better or worse, as a decision-making technique, Pareto analysis helps clarify the actions that could have the greatest positive impact, each problem or benefit is given a numerical score based on the level of impact on the company; the higher the score, the greater its impact. For this situation, it is important to suggest corrective measures. The corrective measures have to be oriented towards all the pages, such as technical, technological, social, political, economic, and ecological.

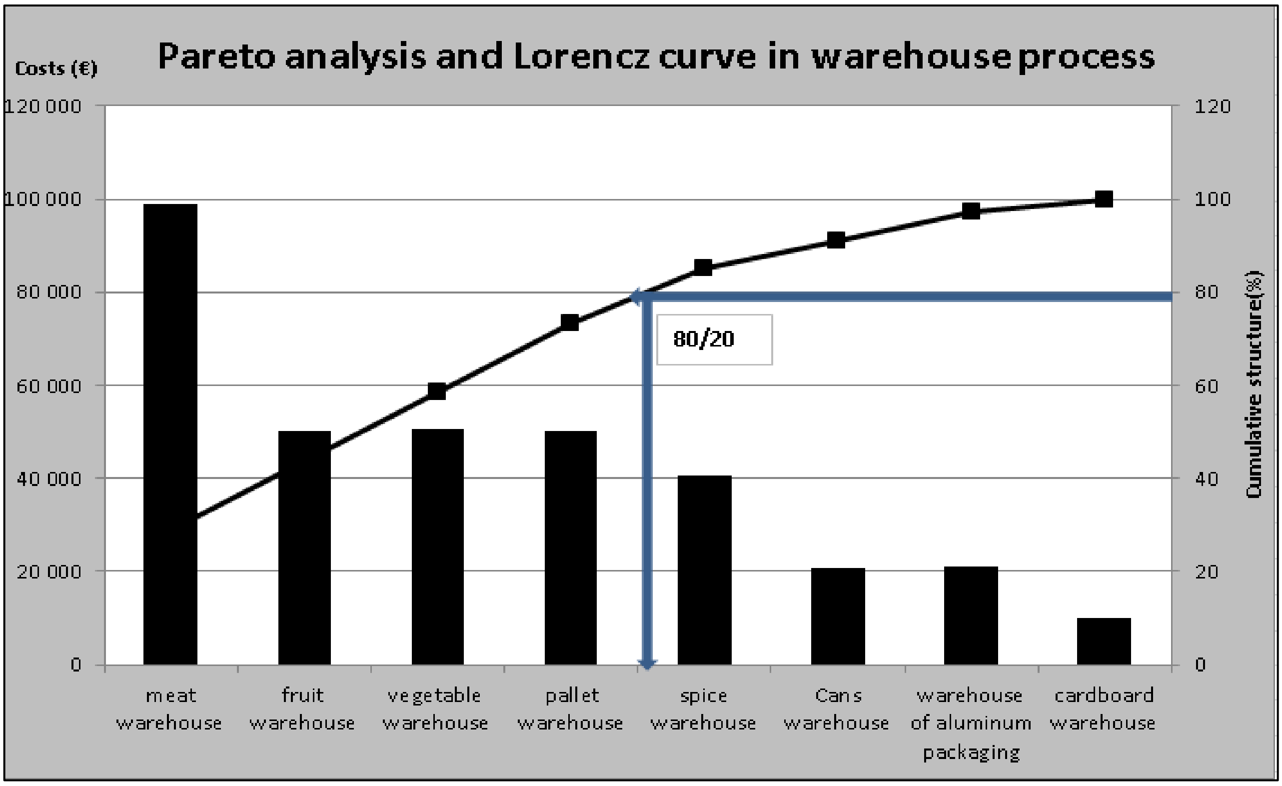

Figure 2 Pareto analysis of stocks
Source: own source

The category of warehouses (Table 5) that need to be addressed is represented by 4 warehouses: meat storage, fruit storage, vegetable storage, and pallet warehouses which make up funds tied up in stocks in the amount of 249 550 €.

Table 5 ABC category of warehouses items

Category	Structure (%)	Cost (€)	CS (%)	CS (%)
A	73%	249 550	<80%	73.77
B	18%	82 024	<95%	91
C	9%	9 875	>95%	97-100

Source: own source

Figure 3 represents ABC category for warehouses in the food company. The "A " category of stocks in the warehouse. In these warehouses it is needed to reduce the level of stocks, and determine the amount of insurance stocks, which will be used in the event of a stock deficit during sales. It is very important to determine the optimal number of stocks in the warehouse. In this part it is important to ensure the necessary quality of stocks and reduce waste due to the reduced quality of meat, fruit, and vegetables. The meat, fruit, and vegetable waste create high costs for food companies. The structure of this category represents 73% of the stocks.

The second "B" category creates 18% of stocks in the warehouse. In the economy, it means 82 024 € costs of the stocks in the warehouse. That kind of stock introduces the spice warehouse and cans warehouse.

The third "C" category creates 9% of stocks in the warehouse. In the economy, it means 9 875 € costs of the stocks in the warehouse. That type of stock introduces the aluminum packing warehouse and cardboard warehouse. This warehouse creates the lowest costs in the warehouses of the food company.

The problem warehouses are on the rules Pareto analysis 80/20 - meat, vegetable, fruit, and pallet warehouses and too ABC category classification of the stocks shows the problem with meat, vegetable, fruit, and pallet warehouse and goods.

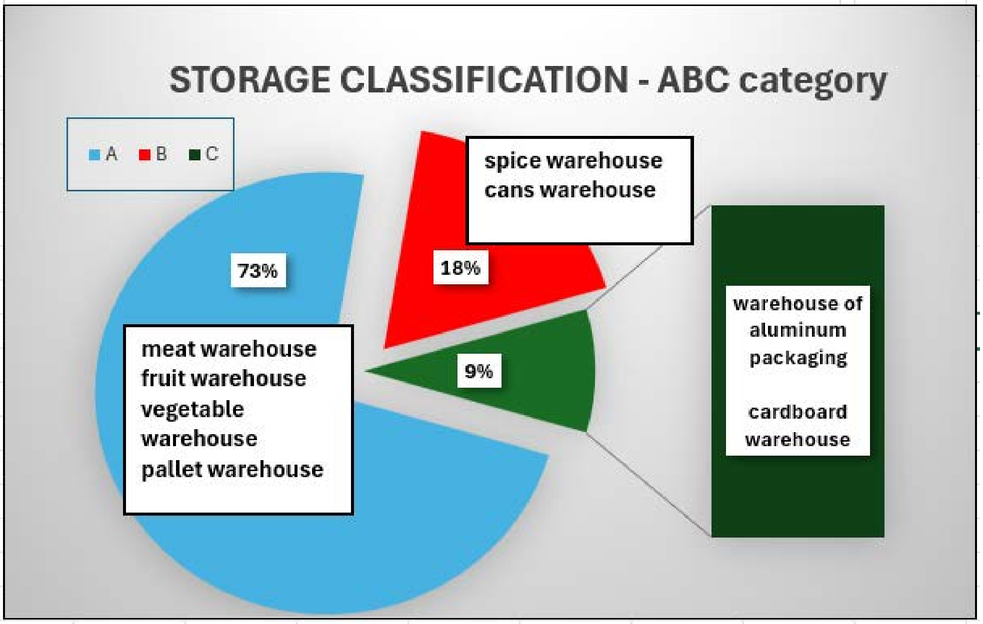

Figure 3 ABC classification of storage
Source: own source

In the results of the research in the year 2023, we suggested corrective measures for solving problems in the warehouses of the selected food company. Those corrective measures could improve the situation in the financial area by reducing costs, improving warehouse operations and systems, the layout of warehouses, and satisfy the customer's satisfaction. Based on these corrective measures, we expect a reduction in some types of costs in the warehouse management of the food company. The main categories of costs are operating costs, transport costs, warehousing costs, damage, stock costs, and labor costs. The results of research in 2023 in the warehouses of the food company recorded deficiencies. The analysis of the real state was provided by methods - Pareto analysis, and ABC classification. Those methods pointed to the critical warehouses and goods - meat, vegetables, fruit, and pallets.

Based on the implementation of corrective measurements in the warehouses, the food companies calculated the warehousing costs in the years 2024 and 2025 (Table 6). We monitor the improvement of the quality and efficiency of warehouse management in food companies in the sense of cost-oriented cost minimization: operating costs, transport costs, warehousing costs, costs of damage, stock costs, and labor costs.

Table 6 Costs after implementation of the corrective measures (501)

Type of warehouse	Costs 2024	Costs 2025	AD 2024/2023 (€)	AD1 2025/2024 (€)
meat warehouse	99 560	96 582	810	-2 978
fruit warehouse	50 230	48 596	110	-1 634
vegetable warehouse	51 269	50 250	819	-1 019
pallet warehouse	50 600	48 500	370	-2 100
spice warehouse	40 260	40 250	-300	-10
cans warehouse	20 100	19 860	-490	-240
aluminium packaging	19 800	19 500	-1 074	-300
cardboard warehouse	8 560	8 500	-1 315	-60

Source: own source

Based on the collection of cost data from the SAP system for the years 2024 and 2025, we investigated the development of costs based on the implementation of corrective measures. We calculated the absolute difference and indicator of the difference in costs for two consecutive years. We calculated the coefficient of efficiency by formula 3 in Table 7. In the year 2024, costs were reduced in four warehouses, which were declared efficient warehouses in terms of efficiency. In the year 2025, inventory costs were reduced in all operating warehouses, and at the same time warehouses declared as inefficient were changed to efficient warehouses.

Table 7 Coefficient of efficiency in the warehouses

Type of warehouse	Ke/2022	Efficiency	Ke/2023	Efficiency
meat warehouse	1.01	Ke>1 Ineffective process	**0.97**	Ke<1 effective process
fruit warehouse	1.00	Ke>1 Ineffective process	**0.97**	Ke<1 effective process
vegetable warehouse	1.02	Ke>1 Ineffective process	**0.98**	Ke<1 effective process
pallet warehouse	1.05	Ke>1 Ineffective process	**0.92**	Ke<1 effective process
spice warehouse	0.99	Ke<1 effective process	0.99	Ke<1 effective process
cans warehouse	0.98	Ke<1 effective process	0.99	Ke<1 effective process
aluminium packaging	0.95	Ke<1 effective process	0.98	Ke<1 effective process
cardboard warehouse	0.87	Ke<1 effective process	0.99	Ke<1 effective process

Source: own source

We calculated the coefficient of efficiency by formula 3 for all types of warehouses in Table 7. In the year 2024, costs were reduced in four warehouses, which were declared efficient warehouses in terms of efficiency. The improvement was recorded in those warehouses: spice warehouse, cans warehouse, aluminum packaging, and cardboard warehouse. Those warehouses are introduced in Category B 18% and Category C 9% of all warehouses. Those categories are not critical on the economic base. All those warehouses were determined effective processes. In the year 2023, inventory costs were reduced in all operating warehouses, and at the same time warehouses declared as inefficient (meat warehouse, fruit warehouse, vegetable warehouse, pallet warehouse) were changed to efficient warehouses. The category of those warehouses is category "A", and it is a critical category from an economic point of view.

5 Discussion

The basis for logistic sustainability we made by the Baruffaldi et.al. The foundation for logistic sustainability was based on the model developed by Baruffaldi et al. Baruffaldi, G. et al. state that reducing costs, improving quality, lead times from customers, workforce availability, health and safety, and effects on the environment are priority factors for effective logistic processes and the basis for logistic sustainability. Critical warehouses were identified through Pareto analysis, and the Lorenz curve was used to determine the threshold for these critical warehouses. Corrective measures were proposed to reduce costs that presented Pinto et.al., improve quality oriented on SMART warehouses by the suggestions of Van Geest et.al., shorten customer lead times in the paper presented by Burganova et.al., enhance workforce availability by the approach BSC presented in the paper by Kádárová et.al., ensure health and safety in warehouses that presented Marzialli et.al. orientated on critical problem and KPI indicators, and minimize environmental impact what was the main part of the paper by Khan et.al. with orientation on architecture and design such as smart warehouse management.

Corrective measures (Figure 4) serve as tools for enhancing quality and efficiency in warehouse management, with impacts across economic, environmental, technical, and social dimensions of the food company. In this research, we proposed several corrective actions for warehouse operations: Warehouse layout redesign based on the warehouse optimization model by Karásek (2013). Increased turnover of food stocks using IoT technology in warehouse management, as presented by Jarasuniene et al. (2023). Modification of transport routes to customers informed by the findings of Marasová et al. (2018) on transport quality. Implementation of a Just-In-Time (JIT) system, as part of a lean warehousing approach, described by Prasetyawan et al. (2020). Reduction of damaged stock waste through the multi-warehouse inventory model by Kumar et al. (2021). Stock transfer system optimization based on the warehouse location approach by Millstein et al. (2022). In this frame were recommended the use of robots and conveyor belts was recommended for inventory optimization. The food company considered renting equipment as part of its strategy to improve warehouse operations.

These corrective measures were implemented in 2024 within the warehouse processes of the food company. The results of these innovations led to measurable improvements in warehouse operations.

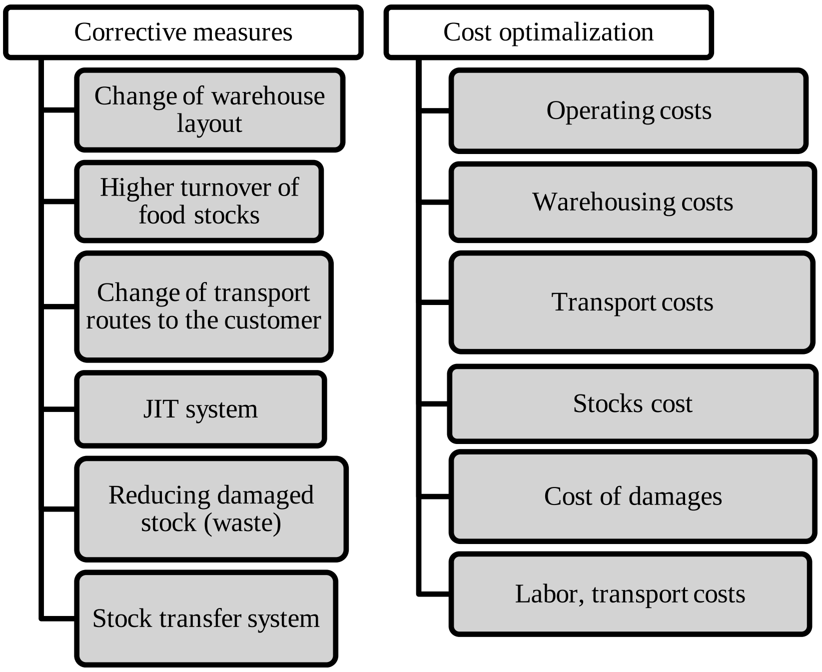

Figure 4 Corrective measures for warehouse process
Source: own source

Based on hypotheses H1: Improving the quality of the warehouse process decreases warehousing costs. This hypothesis was confirmed. A decrease in storage costs of 8341 was recorded in the year 2025 and 1070 in the year 2024. In all warehouses of the food, the company recorded the cost reduction. The implemented correction measures brought positive results for warehouse processes from an economic point of view. The second hypotheses H2: Improving the quality of the warehouse process influences the efficiency of the warehouse process. This hypothesis was confirmed. In the year 2024 there were 4 processes (meat warehouse, fruit warehouse, vegetable warehouse, pallet warehouse) ineffective. After implementing correction measurements those processes became effective. A decrease in efficiency from value 1,00 to value 0.92 was recorded in 4 critical warehouses (meat warehouse, fruit warehouse, vegetable warehouse, pallet warehouse) of the food company, which means increasing efficiency and those warehouse's process is effective. The results of the research in the food company are presented ine the table (Table 8).

Table 8 Results for hypotheses

Category	**2023**	**2024**	**2025**	**H1**	**H2**
Costs (€)	341 449 €	340 379 €	332 038 €		
Cost reduction (€)	-	1070 €	8341 €	Confirmed H1	
(Ke) – coefficient of effectiveness	-	1.00-1.05 ineffective processes 0.87-0.99 effective processes	0.92-0.99 effective processes		Confirmed H2

Source: own source

The results of the research of the selected food company are at a sufficient level of quality warehouse process. The hypotheses were confirmed. Suggesting corrective measures created the conditions for the SMART warehouses process by using machines such as robots, conveyor belts, IoT technologies, BSC approach, digital instruments, lean methods, and KPI indicators. We suggest a new model (SWP) for sustainable warehouse process based on the results of warehouse process optimization in the food company (Figure 5). We are based on the knowledge of other authors who presented benefits in warehouse processes. In the area of digitalization is needed to use the approach Zunic et. all. (2018) presented the warehouse management system. This WMS is one of the most important parts of the working process in food companies. The concept uses artificial intelligence algorithms to improve the standard warehouse management system by giving optimized solutions to users. The implemented concept optimizes stock planning, initial product placement, and the picking zone transfer process, as well as order picking, transport, and tracking processes. The optimized processes can make large time and cost savings and can create a more efficient environment [30].

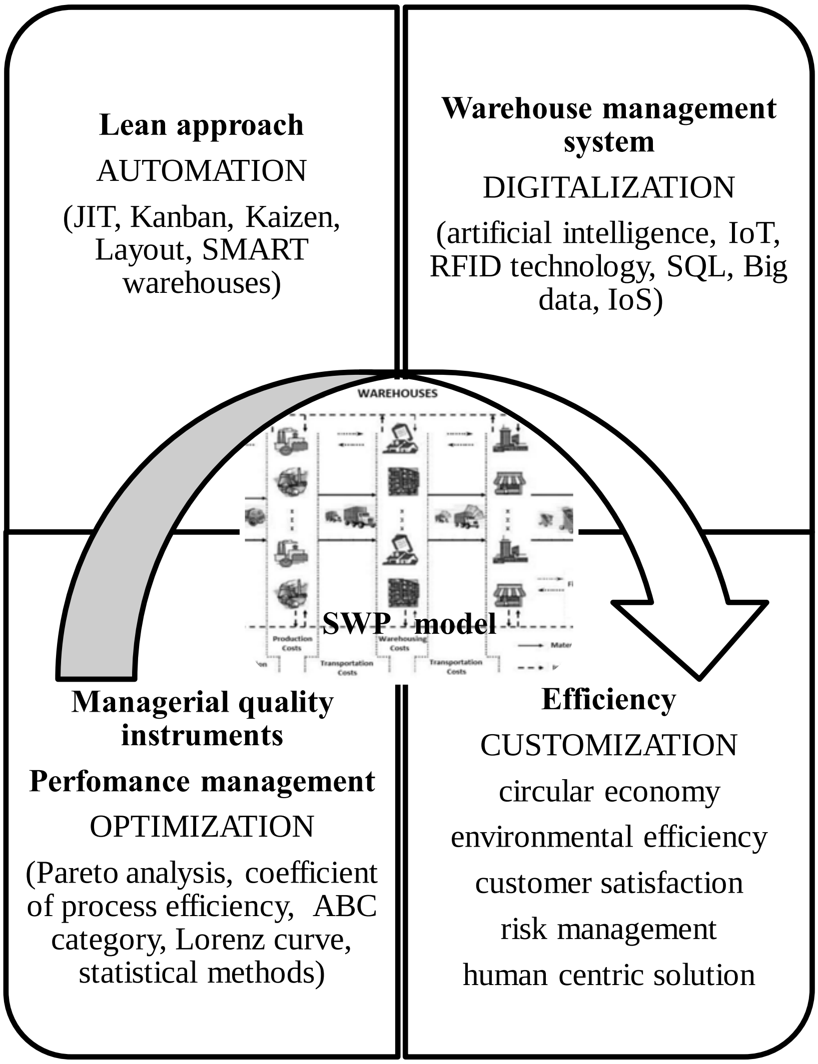

Figure 5 SWP model
Source: own source

The second area of the SWP model is important pillar of customization and efficiency. We go out of comment of Baruffaldi, G. et al. (2020) state that reducing costs, improving quality, lead times from customers, and workforce availability is the basis for logistic sustainability. The efficiency view is important, including economic, environmental, and social efficiency. Kádárová, J. et al. (2015) state that the warehouse process is important to know. Reaction to the risks and investigating the conditions of crises of deficit of stocks is the basis for effective supply and warehouse management.

The third area of the SWP model is important optimization, and this pillar creates part of performance management. Mensah el. al. (2021) said that the logistic sustainability is standing on the priority green logistics management practices are a significant driver of organizational performance, such as environmental sustainability, social sustainability, and business performance. Nantee el. al.. (2021) said that logistics sustainability focuses on automated warehousing systems. on the economic, environmental, and social dimensions of the sustainability performance of those systems. Larson et. al. (2021) said that logistics sustainability is connected with logistics performance. Logistics performance is a driver of economic activity and success; it is also a contributor to environmental degradation in the form of harmful emissions.

The fourth area of the SWP model is oriented on automation and lean logistics instruments. Logistics sustainability focuses on efficient flows from the supplier to the customer, and it depends on internal logistics, transport time, said Burganova et.al. (2021). Jayarathna et. al. (2023) said that logistics sustainability depends on transforming toward a circular economy is a viable strategy for achieving sustainable logistics systems. Fernando et. al. (2023) said that logistics sustainability is connected with a circular economy-based reverse logistics that emphasises the effect of reverse logistics on sustainable resource commitment and financial performance. Gupta et. al. (2022) said that logistics sustainability of the circular economy is oriented on service quality that influences the performance of supply chains. All of those comments presented the lean approach in logistic processes. Lean instruments create the base for connection with digitalization, optimization, and automation. The SWP model creates the pillar of logistic sustainability in various areas of industry and services. Affia et. al. (2022)commented that the logistic sustainability is acomplished by the real-time visibility and traceability in warehousing could be accomplished by implementing the internet-of-things (IoT) technology that is part of the warehouse management system in the SWP model [31]. Simic et. al. (2023) presented the new model based on the integration of the logarithmic percentage change-driven objective weighting (LOPCOW) method and the additive ratio assessment (ARAS) method in the food inventory sector. Industry 4.0 technologies embedded in the warehouse management system (WMS) are needed to improve the automation of material handling activities such as receiving, storing, picking, sorting, packaging, and delivering [32]. Zhou et. al. (2024) presented an Intelligent Warehouse Management System (IWMS) that represents a technological leap forward in the realm of logistics and supply chain management. This sophisticated system integrates a suite of cutting-edge technologies, including artificial intelligence, machine learning, and the Internet of Things, to revolutionize the way warehouses operate [33].

6 Conclusions

The tool for warehouse process optimization is the approach as SMART warehousing by SWP model based on warehouse optimization, better customer service and customer satisfaction, lower costs, faster picking and shipping, tracking of assets and inventory for financial sources, and great accuracy in warehouse operations what was presented in our research of the food company. The main goal of the research was to optimize costs in the warehouse process of the food company. After the implementation of corrective measures (change of warehouse layout, higher turnover of food stocks, change of transport routes to the customer, JIT system, reducing damaged stock (waste), stock transfer system) in the warehouse process we obtained positive results for confirmation of the hypotheses.

Hypothesis H1: Improving the quality of the warehouse process decreases warehousing costs. This hypothesis was confirmed because warehousing costs were decreasing by 8 341€ in the year 2025 and 1 070€ in the year 2024.

Hypothesis H2: Improving the quality of the warehouse process influences the efficiency of the process. This hypothesis was confirmed because the coefficient of efficiency records changes from ineffective process to effective process. Warehouse processes were improved and brought benefits to the food company.

The first benefit was reducing costs, which means increasing financial sources in cash for paying the obligations and debts. The second benefit is effective warehouse processes that satisfy customers. The suggestion of corrective measures can be used as the model for smart warehouse processes in food companies such as an instrument for smart warehouse management. Tiwari (2023) presented that warehouses are crucial components of the logistics industry because their operational efficiency determines the operational efficiency of logistics. With the introduction of Industry 4.0 technologies, the warehouse's role has changed dramatically, the scope of warehouse operation has expanded, and the concept of smart warehouse, which denotes increased automation of traditional warehouse functions, has been introduced. Smart warehouses aim to improve overall service quality, productivity, and efficiency while lowering costs and failures [34]. Min (2023) said changes in the warehouse management have been further accelerated by rapid technological innovations resulting from the fourth industrial revolution (Industry 4.0). One of the most notable technological transformations was smart warehousing concepts. A smart warehouse will bring many managerial benefits, including warehousing cost efficiency, labor productivity, and agility in the era of the knowledge economy [35].

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Rebuilding Iraq's road network: challenges and project management solutions

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Abstract: The state of the road infrastructure in Iraq has severely declined due to the long-term conflict, the instability of the institutions, and the lack of investments, thus interrupting the logistical processes and the development of the country. This study examines the main barriers to the rebuilding of the road system in Iraq and proposes a coherent framework that would combine project-management and logistical paradigms in order to reduce these obstacles. Using a comparative approach to determine international best practices in road-infrastructure delivery, the paper evaluates the appropriateness of the PMBOK, PRINCE2, and Agile approaches in the post-conflict context in Iraq. Such frameworks are assessed together with the enabling technologies, such as Geographic Information Systems (GIS) and Artificial Intelligence (AI), and participatory models of stakeholder-engagement. The research suggests a hybrid model of logistics aligned strategy to fill the identified gaps, in which localisation of PMBOK, PRINCE2, and Agile solutions is the key, with material, information, financial, and human flows optimisation provided by GIS/AI decision support. The approach enhances more transparency, efficiency, and sustainability in the governance of infrastructure. The value of the research is twofold: (i) the combining of project-management stage-gates with the transport-logistics flow control in a post-conflict setting, (ii) the flow based blueprint of delivering, and maintaining the Iraqi road assets.

1 Introduction

The road system in Iraq used to be an essential part of the national development strategy as the foundation of transport logistics, the economy of exchanges, and territorial integration. Between the 1970s and 1980s the state invested many resources in the development of the modern system of highways and arterial roads that bound the urban centres to rural territories and provided the means of trade with other states. The infrastructure was of great essence in facilitating trade and commerce, social mobility and strengthening the strategic military position of Iraq in the region. The road system was a symbol of a vision of connectivity and modernization at its peak [1]. Successive decades of conflict and instability, however, have been gradually eating away at this vision. Starting with the long Iran-Iraq War and made worse in the war in the Gulf and the invasion of Iraq in 2003, a large portion of Iraq infrastructure was either intentionally targeted or poorly maintained. Bridges and roads were hit, logistical centers were hit, and maintenance either stopped or became under-funded. The crisis was further worsened by subsequent insurgencies, occupation and sectarian violence with infrastructure being a victim and an instrument of conflict. The net effect of this prolonged war conflict has caused the road network to be weak and disjointed [1]. The damage of the roads in Iraq has interfered with the main logistics operations such as material flow (aggregates, asphalt, equipment), information flow (permits, designs, work orders, QA/QC data), and financial flow (disbursements, claims, change orders), the performance of the transport logistics, supply chain dependability, and national connection.

Since the hostilities ended, the rehabilitation of the transport logistics network in Iraq has become a challenging task, and the lack of a number of political and institutional challenges has complicated the situation. Lack of proper planning, systemic corruption and lack of technical capability has hampered reconstruction efforts. Inter-provincial and central rivalry has also contributed to slowing down co-ordinated projects. In addition, the external donors and international agencies, as helpful as they are, have tended to focus on short-term goals or act in isolation which has led to fragmented interventions which are not sustainable [2].The research paper is suggested to create a project management framework based on logistics of rebuilding the roads in Iraq, which should improve the governance of material, information, and financial flows during planning, implementation, and maintenance operations. The framework incorporates the recognized project management frameworks (PMBOK, PRINCE2, Agile), as well as logistics flow management and digital tools (GIS, AI), to suggest a context-sensitive hybrid framework to the Iraqi post-conflict limitations, thus going beyond the descriptive review and providing a governance and delivery blueprint. This is the aggregate effect of such hurdles on the current state of the road system in Iraq. A lot of major highways contain holes, broken signs, and broken overpasses [3]. The secondary and rural roads are mostly unpaved or washed off making vast portions of the country inaccessible at some times of the year. Such infrastructural inadequacies not only slow down the day-to-day commute but also disrupted supply chains, accessibility to education and healthcare, and emergency response. In the metropolitan areas like Baghdad, Mosul, and Basra, traffic jams due to poor road networks are the causes of environmental degradation, high vehicular accidents, and poor traffic congestion [4].

Three major research questions will support this study. It initially looks into the ways and means through which the established project management frameworks, such as the Project Management Body of Knowledge (PMBOK), PRINCE2, and Agile methodologies can be localized and used to alleviate the occurrence of coordination failures, minimize change-order risks, and enhance efficiency in the performance of the Iraq road reconstruction programs. Second, it examines the future applications of Geographic Information Systems (GIS) and Artificial Intelligence (AI) to streamline both the informational processes, including data on assets and prioritization and scheduling, and the material processes, including staging, routing, and operations and maintenance, when capacity limits are in place. Third, it also evaluates the governance forms and stakeholder engagement mechanisms best able to strengthen transparency, accountability and collaboration across the project life cycle. The proposed research questions are based on the hypothesis that a hybrid, contextualized project management and logistics framework the combination of structured methodologies with digital and participatory tools will have a significant impact on the flow reliability and the overall performance of a project compared to the traditional, disjointed reconstruction practices. Socioeconomic impact of a faulty road network is so far and wide. Inefficiency in transport raises the prices of goods and services thus reducing affordability and competitiveness in the markets. The jobs in remote areas are lost because mobility is limited, which increases the disparities across the regions. The frustration of the basic needs by the infrastructure increases the level of discontent among the people and destroys the confidence in governmental structures and increases the sense of marginalization, especially in rural and post-conflict groups. In the same context, road reconstruction is not an engineering issue rather, it is a social, economic, and political need [5]. A comparative analysis of the international best practices in road maintenance and delivery is carried out mapping the best practices to the institutional, financial, and operational constraints in Iraq. The synthesis produces a hybrid structure that incorporates structured stage-gate control, Agile responsiveness, and digital decision support tools (GIS/AI). The sources of evidence are peer-reviewed articles, sector reports, and case studies of post-conflict infrastructure. The reconstruction of the roads in Iraq is a crucial step towards fostering the development of national unity and promotion of post-war recovery. A reliable transport logistics system is one that helps in people and goods transportation, encourages trade, strengthens internal communication and improves the provision of state services [6]. It is also strategic in terms of guaranteeing security because the state is able to exude power and access distant locations. Infrastructure development could serve as one of the projects that unites people, as it could become a stabilizing factor in a weak post-conflict setting that would facilitate a steady situation [7]. This study takes the logistics-based project-management approach, which examines the role of process of coordination of material, information, financial, and human flows on performance and sustainability of the road reconstruction initiatives in Iraq.

However, the process of repairing the roads in Iraq does not only require a physical repair. It also needs proper project-management structure that will ensure transparency, efficiency and community involvement. The priorities should be outlined, sustainable financing sources established, cooperation between the stakeholders should be shaped, and instruments of effective planning and implementation should be introduced. Risk assessment, stakeholder mapping, schedule optimization, and quality control should be strictly taken to prevent the earlier failures of the project and to be prepared to build infrastructure both today and in the future [8]. The paper outlines the numerous issues the country of Iraq is struggling with in terms of reconstruction of roads and how the implementation of management practices can mitigate the issues. It uses case-studies, stakeholder reports and international precedents to give a holistic view of the modern day issues and offers solutions to issues which make sense in various contexts thus enhancing the discussion on post-conflict infrastructure reconstruction and the importance of strategic planning in national recovery [4]. There is more than infrastructure involved in the rehabilitation of Iraqi roads and it has to do with the restoration of broken relationships in Iraq. Roads are the symbols of motion, new prospects and hope. When Iraq is on the road to peace and prosperity, proper management of transport logistics projects will play a key role in supporting the vision in the long run. The rest of the paper will be organized in the following way. Section 2 is a literature review on critical success factors in road maintenance and establishes connection between project management and logistics performance. Section 3 examines the institutional, financial, and operational obstacles that limit the efforts to rebuild the roads in Iraq. Section 4 suggests a hybrid system that combines the use of PMBOK, PRINCE2, and Agile systems with the optimization of logistics flows and the utilization of digital technologies (GIS, AI). Section 5 addresses implementation pathways, governance mechanisms and contextual adaptations that should be used to achieve successful implementation. Lastly, the conclusions are made in Section 6, the main insights are summarized, and strategic priorities toward enhancing the road infrastructure recovery in Iraq are outlined.

2 Literature review

This part will explain what is crucial in making road maintenance projects in Iraq successful. The discussion uses a global comparison of research to take lessons from both advanced and less advanced nations, as well as different construction projects. By forming theories from various studies, the purpose is to find approaches and keys to success that match Iraq's situation after the conflict.

Road maintenance means regularly doing work on roads to preserve their function and safety, such as the pavement, shoulders, slopes, drains, and roadside technical devices [9]. By performing these activities, roads are kept in good condition for a longer time and ensure both reliable transport and publics' safety. Such maintenance activities are successful only if there is a good balance of institutional, managerial, financial, and technical factors. Kog et al. pointed out in a key study [10] that project success comes from effectively handling specific aspects. According to [11], the importance of these factors should be considered in big projects, like road construction and maintenance, because they are complex and require many resources.

The work in [12] offers a good description of CSFs as they relate to Intelligent Transportation Systems (ITS), which many road maintenance efforts also have in common. Organizational, management, environmental, and individual patterns are included in how they are categorized. In this case, organizational factors consist of trust, culture, how good communication is, how resources are managed, and the types of oversight used. CSFs in the management category are procurement, setting standards for IT, supervising the steering committee, and managing costs. Regulatory rules and changes in the market or politics are considered environmental factors, but skills, flexibility, and the involvement of users are considered individual factors. In Iraq, these aspects are important because the broken-up institutions and aftermath of conflict cause many difficulties for US operations.

Strong collaboration and effective lines of communication among those involved were recognized by [13] as important, and [14] stressed that clear roles, an emphasis on quality, and strong leadership all support success in sustainability. These recommendations respond strongly to the needs in Iraq's infrastructure sector, which has suffered from delays and inefficiencies due to overlapping roles and poor coordination.

It is practical to develop simple planning methods to manage and improve how maintenance is conducted. Using detailed checklists, as suggested by [15], is one method to improve how tasks are planned. [16] mentioned the significance of noticing and understanding the connections between CSFs to deploy resources where they are of greatest use. [17] further recommended using multidimensional approaches to visually analyse how CSFs depend on one another to develop flexible plans as needed.

In the context of government projects, reference [18] highlights the need to baselessly assess critical success factors (CSFs) in the partnership setups, reference [19] however, argues that legal adherence and regulatory astuteness are paramount prerequisites to successful project execution. Reference [20] also argues that the infrastructure funding through alternative means is needed to maintain the road infrastructure in the emerging economies and suggests that the old model of funding the infrastructure is no longer relevant and discusses that new type of financing tools should be used which is especially relevant in Malaysia where the infrastructure financing problems are compounded by the fact that the fiscal situation is a challenge.

As is stated in reference [21], the cost savings of outsourcing road maintenance services in Sweden to the private services were between 8 percent and 20 percent compared to the same government-operated program. These empirical results support the hypothesis that the privatized or performance-based maintenance solutions can result in cost-efficiency in Iraq, where the capacity of the government sector is still stretched. Similarly, reference [22] has reviewed the implementation of computerized Road Management Systems (RMS) and has argued that effective implementation depends on compatibility of three fundamental areas of the system which include processes, people and technology and suggested that lack of sufficient funding and commitment by stakeholders across these areas demolishes RMS projects.

In the Palestinian setting, reference [23] established high levels of inefficiency that are linked to a deep dependency on foreign contractors, who performed majority of the maintenance works on the urban roads, thus making the necessity of capacity building among local municipal authorities a priority. The importance of safety was also discussed in reference [24], which mentioned occupational safety as one of the non-negotiable standards of the success of construction projects. Other CSFs as stated by reference [25] include clear tasks of the contract.

Road asset management is one of the areas where optimization methodologies are being applied. A multi-objective particle swarm optimization (PSO) algorithm presented in [26] aims at optimising the pavement maintenance planning and has been shown to be better at refining the quality of solutions to be found in large transportation networks. This type of computational tool promises potential use in the Iraqi environment that is data-sparse and resource-limited, allowing the prioritization of evidence and allocate resources in such manner, which further is possible as shown in reference [27].

Reference [28] reviewed road construction projects in Kenya with specific focus on the transparent contractor selection procedure and the promotion of insulation of the procurement operations against the influence of politics. The research proposed the establishment of a centralized contractor performance registry to increase accountability, which may be a radical change to the very disjointed procurement system used in Iraq. Performance-Based Road Maintenance

Contracting (PBRMC) is a new paradigm, which has gained momentum around the world as argued in reference [29]. With the performance-based incentives and penalties, governments can be able to ensure the quality of their services as well as be able to optimise the cost efficiencies by delegating the maintenance duties to the private enterprises. Experience shows that properly designed PBRMC structures can maintain road infrastructure in an overall positive state at lower lifecycle prices as has been shown in reference [29]. Such models may be essential in ensuring that the long-term sustainability is realized despite the fiscal and operational limits in Iraq.

The paper has also discussed the common problems, which initiate change orders in maintenance contracts in the United States; the study, reference [9] identified a list of factors such as lack of scope definition, poor cost estimates, design revisions and lack of verifying the site, which contributes to the need of accurate pre-construction evaluations and sturdy contingency plans. These lessons can be directly related to Iraq, where change orders and scope creep are the common pests in the project timelines and budgets. Despite a wealth of global literature outlining key success factors of road maintenance projects, there remains a lot of gaps in trying to rationalize the information to the Iraqi context. A substantial part of the existing literature focuses on countries that have relatively stable political and institutional structures, but Iraq still has to deal with the post-conflict fragmentation, poor governance, and frequent political interference in the work of the government. The lack of localized research that examines the effects of how systemic factors, including the corruption in procurements, the absence of accountability by contractors, and poorly enforced regulations, hinder the operations of the road maintenance programmes in Iraq is lauded. Furthermore, the global scholarship focuses on the stakeholder coordination, project planning tools and performance-based contracts, which are either poorly developed or inconsistently implemented in the Iraqi setting. There is limited empirical information available about the ability of the Iraqi municipalities to take care of maintenance activities and most of the tasks are contracted without proper supervision. Moreover, there has not been much exploration on financing mechanisms that fit Iraq fiscal constraint like the use of public- private partnership or results-based budget. The lack of uniform and integrated contractor performance monitoring apparatus and maintenance procedures also serve to hinder the propagation of international research-based best practices. These contextual shortcomings underline the urgent need for Iraq-specific frameworks and evidence-based models that can adapt global success factors to the realities of local infrastructure governance and execution. Table 1 summarises the key studies on Critical Success Factors in Road Maintenance and Construction Projects.

Table 1 Summary of key studies on critical success factors in road maintenance and construction projects

Author(s)	Context	Key Findings
[Kog and Loh, 2012] [10]	General construction projects	Identified senior management support, contractor competence, and project manager involvement as critical for budget, schedule, and quality outcomes.
[Toor and Ogunlana, 2009] [11]	Large-scale construction projects	Emphasized the need to assess CSFs in complex infrastructure projects.
[Ataei Jafari and Ahmadvand, 2018] [12]	Intelligent Transportation Systems (ITS)	Developed a CSF framework including organizational, management, environmental, and individual factors.
[Li et al., 2019] [13]	General project management	Highlighted the importance of communication and cooperation among stakeholders.
[Banihashemi et al., 2017] [14]	Sustainable project delivery	Stressed clear responsibilities, high-quality work, and competent project managers.
[Ghanbari and Mojtahedzadeh Asl, 2021] [15]	Maintenance planning	Recommended use of checklists for improved planning and monitoring.
[Chen et al., 2012] [16]	Project management methodology	Advocated identifying interrelations between CSFs to focus resources.
[Williams, 2016] [17]	Success modeling	Demonstrated success in factor interactions using causal loop models.
[Osei-Kyei and Chan, 2017] [18]	Public-private partnerships	Suggested CSF identification is crucial for PPP success.
[Tabish and Jha, 2011] [19]	Government projects	Found adherence to regulations as the most important CSF.
[Obeng and Tuffour, 2020] [20]	Developing countries	Emphasized the need for alternative financing mechanisms in road maintenance.
[Yarmukhamedov et al., 2020] [21]	Sweden	Found outsourcing road maintenance to be more cost-effective than public provision (8–20% savings).

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[McPherson and Bennett, 2006] [22]	Computerized Road Management Systems	Identified processes, people, and technology as critical, with funding as an enabler.
[Issa and Abu-Eisheh, 2017] [23]	Palestine	Highlighted the overreliance on foreign contractors and the need to empower municipalities.
[Dann and Fry, 2009] [24]	Construction safety	Emphasized safety as a fundamental CSF.
[Nawi et al., 2012] [25]	Construction partnerships	Noted the importance of stakeholder engagement, team integrity, and role clarity.
[Mahmood et al., 2018] [26]	Pavement maintenance design	Developed a multi-objective PSO algorithm for efficient planning in large networks.
[Osman and Kimutai, 2019] [28]	Kenya	Advocated for transparent contractor selection and anti-corruption mechanisms.
[Shrestha and Shrestha, 2019] [9]	U.S. road maintenance	Found frequent change orders due to poor scoping, cost errors, and design changes.
Gap in Iraqi Context	Iraq	Limited local studies, weak municipal capacity, insufficient regulation, absence of performance monitoring systems, and lack of tailored financing models hinder the adaptation of global CSFs.

3 Challenges in rebuilding Iraq's road network

It is not easy to rebuild Iraq's roads, as the tasks are technical, political, financial, and involve operations. Between 2003 and now, various initiatives have involved fixing infrastructure, but their performance has frequently been stopped by systemic issues, so results have been varied throughout the country. All these problems must be tackled and properly understood to maintain the reliability, safety, and use of Iraq's transport logistics services [30].

The infrastructure in many places is in very bad shape, which is creating serious issues. Years of neglect, roads being heavily used by the military, and no regular maintenance have caused potholes, faulty shoulders, and damaged drainage in highways and rural areas. According to the World Bank in 2018, more than 70% of Iraq's transport infrastructure was damaged in decades of fighting. The task of rehabilitation is made harder by using old engineering standards and not having digital systems to help manage roads. Many areas ignore gathering new soil or geotechnical information, which leads to choosing inaccurate materials or questionable designs that fall apart quickly. In addition, not having enough skilled engineers and labourers, in combination with a lack of acceptable access to advanced construction tools and quality monitors, further adds to the problem of meeting building goals.

Many governance-related obstacles slow down the reconstruction of roads. Because Iraq's system gives every government level a lot of authority, there is often conflict over duties, lengthy bureaucratic processes and poor management of resources. Issues with corruption are common in public contracting and choosing the winning bidder. Iraq is listed in the 2022 Corruption Perceptions Index by Transparency International, at number 157 out of 180 countries. The weakness of institutions makes it possible for projects to be given out based on political ties instead of skills, which leads to poor results or incomplete projects. Since laws are often not enforced properly, some contractors can ignore the specifications, which leads to roads that are less safe and do not last as long.

Financial issues cause another big challenge. Oil wealth alone is not enough to keep Iraq's economy safe, which is vulnerable because it is overly tied to oil revenues and is influenced by global shifts. Because of the COVID-19 pandemic and tumbling oil prices in 2020, the government had difficulty funding projects, causing several infrastructure projects to be put on hold or cancelled. According to the International Monetary Fund (2022), Iraq's capital investment in infrastructure had fallen to approximately 3.5% of GDP, far below what is required to restore basic service levels. Although international donors pledged more than $30 billion at the Kuwait International Conference for the Reconstruction of Iraq in 2018, a substantial portion of these funds remain tied to conditional loans or aid packages that have been slow to materialize due to administrative inefficiencies and donor concerns over transparency and risk. Operational and logistical issues further complicate reconstruction initiatives. In provinces previously affected by conflict, such as Nineveh and Anbar, the presence of unexploded ordnance and landmines poses a serious hazard to construction crews, requiring costly and time-consuming clearance operations before roadwork can begin. Transportation of materials is often delayed due to the poor state of secondary roads, frequent checkpoints, and disrupted supply chains. According to a 2020 report by UNOPS, 60% of road reconstruction projects in conflict-affected areas experienced significant delays because of procurement challenges, lack of access to heavy equipment, and shortages in essential construction materials. These logistical disruptions are exacerbated by the highly fragmented construction sector in Iraq, which is dominated by small, under-resourced local contractors who often lack the capacity to deliver on large-scale or technically demanding infrastructure projects.

That mixture of technical issues, mismanaged governance, budget shortages, and logistical hurdles has meant Iraq's road reconstruction is very fragile. Focused efforts to handle each challenge together are needed for rebuilding and modernizing Iraq's roads to be successful. Transforming Iraq's roads into reliable and strong assets requires a well-planned and properly funded method, using institutional changes, transparent procurement, and new skills and funding, all done quickly.

4 Project management solutions

To deal with the various hurdles in rebuilding Iraq's roads, strong project management, flexible approaches, and advanced technology are necessary (Table 2). The many barriers in post-conflict settings, such as existing challenges, different groups involved, and logistical hurdles, require planning, execution, and evaluation to be well structured and well thought out. Recognized worldwide, the PMBOK, PRINCE2, and Agile give thorough guidelines and adaptable methods that match the requirements of Iraq.

The PMBOK created by the Project Management Institute (PMI) notes that there are five process groups in project management: initiation, planning, execution, monitoring and control, and closing. Because road projects in Iraq often face cost overruns, changes in the proposed scope, and delays, the knowledge areas of scope, time, cost, quality, and risk management are especially appropriate. Using PMBOK's strategy allows project objectives to match what stakeholders anticipate, improves resource investment, sticks to the timeline, and reduces possible risks. For example, using PMBOK risk management practices can prevent or lessen contract disputes, requests for changes, and common delays in Iraq's public facilities.

Since PRINCE2 is a flexible process method used in public sector projects around the world, it matches the governmental structure of Iraq. This way of managing focuses on clear management positions, explaining business decisions and planning products that support accountability and transparency in Iraq's infrastructure area. Organizations in the road sector need good control over lengthy reconstruction projects, and a good way is to follow PRINCE2 practices. Also, having reviews and exception-based reporting at regular intervals would allow Iraq to quickly monitor and remedy issues in its changing political climate.

While traditional frameworks provide structure, Agile methodologies introduce flexibility and responsiveness, which are crucial in unstable or rapidly changing contexts. Although Agile was originally developed for software development, its iterative cycles, continuous feedback loops, and focus on stakeholder collaboration have proven effective in construction and infrastructure projects, particularly those involving adaptive planning or innovation [31]. Applying Agile principles can be beneficial in pilot programs or modular road rehabilitation efforts in Iraq, where on-the-ground realities often diverge from initial plans. Agile's participatory approach also supports community involvement, which is essential for project legitimacy and local ownership.

In parallel with management frameworks, the deployment of technological tools can significantly enhance project efficiency and decision-making. Geographic Information Systems (GIS) allow for precise mapping, spatial analysis, and visualization of road networks, enabling planners to assess existing infrastructure conditions, plan routes, and identify high-priority areas for maintenance or reconstruction. By using GIS, traffic movement can be modeled, the environment can be evaluated, and various infrastructure projects can be coordinated across industries.

Managing infrastructure can be transformed by the increasingly important technology of Artificial Intelligence (AI) [32]. AI-powered systems can optimize the timing for maintenance, find problems in the construction using sensor-collected information, and anticipate if a project could be delayed or its original budget surpassed based on previous issues. Since human resources and data processing power are few in Iraq, AI equipment helps make smarter decisions, automate daily activities, and ensure resources are used properly [32].

Project success is also based on the importance of good stakeholder engagement models. Engagement frameworks such as the Stakeholder Circle and the Salience Model make it easier to find and organize stakeholders by their level of power, interest and influence. In the divided political and social state of Iraq, these methods can help more people be involved in planning, keep conflicts to a minimum, and unite various interests. Talking with people in the area, construction teams, NGOs, and government officials strengthens trust, makes things clearer, and encourages sharing ideas to enhance the way the project is run.

When these management approaches, digital tools, and concerns for stakeholders are integrated, they guide Iraq in reaching better results for its road upkeep and rebuilding. A hybrid strategy—blending the structure of PMBOK or PRINCE2 with the adaptability of Agile, supported by real-time GIS-AI platforms and participatory planning—offers the most promising pathway toward resilient and sustainable infrastructure outcomes in the Iraqi context.

Table 2 Summary of project management solutions for road infrastructure in Iraq

Solution Type	Approach/Tool	Description and Relevance to Iraq
Project Management Framework	PMBOK (Project Management Body of Knowledge)	Offers a structured approach through the process groups and knowledge areas. Helps manage risks,

		timelines, costs, and quality in Iraq's volatile infrastructure environment.
Project Management Framework	PRINCE2 (Projects I N C o n trolled Environments)	Focuses on accountability, stage-based control, and product-focused planning. Supports public sector needs for transparency and governance in Iraq.
Project Management Methodology	Agile	Provides flexibility and iterative planning for complex and changing environments. Suitable for modular and pilot road maintenance efforts in Iraq.
Technological Tool	GIS (Geographic Information Systems)	Enables spatial analysis, road mapping, and prioritization of maintenance zones. Helps in planning and environmental assessments.
Technological Tool	AI (Artificial Intelligence)	Facilitates predictive maintenance, resource optimization, and delay forecasting. Useful in Iraq for augmenting capacity and automating decision-making.
Stakeholder Engagement	Stakeholder Circle, Salience Model	Identifies, maps, and prioritizes stakeholders based on influence and interest. Supports inclusive planning and reduces conflict in fragmented Iraqi contexts.
Hybrid Strategy	Integrated Application of PM- BOK/PRINCE2 with Agile and Technology	Combines structure, flexibility, and innovation. Enhances project delivery, monitoring, and sustainability of Iraq's road infrastructure reconstruction.

Figure 1 illustrates a conceptual flowchart summarizing the key pillars of effective project management strategies for road infrastructure projects in Iraq. The diagram is structured into three main categories:

- **Traditional Framework:** This component is represented by a hierarchical icon, referring to structured methodologies such as PMBOK and PRINCE2. These frameworks guide scope, time, cost, and quality management within infrastructure projects.

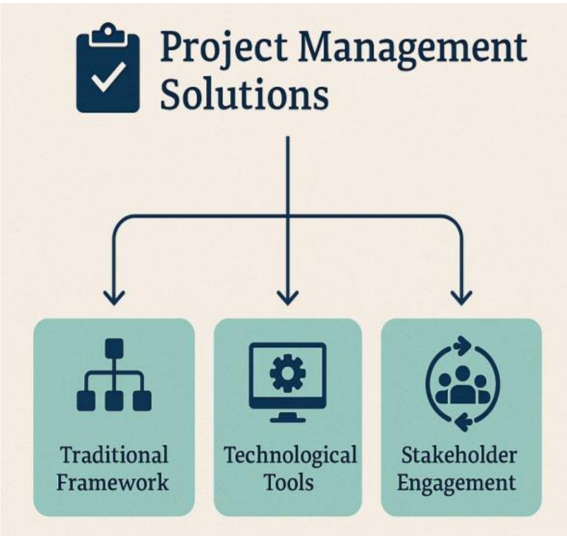

Figure 1 Project management solutions

- **Technological Tools:** Illustrated with a gear-and-monitor symbol, this category emphasizes the integration of Geographic Information Systems (GIS) and Artificial Intelligence (AI) to support predictive maintenance, spatial analysis, and resource optimization.
- **Stakeholder Engagement:** Indicated by a circular people-centered icon, this area focuses on participatory planning and collaborative decision-making using stakeholder identification and engagement models to enhance transparency and community involvement.

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The flowchart captures the essence of a hybrid management strategy that combines process discipline, digital innovation, and inclusive governance to overcome the unique challenges of post-conflict infrastructure reconstruction in Iraq.

5 Results and discussion

Assessment of the suggested project-management solutions, including frameworks, technological integration, and stakeholder interaction, shows a strong fit between internationally accepted best practices and urgent requirements of the Iraqi road-maintenance industry. Holistically, a combination of PMBOK, PRINCE2, Agile approach, GIS and AI tools, and participatory engagement models can create a powerful and flexible system of infrastructure reconstruction. However, the success of these solutions depends on the institutional readiness of Iraq, socio-political stability, and capacity to implement.

The practices that contribute to the quality of information flow (with more comprehensible designs, reviews of stage-gate and digital quality assurance/quality control) are related to fewer rework, less change orders, stabilisation of financial flows (exhibited by the reduced variation in the progress payment and claims), as well as minimisation of material wastage in synthesised case studies and empirical findings. Guided staging and routing of asphalt and aggregate materials, made possible by GIS, reduce the cycle time of asphalt and aggregate products, leading to material-flow reliability and productivity of the site. At the same time, Agile cadence enhances human resource coordination (crews, inspectors) through disturbed access and security restrictions.

Structured frameworks, like PMBOK and PRINCE2, offer critical components of project governance, like clear processes and risk control, and role definition. Their implementation has the capacity of significantly decreasing inefficiencies and fragmentation in the Iraqi system of infrastructure delivery whereby projects are often characterized by slow schedules, scope ambiguities and contractual wrangles. Despite the fact that these frameworks have worked well in many other international settings, their implementation in Iraq has been inconsistent and superficial in many instances. According to interviews and field reports, formal compliance with such structures may be observed in documentation of the project but planning and implementation processes are often compromised with political interferences, lack of professional staff, and lack of coherent monitoring systems.

The flexibility of Agile method is a very important continuation to the conventional approaches especially in pilot or modular road -maintenance projects where flexibility and change responsiveness are of paramount importance. The iterative format of planning, feedback of Agile and the user-centered ideology may be particularly useful in the volatile situation in Iraq where field conditions are constantly different to initial plans. Nonetheless, the cultural change that is necessary to adopt Agile principles, including decentralisation of power and encouragement of real-time feedback on the stakeholders, is not well developed in the bureaucratic sphere of Iraq.

Another enabler of efficiency and transparency with high potential is technological tools such as GIS and AI. GIS is capable of supplementing spatial planning, real-time monitoring of the project, and prioritising interventions using current data. The AI-based models can also assist with predictive maintenance and analyse data automatically, thus overcoming the ongoing poverty of the Iraqi market in qualified planners and analysts. However, the implementation of these tools in practice is limited by the limited digital infrastructure, lack of stability in the availability of data, and the low level of digital literacy of technical personnel of local agencies. The realisation of the full potential of those technologies is thus dependent, to a great degree, on investment in staff training, integration of these systems, and governance of data.

Stakeholder engagement models have turned out to be critical in the social acceptability of projects. Since infrastructural development projects in Iraq tend to overlap with the interests of ethnic, tribal, and political structures, they should consider this by including everyone to minimize the risk of conflict and create equalized benefits distribution. The Stakeholder Circle and Salience Model helps the planners find the essential actors, address the expectations, and encourage the participation. Practically, though, the participation of Iraqi road projects remains fairly infrequent, with the majority of it being the official postulates and short-term consultations, which pay no attention to the actual needs of the local people. This lack shows that there is urgent need to have more powerful reforms and more civic education so that participatory planning can grow to be an occasion rather than a practice.

The gap between theory and practice can be investigated and with the help of the gap, one can find that the difficulties are caused by the limited nature of the environment of the post-war government of Iraq and not by the lack of plans. The very presence of a universal model has nothing to do with success on the ground instead, contextual adjustments, well-built government backing and long-term investments are necessary to empower institutions. New project-management solutions are impossible without the reform of the procurement, mitigation of corruption, and the inter-agency communication problems.

In general, the analysis highlights the importance of the hybrid methodology that incorporates PMBOK, PRINCE2, Agile methodology, digital tools and stakeholder involvement. The most important consideration by Iraq is ensuring the practical application of these methodologies in consideration of the governance structures, capacity building and the development of trust by the people in the system. The gap between the desired results and the real performance requires both the technological improvements as well as the systemic changes on a deeper level.

6 Conclusion

The reconstruction of the Iraqi road system is a multidimensional project, which is not limited to engineering factors, but also covers the aspects of governance, financing, institutional coordination, and collecting the stakeholders. This study focused on the localization of the proven project management frameworks to reduce coordination failures and change-order risks, as well as the extent to which they can be optimized to include logistics and the digital technologies to increase the reliability of processes and efficiency of delivery. Comparative analysis showed that the successful adaptation of these frameworks in Iraq is dependent on four interconnected strategic dimensions: (1) strengthening of institutional integration and alignment of governance between national and provincial agencies; (2) the integration of the logistics-based flow management to coordinate the material, information, financial, and human resources; (3) the use of the digital platform, including GIS and AI to support a data-driven decision-making process and predictive project control; and (4) the institutionalization of the participatory stakeholder mechanisms that promote transparency and accountability in procurement and delivery. The combination of these strategic dimensions deals with the gap in implementation between international standards and domestic practice, the cause of which is a weak governance system, divided responsibilities, and limited technical capacity. The empirical evidence supports a hypothesis according to which a hybrid, localized project-management-logistics structure can be identified to have a significant positive influence on the coordination reliability and performance of a project in comparison with traditional methods.

As a sustainable development step, Iraq needs to develop management skills in existing state institutions, put in place interoperable digital planning and monitoring, and restructure regulatory processes in a way that creates a sense of transparency and joint agency. The other aspect that is significant is the nature of participatory engagement that has been embedded within the project lifecycle to enhance legitimacy and community ownership. Through these strategic dimensions operationalized, Iraq can cease the ad hoc reconstruction operations and move on to an integrated system of infrastructure governance- an order that is consistent with the worldwide project management rules and local logistical facts. By doing so, the nation will be able to convert its road network into a robust platform to economic recovery, connectivity in the region, as well as long term national development.

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A slack-based MSME development model: a strategic solution to improve business performance and growth

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Keywords: logistics resources, manufacturing smes, organizational performance, resource slack, sustainable logistics innovation.

Abstract: This study investigates how resource slack supports logistics-dependent business systems and influences organizational performance and growth in manufacturing SMEs operating in supply and distribution environments. It specifically examines the mediating roles of organizational resilience and sustainable logistics innovation, as well as the moderating roles of organizational learning and logistics resources. A quantitative research approach was employed, with data collected from 100 manufacturing SMEs operating in resource-constrained yet logistics-intensive environments. Structural equation modeling (SEM) was used to analyze both the direct and indirect effects of resource slack on organizational performance and growth. The results reveal that resource slack positively affects organizational performance both directly and indirectly through sustainable logistics innovation, while its indirect effect through organizational resilience is rejected. Sustainable logistics innovation is shown to be a key driver of business growth by leveraging slack resources for eco-efficient packaging, transport optimization, and distribution agility. Moreover, organizational learning strengthens the effect of resource slack on organizational resilience, while logistics resources amplify the effect of resource slack on sustainable logistics innovation. These findings suggest that SME managers should strategically manage slack resources such as production buffers, warehouse capacity, and supplier relationships to enhance resilience and foster sustainable logistics innovation. This study uniquely integrates slack theory, logistics resource configuration, and sustainability-oriented innovation to explain how SMEs convert slack into competitive advantage under logistics constraints.

1 Introduction

The external environment plays a critical role in shaping the direction and success of small and medium-sized enterprises (SMEs). Factors such as economic conditions, government regulations, technological changes, and socio-cultural trends significantly influence organizational survival and growth [1-3]. Within this context, organizational performance has become one of the most extensively studied dependent variables in management and strategy research [4]. To achieve better performance, SMEs must strategically optimize their resources to align with external demands while maintaining operational flexibility [3]. Choosing the right strategy becomes essential for navigating dynamic environments and achieving business goals [5,6].

From the perspective of the resource-based view [7,8], slack resources can provide the flexibility necessary for SMEs to adapt to change, realign operations, and sustain growth. Slack resources, which is defined as the pool of organizational resources available for redeployment [9], have been shown to support resilience, which enable firms to withstand unexpected disruptions while maintaining stability. In logistics-intensive sectors, such slack may manifest as buffer inventory, extra warehouse capacity, supplier redundancy, or excess transportation capability. These resources provide room for continuous improvement, innovation, and rapid response, especially during periods of turbulence [10].

However, slack resources may also create inefficiencies if not strategically managed [11,12]. Underutilized resources can increase operating costs without adding commensurate value, thereby reducing profitability. SMEs that become complacent with abundant slack may fail to remain responsive to market changes or evolving customer needs.

Furthermore, a lack of pressure to innovate can result in stagnation and weak competitiveness. Prior studies have highlighted that business growth is strongly tied to organizational performance [13], and that complementary factors such as organizational learning and intangible assets play important roles in maximizing the benefits of slack [14]. Organizational learning enhances a firm's capacity to absorb knowledge and adapt to change, while logistics resources, such as supplier relationships and technological capabilities enable firms to generate long-term value.

In the logistics-dependent manufacturing SME sector, slack resources take on particular importance. Limited slack can restrict the ability of firms to innovate in logistics operations [15], adopt digital tools, or expand distribution capacity, while strategic slack utilization can drive resilience and growth [16]. Sustainable logistics innovation, for example, enables SMEs to transform slack resources into eco-efficient practices such as optimized transport routing, green packaging, or reduced energy use in warehouses [9]. Similarly, logistics resources, including IT systems, supplier networks, and relational capital, can amplify the benefits of slack and support sustainable competitiveness [17].

Despite increasing interest in SME resilience and innovation, empirical research integrating resource slack with logistics capability development and sustainable logistics innovation remains limited [18], particularly in manufacturing industry in emerging countries. Existing studies typically examine slack in general strategic or financial terms, without explicitly considering how slack supports logistics flows, supply-chain responsiveness, and eco-efficient distribution systems in SMEs [1,6]. Furthermore, very few studies explore the simultaneous roles of organizational resilience and sustainable logistics innovation as mediating mechanisms, or examine how logistics resources and organizational learning conditions amplify the productivity of slack resources [9,10]. This creates a significant knowledge gap regarding how and when slack becomes an enabler of logistics-based competitive advantage. To address this gap, this study proposes an integrated slack–resilience–logistics innovation framework for manufacturing SMEs operating in logistics-intensive environments. Focusing on SMEs in Bekasi and Cirebon, two major industrial logistics corridors in Indonesia, this research examines how slack resources are transformed into logistics capability, distribution agility, and sustainable performance outcomes, moderated by learning orientation and logistics resource strength. By combining the resource-based view with sustainable logistics and resilience perspectives, this study advances theory by positioning slack not merely as excess resources, but as strategic logistics capital that can catalyze innovation, supply-chain continuity, and long-term growth in resource-constrained SMEs.

2 Literature review

2.1 *Resource-based view*

As stated by [8], resources in an organization include all owned assets, including capabilities, attributes, information, knowledge, and so on. [19] defines them as tangible and intangible assets that are semi-permanently tied to an organization. [20] emphasizes that organizational resources represent important potential in improving business performance and supporting sustainable growth. From the RBV perspective, resource slack can be viewed as potential that can be transformed into competitive advantage. [21] explain that slack is an actual resource surplus that allows an organization to adapt to pressures and adjust to external conditions. As strategic thinking develops, knowledge and logistics-related capabilities are increasingly recognized as critical resources in achieving organizational performance. Thus, the RBV approach is used in this study because it highlights the importance of internal resources owned by the organization, including slack resources and logistics resources, which can provide additional flexibility and capacity to face change. These resources enable SMEs to take advantage of strategic opportunities to improve business performance, strengthen organizational resilience, and foster sustainable logistics innovation [8,19].

2.2 *Resource slack and organizational performance*

[21] define slack as the collection of company resources that exceed the minimum amount needed to produce a given level of output. These excess resources can be either utilized or left unused, depending on organizational needs [12]. Slack can take the form of excess financial, human, material, or technological resources, which may be mobilized to support operational activities. In logistics-dependent SMEs, slack may manifest as inventory buffers, unused production capacity, additional warehouse space, or excess supplier networks that can be strategically allocated to meet market demands. Resource slack provides organizations with the ability to cope with change and adapt to environmental uncertainty [22]. Slack can also motivate managers to reallocate resources and pursue initiatives that enhance performance. By enabling firms to explore new opportunities and strengthen resilience, slack supports long-term competitiveness and sustainable performance [10]. [20] emphasized that slack provides flexibility to address unexpected changes and redirect the organization toward more advantageous directions. Overall, slack allows SMEs to increase responsiveness to market changes, strengthen innovation capacity, reduce operational risks, and improve overall business outcomes. In logistics-dependent contexts, these benefits extend to enhanced supply chain responsiveness, delivery reliability, and customer satisfaction. These arguments provide the basis for the following hypothesis:

H1. Resource Slack is positively correlated with organizational performance.

2.3 The mediating role of sustainable logistics innovation

From the RBV perspective, organizations with greater resources are often considered superior to those with fewer resources [8]. Scholars argue that slack resources can protect organizations by providing flexibility in operations, which in turn enhances performance and supports innovation [11]. [16] highlight that slack is crucial for organizational sustainability because it creates space for experimentation. For example, when firms have surplus capacity, skilled employees, or financial reserves, they can allocate a portion of these resources toward innovative projects or process improvements. In logistics-dependent SMEs, resource slack is particularly important for enabling sustainable logistics innovation. Excess resources can be directed toward eco-efficient practices such as adopting green packaging, optimizing transport routes, reducing energy consumption in warehousing, or implementing digital tracking systems. Such initiatives not only strengthen environmental performance but also improve cost efficiency and responsiveness to customer needs. [23] further notes that slack resources allow organizations to invest in innovative practices, ultimately enhancing overall performance. Therefore, sustainable logistics innovation acts as a key mechanism through which resource slack contributes to organizational performance. By channeling slack into logistics-oriented innovations, SMEs can achieve both operational efficiency and long-term competitiveness.

H2. Sustainable logistics innovation mediates the relationship between resource slack and organizational performance.

2.4 The mediating role of organizational resilience

Slack resources within an organization can serve as a reserve asset for the organization to face threats in the business environment. Slack resources can form a significant internal organizational strength, increase operational flexibility and capacity to adapt to change, thereby strengthening organizational resilience [21]. As stated by [21], slack is a collection of resources within an organization that exceeds the minimum required and can be used to improve organizational performance by increasing resilience. [10] state that slack resources function as a reliable buffer to face changes in the business environment and uneven performance flexibility. Furthermore, slack also allows organizations to experiment with innovation without sacrificing operational stability [11]. By leveraging available resources, organizations can increase flexibility and adaptability, ultimately influencing organizational resilience in facing challenges and strengthening organizational performance. Organizational resilience emerges as a determining factor that can optimize organizational performance. Resilient organizations are able to identify, allocate, and utilize available resources effectively in facing challenges. With strong resilience, organizations are not only able to maintain operations during times of crisis but also able to innovate and adapt, thereby improving overall performance.

H3. Organizational resilience mediates the relationship between resource slack and organizational performance.

2.5 Organizational performance and business growth

From a strategic management perspective, the relationship between organizational performance and business growth is a mutually reinforcing one. As stated by [24], superior performance is not only an indicator of success but also a key driver that enables a business to grow sustainably. Organizational performance refers to how effectively an organization meets its goals and objectives [25]. Organizational performance encompasses various aspects, including financial performance, operational efficiency, employee engagement, customer satisfaction, and overall strategic alignment. High organizational performance is required to maintain business growth, as it directly influences the firm's ability to compete. Performance is defined as a set of indicators, both financial and non-financial, which contain information regarding goal achievement and results [4]. He also states that organizational performance encompasses various aspects, including financial performance, operational efficiency, employee engagement, customer satisfaction, and overall strategic alignment. High organizational performance is crucial for sustaining business growth because it directly impacts a company's ability to compete in the market. Performance is defined as a set of indicators, both financial and non-financial, that provide information on the achievement of goals and outcomes. [26] state that organizational performance is the foundation that can determine the direction and success in driving business growth.

H4. Organizational performance has a positive influence on business growth.

2.6 Moderating role of organizational learning and logistics resources

As the business environment changes and competition intensifies, organizations are increasingly aware of the importance of resilience for their survival and growth. In dynamic environments, sufficient resource reserves provide firms with the ability to adapt and endure. From the perspective of the resource-based view, the presence of slack resources enables organizations to engage in learning. Slack provides additional capacity that can be allocated to developing new knowledge, skills, and capabilities [9]. [27] classifies organizational learning into exploitative and explorative modes. Explorative learning encompasses search, risk-taking, and flexibility, while exploitative learning emphasizes refinement, efficiency, and incremental improvement. As a dynamic process, organizational learning allows organizations to continuously adapt based on accumulated knowledge and experience, thereby strengthening their rresilience. In logistics-dependent SMEs, organizational learning is particularly important for developing capabilities such as supply chain coordination, process redesign, and adoption of sustainable logistics practices. This learning capacity strengthens the relationship between slack resources and organizational resilience by leveraging new ideas, supporting innovation, and improving operational efficiency.

H5a. Organizational learning moderates the relationship between resource slack and organizational resiilience, such that the relationship is stronger when organizational learning is high.

[28] emphasized in the strategy literature that resources and capabilities are crucial for building superior performance. In logistics-intensive contexts, logistics resources, such as transportation infrastructure, warehousing capacity, IT systems, supplier and customer relationships, and distribution networks, represent critical capabilities for achieving competitive advantage [17]. These resources not only support operations but also enhance the ability of firms to convert slack into meaningful outcomes. When SMEs possess strong logistics resources, they are better able to channel slack into sustainable logistics innovation [9]. For example, firms with advanced inventory management systems or robust supplier partnerships can use excess capacity to introduce eco-efficient processes, optimize delivery routes, or reduce waste in production and distribution. [23] noted that resource advantages amplify the impact of slack, making it more likely to translate into innovation and performance gains. Therefore, logistics resources serve as strategic enablers that strengthen the connection between slack and sustainable innovation.

H5b. Logistics resources moderate the relationship between resource slack and sustainable logistics innovation, such that the relationship is stronger when logistics resources are high.

Based on the previous studies that have been presented, the model of this research is proposed as follows.

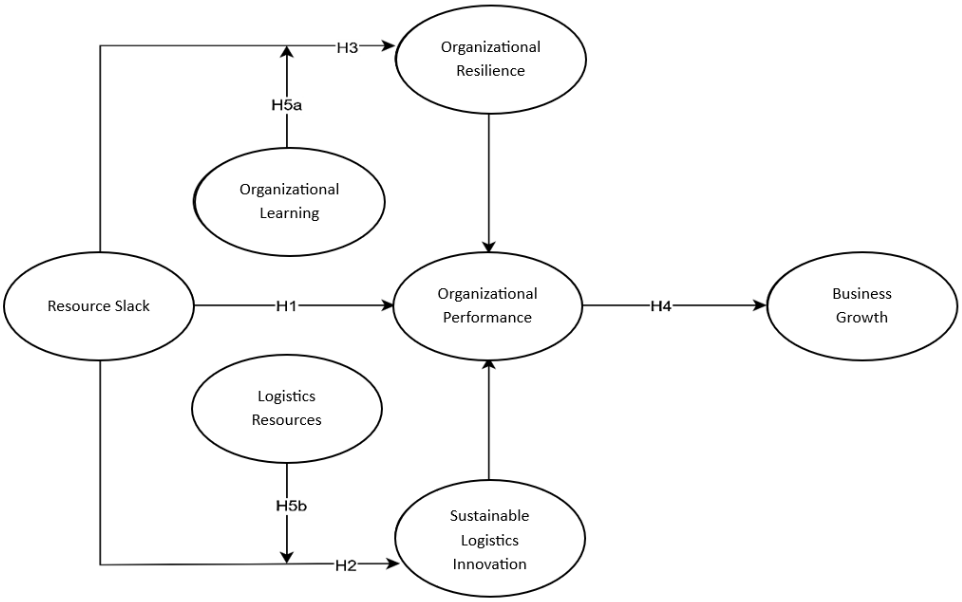

Figure 1 Research model

3 Methodology

3.1 Research design

This study employs a quantitative research design to examine the influence of resource slack on organizational performance and business growth, with organizational resilience and sustainable logistics innovation as mediators, and organizational learning and logistics resources as moderators. Structural Equation Modeling with Partial Least Squares (SEM–PLS) was used to test the hypothesized relationships, as this method is suitable for predictive analysis, complex moderation–mediation models, and exploratory research contexts with relatively small samples. Compared to covariance-based SEM (e.g., AMOS), PLS-SEM was selected due to its robustness for models emphasizing variance explanation and theory development rather than confirmatory fit testing.

The population of this study consists of manufacturing SMEs operating in Bekasi and Cirebon, Indonesia. These SMEs were selected because of their significant dependence on logistics and distribution activities for competitiveness. Respondents were purposively chosen to ensure they met the criteria of (1) being classified as small or medium enterprises according to Indonesian regulations, and (2) engaging in logistics-dependent operations such as supply chain coordination, distribution, or transport-related activities. A total of 100 valid responses were collected and used for analysis.

Data were collected using a structured questionnaire distributed to SME owners and managers. The questionnaire included items measuring resource slack, organizational resilience, sustainable logistics innovation, organizational learning, logistics resources, organizational performance, and business growth. Responses were recorded on a Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). Data were analyzed using SEM–PLS with SmartPLS software. The analysis included evaluating the measurement model (validity and reliability of constructs) and the structural model (hypotheses testing through path coefficients, t-statistics, and R^2 values).

3.2 Variable Measurement

The measurement of variables in this study was adapted from established scales in previous research. Resource slack was measured through indicators reflecting excess capacity, financial reserves, human resource flexibility, and inventory buffers, drawing on the works of [21]. Organizational resilience and organizational performance was evaluated through the indicators developed by (Essuman et al., 2022. To capture sustainable logistics innovation, items were developed to evaluate eco-efficient packaging, energy-saving transport practices, optimized routing, and the reduction of logistics waste, consistent with [16,23]. Organizational learning was measured by incorporating both exploitative and explorative learning processes, such as efficiency improvement, experimentation, and flexibility, based on [27,30]. Logistics resources were measured using indicators related to IT systems, supplier and customer networks, transportation and warehousing capabilities, and distribution infrastructure, in line with [17,28]. Finally, business growth was assessed through measures of revenue growth, market expansion, and increased customer base, following [3].

4 Results and discussion

4.1 Respondents' characteristics

The respondents in this study were drawn from SMEs operating in sectors that are highly dependent on logistics and distribution activities. As shown in Table 1, the majority were engaged in food and beverage (36%), handicraft (21%), and fashion (18%), all of which represent manufacturing-oriented industries with significant reliance on supply chain management, packaging, and distribution to reach domestic and international markets. Other respondents were from agribusiness (8%), which involves perishable goods requiring efficient transport and storage systems, and from creative product (10%) and digital-enabled SMEs (with physical product distribution (8%), which, while less manufacturing-intensive, also rely on logistics processes such as distribution of products, digital platforms, and supporting materials.

Table 1 Respondent profile

Category		Total	Percentage
Type of Industry	Food and Beverage (Manufacturing)	90	36%
	Craft & Artisan Products (Manufacturing)	52	21%
	Fashion & Apparel Production	44	18%
	Digital-enabled SMEs (with physical product distribution)	19	8%
	Agribusiness Processing & Distribution	21	8%
	Creative Product	24	10%
Years of Business Establishment	5 – 10 Years	93	37%
	10 – 15 Years	74	30%
	15 – 20 Years	50	20%
	More than 20 Years	33	13%
Number of Employees	10 – 15 Employees	123	49%
	15 – 20 Employees	96	38%
	25 – 30 Employees	31	12%
Annual Income	100.000.000 – 500.000.000 (IDR)	175	70%
	More than 500.000.000 (IDR)	75	30%

Most of the SMEs had been established between 5-15 years (67%), indicating a relatively mature stage of business development. In terms of firm size, nearly half employed 10-15 workers (49%), with another 38% employing 15-20 workers, consistent with Indonesia's SME classification. Annual income data show that 70% earned between IDR 100,000,000-500,000,000, while 30% reported more than IDR 500,000,000. This profile confirms that the majority of respondents were logistics-dependent manufacturing SMEs that face challenges of resilience, innovation, and competitiveness in dynamic market environments.

4.2 Outer model evaluation

Based on the results of the validity and reliability tests, the construct results show an Outer Loading value above 0.7, meeting the recommended threshold for good indicator validity [31]. The AVE (Average Variance Extracted) value for all variables is above 0.5, indicating that more than 50% of the indicator variance is explained by the related construct, thus achieving convergent validity [32]. Furthermore, the Composite Reliability (CR) value for all variables is higher than 0.7, indicating good internal consistency. In addition, the Cronbach's Alpha and rho_A values are also above 0.7 for all constructs, indicating adequate reliability. Overall, these results indicate that all research variables meet the requirements for validity and reliability.

Table 2 Results of validity and reliability test

Variable	Item	Indicators Outer Loading	AVE	C.R	rho_A	Cronbach's Alpha
Resource Slack	RS1	0.771	0.632	0.873	0.804	0.777
	RS2	0.814				
	RS3	0.792				
	RS4	0.802				
Sustainable Logistics Innovation	SLI1	0.782	0.695	0.901	0.853	0.853
	SLI2	0.871				
	SLI3	0.875				
	SLI4	0.801				
Organizational Resilience	OR1	0.798	0.674	0.892	0.892	0.839
	OR2	0.802				
	OR3	0.839				
	OR4	0.845				
Organizational Learning	OL1	0.734	0.554	0.861	0.861	0.799
	OL2	0.729				
	OL3	0.744				
	OL4	0.770				
	OL5	0.745				
Logistics Resource	LR1	0.718	0.637	0.925	0.925	0.905
	LR2	0.831				
	LR3	0.817				
	LR4	0.804				
	LR5	0.830				
	LR6	0.858				
	LR7	0.718				
Organizational Performance	OP1	0.802	0.618	0.936	0.936	0.884
	OP2	0.798				
	OP3	0.756				
	OP4	0.775				
	OP5	0.785				
	OP6	0.789				
	OP7	0.790				
	OP8	0.810				
	OP9	0.767				
Business Growth	BG1	0.767	0.603	0.820	0.820	0.795
	BG2	0.799				
	BG3	0.763				

Table 3 Discriminant validity with Fornell-Larcker criterion

	BG	LR	OL	OP	OR	RS	SLI
BG	0.745						
LR	0.540	0.798					
OL	0.471	0.521	0.745				
OP	0.733	0.583	0.506	0.725			
OR	0.455	0.507	0.672	0.546	0.821		
RS	0.368	0.330	0.477	0.360	0.578	0.772	
SLI	0.436	0.476	0.665	0.487	0.816	0.630	0.833

Based on the results of the discriminant validation test using the Fornell-Larcker criteria, each construct meets the discriminant validation requirements because the square root value of AVE (diagonal value) of each construct is greater than the correlation between constructs (off-diagonal value). For example, the AVE value of Business Growth (BG) of 0.745 is greater than its correlation with other variables such as Logistics Resources (LLR) (0.540) and Organizational Performance (OP) (0.733). This indicates that each construct is more correlated with its own indicators than with other constructs, thus meeting the discriminant validation criteria. Thus, each variable in this model is considered sufficiently distinguishable from other variables.

Table 4 Heterotrait-Monotrait (HTMT)

	BG	LR	OL	OP	OR	RS	SLI
BG							
LR	0.726						
OL	0.688	0.601					
OP	0.761	0.640	0.602				
OR	0.632	0.561	0.816	0.631			
RS	0.520	0.367	0.590	0.422	0.695		
SLI	0.596	0.524	0.801	0.556	0.213	0.287	

The results of the HTMT (Heterotrait Monotrait) test show that all HTMT values between constructs are below the recommended threshold of 0.85 for good discriminant validity [33]. For example, the HTMT value between Business Growth (BG) and Logistics Resources (IR) is 0.726, and between Organizational Learning (OL) and Organizational Resilience (OR) is 0.816, both of which are still within acceptable limits. Since no HTMT value exceeds 0.85, this indicates that each construct in this model can be well distinguished from the others, thus achieving discriminant validity.

Table 5 Inner VIF multicollinearities

	BG	LR	OL	OP	OR	RS	SLI
BG							
LR							1.143
OL					1.294		
OP	1.000						
OR				3.556			
RS				1.677	1.337		1.177
SLI				3.923			

The results of the Inner Variance Inflation Factor (VIF) test show that all VIF values are below the recommended threshold of 5.0, except for the relationship between Sustainable Logistics Innovation (SI) and Organizational Resilience (OR) which has a VIF value of 3.923 and 3.556 but is still within acceptable limits [31]. The VIF value indicates that there is no significant multicollinearity problem in the model, meaning that no independent constructs are highly correlated with each other. For example, the VIF value for Resource Slack (RS) against Organizational Resilience (OR) is 1.677 which is still relatively low, indicating low multicollinearity and independent variables do not interfere with each other. Overall, multicollinearity in this model does not interfere with the quality of the estimation results.

4.3 Inner model evaluation

The R Square test results show that the variables Business Growth (BG), Organizational Performance (OP), Organizational Resilience (OR), and Sustainable Logistics Innovation (SI) have varying values. The R Square of 0.537 for Business Growth indicates that 53.7% of the variation in Business Growth can be explained by Organizational Performance. This value is classified as moderate [31]. The R Square for Organizational Performance of 0.302 indicates that 30.2% of the variation in Organizational Performance is explained by the model, which is classified as a weak to moderate influence. Meanwhile, OR has an R Square value of 0.539 which indicates a moderate influence with 53.9% of the variation in Organizational Resilience explained by other variables. Finally, Sustainable Logistics Innovation has an R Square value of 0.508 which indicates that 50.8% of the variation in Sustainable Innovation can be explained by the model. Overall, these results indicate that the model has moderate predictive ability towards the dependent variable, in accordance with the accepted threshold in the PLS-SEM model.

Table 6 R square

	R Square	R Square Adjusted
Business Growth	0.537	0.535
Organizational Performance	0.302	0.294
Organizational Resilience	0.539	0.534
Sustainable Logistics Innovation	0.508	0.502

Table 7 Q square

	SSO	SSE	Q^2(=1-SSE/SSO)
Business Growth	753.000	537.322	0.286
Organizational Performance	2259.000	1925.751	0.148
Organizational Resilience	1004.000	652.265	0.350
Sustainable Logistics Innovation	1004.000	671.322	0.331

The Q Square (Q^2) test results show the model's predictive ability. Based on the Q^2 value, Business Growth (BG) has a Q^2 value of 0.286, indicating that the model has moderate predictive ability for this variable [31]. For Organizational Performance (OP), a Q^2 value of 0.148 indicates weak predictive ability. Meanwhile, Organizational Resilience (OR) has a Q^2 value of 0.350, indicating a fairly strong prediction. Lastly, Sustainable Logistics Innovation (SLI) shows moderate predictive ability with a Q^2 value of 0.331. In general, a Q^2 value above 0 indicates that the model has predictive relevance, where a value between 0.02 and 0.15 indicates weak prediction, 0.15 and 0.35 indicates moderate prediction, and above 0.35 indicates strong prediction.

Table 8 Results of Hypothesis Test

Hypothesis	Path	Beta	T-Value	Sig.	Decision
H1	RS → OP	0.554	6.774	0.000	Accepted
H2	RS → SLI → OP	0.329	5.711	0.000	Accepted
H3	RS → OR → OP	0.051	1.064	0.324	Not Accepted
H4	OP → BG	0.733	27.809	0.000	Accepted
H5a	RS x OL → OR	0.438	7.840	0.000	Accepted
H5b	RS x LR → SLI	0.169	3.767	0.000	Accepted

The results of the hypothesis testing indicate that most hypotheses are accepted with a high level of significance. H1 tests the relationship between resource slack (RS) and organizational performance (OP) with a beta value of 0.554 and a T value of 6.774, indicating a significant positive influence ($p < 0.001$). H2 shows that sustainable logistics innovation (SLI) mediates the relationship between RS and OP with a beta of 0.329 and a T-value of 5.711 ($p < 0.001$). However, H3 which tests the mediation of organizational resilience (OR) is not significant (T-value 1.064, $p > 0.05$), so the hypothesis is rejected. H4, the relationship between organizational performance and business growth (BG), is highly significant with a beta of 0.733 and a T-value of 27.809. The moderating role of organizational learning (OL) in H5a is significant with a beta of 0.438 and a T-value of 7.840, and the moderating role of logistics resources (LR) in H5b is significant with a beta of 0.169 and a T-value of 3.767 supporting the argument that organizational learning and logistics resources strengthen the relationship between RS and innovation outcomes, as well as organizational resilience.

4.4 Discussion

This study employs the RBV approach of [8,20] to examine the influence of resource slack on organizational performance and its impact on business growth by considering the mediating roles of sustainable logistics innovation and organizational resilience. It further examines the moderating roles of organizational learning and logistics resources. Consistent with prior studies, resource slack can act as a reserve that enables organizations to innovate, adapt to environmental changes, and improve operational efficiency, ultimately contributing to SME performance [12]. The findings of this study support those of [10], who argued that unused resources can be leveraged to improve efficiency and innovation, thereby enhancing overall performance (H1). In the case of logistics-dependent SMEs, slack takes the form of unused production capacity, reserve funds, or underutilized labor, which can be mobilized to strengthen supply chain responsiveness, packaging, and distribution processes. Based on these findings, SMEs that manage slack effectively are able to optimize logistics and internal processes, ultimately improving competitiveness and performance. The results further indicate that sustainable logistics innovation mediates the relationship between resource slack and organizational performance (H2). As [16] suggest, slack is a valuable antecedent of sustainable innovation. When slack is directed toward eco-efficient logistics practices such as optimized transportation, waste reduction, or green packaging, it enhances operational performance while supporting sustainability goals. In other words, slack resources allow SMEs to experiment with logistics process improvements that translate into performance gains. However, excessive slack may sometimes reduce the pressure to innovate, leading to complacency. This finding reflects the dual role of slack: while it creates opportunities for sustainable logistics innovation, it must be strategically managed to avoid inefficiency.

Contrary to expectations, the results show that organizational resilience does not strongly mediate the relationship between resource slack and organizational performance (H3). This differs from prior research, such as [10], which found resilience to be a strong pathway. In this study, slack itself appears sufficient to directly enhance organizational performance without relying on resilience as a mediator. This suggests that manufacturing SMEs with adequate slack can adapt effectively to disruptions and restore operations without necessarily developing resilience as an intermediary capability. As [9] noted, absorbed slack—such as reserve funds or additional workforce capacity—can directly support flexibility and responsiveness, reducing the need for resilience to act as a primary channel.

The study also confirms that organizational performance has a significant impact on business growth (H4). This finding supports prior work suggesting that SMEs that exploit opportunities in the external environment are more likely to achieve growth [29]. High performance allows firms to leverage new technologies, strengthen logistics partnerships, and respond to market changes with agility, thereby driving business expansion. The results align with [26] and [34], who emphasized that organizational performance includes both financial and non-financial aspects, which collectively foster sustainable business growth.

Finally, this study highlights the moderating roles of organizational learning and logistics resources (H5a and H5b). The results show that organizational learning strengthens the impact of resource slack on organizational resiilience. Through learning, SMEs can transform slack into valuable logistics and operational improvements. Continuous learning enables firms to analyze logistics bottlenecks, adopt digital supply chain tools, and implement adaptive distribution strategies. This finding reinforces the importance of learning as a dynamic capability that allows firms to adapt, innovate, and strategically reallocate slack.

Similarly, logistics resources emerge as an important moderator of the relationship between slack and sustainable logistics innovation. SMEs with well-developed logistics resources such as transportation systems, warehousing capacity, supplier relationships, and IT platforms, are more effective in channeling slack into innovative logistics practices. These resources provide the infrastructure and networks necessary for slack to translate into green and efficient logistics solutions. Consistent with [23], this study confirms that resources enhance the effectiveness of slack by enabling its conversion into sustainable logistics innovation. Therefore, logistics resources serve as a crucial capability that amplifies the strategic value of slack and strengthens SME competitiveness.

5 Conclusion

Although the relationship between organizational performance and business growth has been widely examined in the literature, this study highlights the importance of specific logistic drivers, namely resource slack, sustainable logistics innovation, organizational resilience, organizational learning, and logistics resources, that play a crucial role in strengthening SME performance and driving business growth. The findings underscore that in logistics-intensive environments, the strategic management of slack resources supports smoother material, information, and distribution flows, allowing firms to remain agile and competitive. By leveraging slack resources, SMEs can achieve greater flexibility in adapting to market dynamics, while also fostering innovation and resilience that ultimately encourage growth. This study concludes that effective slack utilization, sustainable logistics innovation, and learning capabilities are essential for enhancing performance and sustaining competitiveness in supply chain industries.

From a theoretical standpoint, this study enriches the resource-based view (RBV) by demonstrating that slack resources should not only be seen as buffers in uncertain conditions but also as enablers of sustainable logistics innovation, resilience, and growth. These findings extend RBV by showing how slack resources, when combined with logistics resources (e.g., warehousing capacity, transportation assets, supplier relationships, and IT-enabled logistics systems) and organizational learning, can be transformed into dynamic capabilities that sustain performance in logistics-dependent SMEs.

The study also carries important practical implications. SME managers should recognize that resource slack such as excess capacity, inventory buffers, or reserve funds can be strategically redirected to improve logistics operations and foster sustainable innovation. Strengthening organizational learning and investing in logistics resources, including IT systems, warehousing, and supplier networks, will allow firms to convert slack into tangible performance improvements. Policymakers and SME support institutions should also design interventions that help firms build logistics capabilities and resilience, as these are critical foundations for competitiveness and sustainable growth in manufacturing sectors.

Finally, this study has several limitations that open avenues for future research. The research was conducted with a specific sectoral sample of manufacturing SMEs in Indonesia, which may limit generalizability to other industries or regions. Future studies could explore additional industries, apply longitudinal or mixed-method designs, or examine complementary constructs such as digital supply chain readiness, logistics technology adoption, circular supply chain practices, and logistics policy support. Such research would provide more comprehensive insights into how SMEs can leverage slack resources to thrive in dynamic and logistics-intensive environments.

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Sustainability evaluation of material handling machines in intralogistics: a simulation-based approach

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Keywords: intralogistics, material handling, sustainability, simulation.
Abstract: As sustainability becomes a strategic imperative in industrial operations, a comprehensive evaluation of material handling equipment's environmental, economic, and social impacts is essential. This study proposes a novel simulation-based framework to assess and compare the sustainability performance of forklifts and Automated Guided Vehicles (AGVs) in warehouse-to-assembly line operations. Leveraging the Triple Bottom Line (TBL) approach, we integrate technical, environmental (e.g., energy consumption, GHG emissions), economic (operational costs), and social (ergonomics) indicators into a unified evaluation model. Using Siemens Tecnomatix Plant Simulation, we model an automotive intralogistics scenario where components are transported from the warehouse to the assembly stations. Our results reveal that AGVs outperform forklifts in terms of energy efficiency (44% lower consumption) and scalability, but exhibit higher idle times (46.11%). In contrast, forklifts offer greater operational flexibility. The study presents a replicable methodology for dynamic sustainability assessment in intralogistics and provides actionable insights for technology selection, demonstrating how trade-offs between automation and social-centric systems influence sustainable outcomes in manufacturing environments.

1 Introduction

Intralogistics refers to the transportation, storage, and handling of materials within a facility, and is crucial for the efficiency of supply chain operations [1]. As global sustainability becomes increasingly important, the intra-logistics sector must adopt eco-friendly methods that optimize resource utilization while maintaining financial stability in the long run. Improving the sustainability of material handling helps companies meet their social responsibility goals while lowering costs, increasing efficiency, and gaining a competitive edge [2,3]. Moreover, the implementation of advanced technologies such as the Internet of Things (IoT), big data analytics, and artificial intelligence (AI) enables real-time oversight and enhancement of material handling procedures [4]. These technologies facilitate predictive maintenance, enhance inventory management, and improve the accuracy of route planning. This reduces unnecessary movement and energy consumption. IoT sensors can monitor the usage of material handling equipment, allowing for quick repairs, preventing equipment breakdowns, extending its lifespan, and reducing the need for replacements. This is good for the environment.

In the automotive sector, the transportation of supplies from warehouses to automobile assembly plants is a crucial component of the manufacturing process [5]. The efficacy of this procedure directly influences production flow, inventory precision, and system responsiveness [6]. Forklifts and Automated Guided Vehicles (AGVs) are integral to this process. When determining their placement, one should consider not just their mobility but also their influence on other sustainability metrics. A multitude of researchers and practitioners employ the Triple Bottom Line (TBL) framework to obtain a comprehensive understanding of sustainability. This concept categorizes sustainability into three primary components: economic, environmental, and social. Every component is equally vital for attaining equilibrium and enduring influence [7]. The economic aspect examines how long a system can remain financially stable. It focuses on aspects such as low startup costs, energy-efficient operations, and reduced maintenance costs for material handling equipment. The ecological or environmental aspect is about doing the least amount of damage to the planet. This includes reducing emissions when getting raw materials, making equipment easier to recycle, and making parts that are stronger

[8]. The social dimension examines how people utilize technology and systems, considering factors such as safety, comfort, and job satisfaction. In recent years, an increasing number of people have come to realize that protecting the environment often yields better social and economic outcomes. This illustrates the profound connection between these two areas and the crucial importance of being environmentally responsible in achieving full sustainability [9].

Sustainability in warehouse material handling is acknowledged as essential for enhancing operational efficiency and mitigating environmental damage [10]. Recent studies [11,12] mainly concentrate on general logistics performance or particular operational measures, frequently overlooking thorough sustainability assessments for specific material handling operations. This mismatch is especially apparent in contemporary warehouses, where automated technology, such as forklifts and AGVs, is increasingly prevalent. Despite the growing use of these devices, a rigorous framework for assessing them across various sustainability dimensions, technical, environmental, economic, and social, remains absent. Moreover, despite the extensive use of simulation tools for performance analysis, their full potential to enhance sustainability-focused decision-making in intralogistics has yet to be realized. This work presents a simulation-based evaluation system designed to assess the sustainability performance of material handling devices, specifically forklifts and AGVs, within the warehouse-to-assembly-line process. We utilize Siemens Tecnomatix Plant Simulation to construct the simulation model. This study examines the system outlined in section 5, namely the transportation of components from a warehouse (source) to an automotive assembly plant. This study presents a comparative analysis of forklifts and AGVs across various operational contexts, utilizing a comprehensive sustainability framework that encompasses technical, environmental, economic, and social factors. The findings offer actionable insights that support data-driven approaches to improve sustainability in various production settings.

2 Literature review

Intralogistics, which focuses on managing material flows within manufacturing facilities, has experienced remarkable changes with the rise of Industry 4.0 [13]. The introduction of digital technologies has led to the development of smart warehouses and factories, where interconnected systems work together to boost operational efficiency and adaptability [14]. This evolution is often referred to as "Warehouse 4.0," highlighting the utilization of innovations such as the Internet of Things (IoT), cyber-physical systems (CPS), and autonomous robots to enhance warehouse operations. These advancements enable real-time data collection, improve decision-making processes, and optimize resource use, ultimately streamlining intralogistics activities. However, despite these advancements, the integration of sustainability evaluation within such digitalized intralogistics environments remains limited, with most studies focusing primarily on productivity and automation performance rather than holistic sustainability outcomes. For example, a study by [15] focused on improving Automated Storage and Retrieval Systems (AS/RS) through the development of an innovative shuttle vehicle equipped with an integrated picking mechanism. While this system enhances operational efficiency and reduces manual labor, its broader sustainability implications, such as energy usage and life cycle impacts, remain underexplored. Similarly, Venkatadri and Murrenhoff [16] identified the need for a comprehensive framework that incorporates multiple decision-making layers and demonstrated how AI techniques, such as supervised learning and computer vision, can enhance operational efficiency. By emphasizing the value of human collaboration and aligning with the principles of Industry 5.0, the study highlights the role of AI in improving adaptability and innovation in modern logistics environments. Yet, such frameworks often lack explicit environmental or social evaluation metrics. Further studies by [13,17] explored the application of AI in managing internal material flows and echoed the call for structured frameworks that integrate intelligent technologies while maintaining a strong focus on socially centered design.

Material handling machinery is essential for enterprises and industries. Initially, they may appear markedly unlike; yet, a more thorough examination reveals numerous structural and functional commonalities. According to their structure and use, they can be categorized into approximately 15-20 principal varieties, including cranes. The precise quantity may vary according to expert categorizations of particular subtypes (for instance, the distinction between traveling and jib cranes). Figure 1 illustrates a method for assembling several types of material handling machinery**.** The method of material movement is a critical aspect that distinguishes material handling equipment. This is defined by the handling method, which fundamentally shapes the machine's structure and function. There are four primary methods used in material handling systems [18]:

- Mobile handling units – Goods move on mobile machines; the machine itself defines movement characteristics like speed and route.
- Loading arms – Typically used for short distances, these fixed systems have rotating arms mounted to a wall or floor, equipped with grippers or hoists.
- Transport channels – These fixed or moving systems provide structured pathways for goods, often relying on gravity or other machines for loading/unloading.
- Tractive element systems – Goods are placed on transport carriers (e.g., plates, hangers) pulled along a line by chains, cables, or wheels.

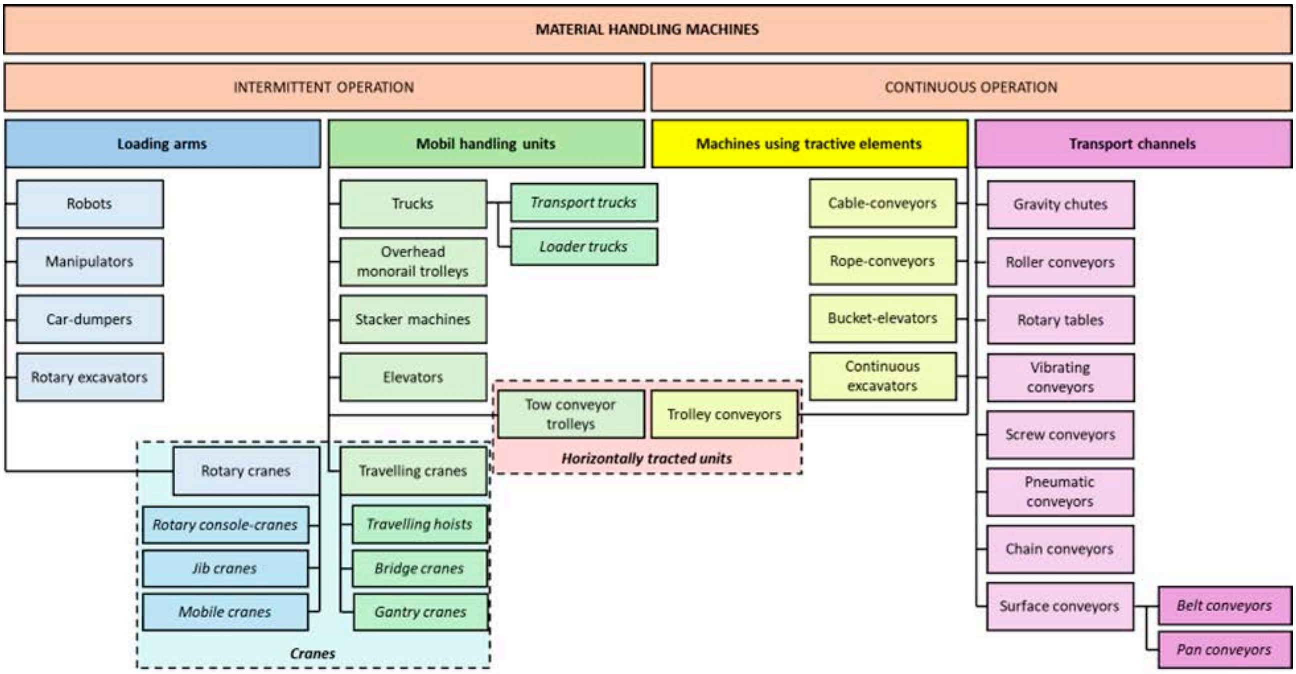


Figure 1 Overview of the main types of material handling machines

Mobile handling units and mobile cranes pose significant sustainability challenges. Mobile devices, on the other hand, require onboard power sources, such as batteries or internal combustion engines. This raises environmental concerns about emissions and resource use. Fixed systems, on the other hand, are usually powered by electricity and used indoors. Material Handling Equipment (MHE) is gaining more attention due to its environmental, economic, and social impacts, as well as its operational efficiency. This is because sustainability is becoming more important in industrial operations. People have used traditional methods, such as Life Cycle Assessment (LCA), to evaluate how these systems impact the environment. For instance, Vujicic [19] conducted a comparative study of diesel and electric cargo-handling machinery in port environments, demonstrating that electric alternatives significantly reduce greenhouse gas emissions, while Erkayaoğlu and Demirel [20] highlighted the context-dependent nature of sustainability assessments by showing that while belt conveyors had greater climate-related impacts, they also had lower acidification than mining trucks. These findings underscore the necessity of scenario-specific and system-oriented evaluation. Building on this, researchers have developed a structured framework that integrates multiple sustainability dimensions, typically organized in tabular or multi-criteria formats, to assess trade-offs across technical, environmental, economic, and social domains. A notable example is [21], who proposed a comprehensive framework for assessing the environmental and social sustainability of logistics halls. Their study addressed a critical gap in the application of Life Cycle Sustainability Assessment (LCSA) within the construction and logistics sectors by incorporating metrics such as worker safety and community impact alongside environmental considerations. This integrative approach offers a valuable foundation for extending sustainability evaluation into other domains of intralogistics.

Further [22] introduced a reverse logistics framework promoting modularity and reusability in MHE to minimize waste and extend equipment lifespan, while [23] advocated for holistic sustainability models that move beyond isolated environmental metrics by embedding social and economic indicators to support more balanced, long-term decision-making in logistics and manufacturing systems. Despite these contributions, current frameworks largely remain static and design-oriented, lacking applicability in dynamic operations where real-time factors, such as energy consumption, emissions, and ergonomic performance, fluctuate in response to process conditions. While Nantee and Sureeyatanapas [24] assessed the broader impacts of Logistics 4.0 technologies on corporate sustainability, their approach focuses mainly on static warehouse infrastructures. It lacks the methodological specificity needed to capture energy use, emissions, and ergonomic impacts in real-time, process-driven contexts. Addressing this methodological gap, the present study introduces a simulation-based, multi-criteria evaluation framework that operationalizes sustainability assessment in a discrete manufacturing environment. By comparing AGVs and forklifts within the warehouse to car assembly station, this research advances the practical evaluation of sustainability in the dynamic intralogistics context. Bridging the theoretical framework with measurable industrial applicability.

3 Methodology

3.1 Research design and approach

This study employs a simulation-based research design to evaluate the sustainability performance of material handling machines within intralogistics, with a particular emphasis on the material flow from warehouse operations to car assembly lines (referred to as Process 5). The methodology consists of four main stages: a comprehensive literature review to identify relevant sustainability indicators; schematic modeling of intralogistics operations; implementation of simulation models using Siemens Tecnomatix Plant Simulation 2404; and a structured sustainability assessment based on technical, environmental, economic, and social criteria.

3.2 Description of schematic

Figure 2 illustrates the step-by-step process of assembling a car and the tools used to transport the materials. Pre-assembly: This is the first step in assembling components, where parts and pieces are grouped together before being transferred to the main assembly line. Car Assembly: This is the first step in assembling a car from pre-existing parts and components. The final step is the inspection and quality control, which occurs when the car is assembled. This document provides a comprehensive overview of each step and the associated intralogistics processes. An automotive manufacturing facility's material handling system comprises numerous interconnected intralogistics operations that facilitate the smooth movement of parts and subassemblies from one stage of production to the next. To make things more efficient, reduce manual labor, and facilitate just-in-time manufacturing, each process utilizes a wide range of machines and automation technologies.

Process 1: Transporting raw sheet metal components from the Sheet Metal Factory to the warehouse requires transferring them to the Pre-assembly section. Automated storage and retrieval systems (AS/RS), conveyor systems, AGVs, and towing trucks enable this transfer. These systems ensure a consistent and dependable supply of raw materials to the pre-assembly line, indicating that upstream component preparation is disrupted only when necessary.

Process 2: The transfer of components and supplementary parts from the warehouse to the Pre-Assembly stage. This procedure employs material handling apparatus, including forklifts, automated storage and retrieval systems, and robotic manipulators. Forklifts are primarily used for the transportation of large and heavy objects. AS/RS and robotic arms enhance the storage and retrieval of diminutive components, hence improving inventory management and minimizing human error.

Process 3: Transporting from Sheet Metal Factory to Car Assembly Line: Specific sheet metal components can be transported directly from the mill to the assembly line, thereby bypassing the pre-assembly phase. This is particularly significant for larger components that do not necessitate assembly. Overhead cranes typically transport heavy components, while lightweight or medium-sized components are conveyed by AGVs or towing tractors. This adaptability enhances the modularity and efficiency of the manufacturing process.

Process 4: The transition from Pre-assembly to Car Assembly involves transferring pre-assembled components from the pre-assembly line to the final automobile assembly line. A mix of conveyor belts, robotic arms, automated AGVs, and forklifts is necessary to achieve this. These technologies work together to ensure a consistent supply of components in the primary assembly zone. This facilitates seamless and effective car assembly processes.

Process 5: The transfer of components or subassemblies from the warehouse to the Car assembly line is a pivotal phase in logistics. This procedure employs forklifts, AS/RS, and AGVs to guarantee the timely and accurate delivery of necessary components. This process must be exceptionally efficient to uphold the total manufacturing schedule. This is particularly crucial for punctual deliveries, as any delays can directly affect assembly line operations.

Intralogistics plays a crucial role in ensuring that materials and parts are moved efficiently between the different stages of the car assembly process. The use of various material handling machines, such as conveyor belts, AGVs, forklifts, and AS/RS systems, ensures that each stage is supplied with the necessary components without delay, thereby reducing downtime and increasing overall productivity. Proper synchronization of these intralogistics processes is essential for maintaining a smooth and continuous production flow, ultimately leading to the efficient assembly of the final product, the car.

This study exclusively examines Process 5, the internal material handling operation responsible for transporting components from the warehouse to the vehicle assembly line. The decision to segregate this procedure was grounded in both strategy and pragmatism. In automotive production, Process 5 is crucial since it represents the final stage in intralogistics, preceding the assembly of components in the final assembly process. Assembly lines rely on just-in-time (JIT) and just-in-sequence (JIS) systems; therefore, any inefficiencies or delays can directly impact the assembly line, leading to costly downtime and production losses. Concentrating on this phase enables the identification of critical operational bottlenecks where enhancements can yield considerable benefits. Moreover, Process 5 possesses a well-delineated and reproducible scope, rendering it optimal for high-fidelity simulation with Siemens Tecnomatix Plant Simulation. This regulated setting enables the precise measurement of sustainability metrics, including energy consumption, emissions, and temporal efficiency, particularly when evaluating the performance of AGVs and forklifts. This emphasis addresses a notable deficiency in the literature, as the majority of research examines intralogistics as a whole, rather than the distinct issues posed by each subprocess. From a pragmatic standpoint, Process 5 provides readily available data and operational transparency, enabling accurate modeling and real-world applicability. This paper provides theoretical insights and practical methods for enhancing sustainability in smart manufacturing, with a focus on this crucial link in the logistics chain.

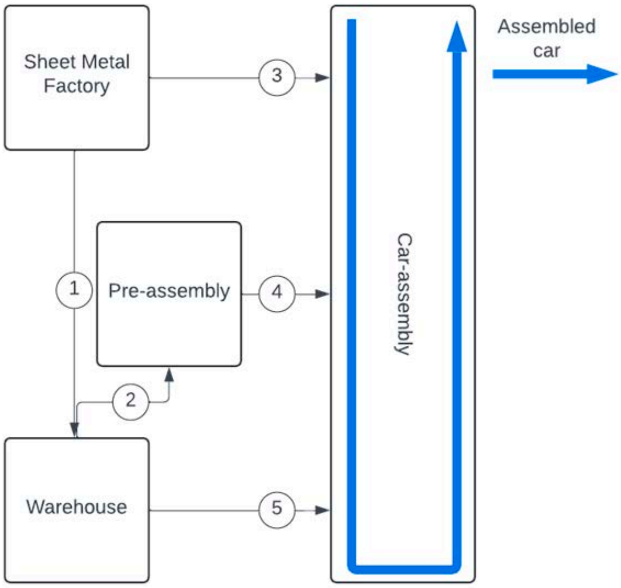


Figure 2 Schematic of car assembly plant

3.3 Simulation environment setup

The simulation environment was constructed using Siemens Tecnomatix Plant Simulation 2404, aligning with [25] methodology for modeling intralogistics in flexible manufacturing systems. Similar to their study, our model is a robust software platform for modeling and analyzing logistics systems and industrial processes, aligning with their research. The primary aim of the model is to replicate Process 5, which involves transferring materials from a Warehouse (source) to several Automobile Assembly Stations (Station 1–Station 4). The emphasis is on employing forklifts and AGVs as the principal intralogistics transporters. In the simulation, forklifts are programmed to retrieve components from a central loading location designated as "PartSequence," representing the warehouse, and thereafter deposit them at designated unloading stations along the assembly line. Each station functions as a distinct auto assembly workplace, with forklifts adhering to a specified routing logic to guarantee prompt and equitable distribution. Key simulation parameters include vehicle routes, travel velocities, handling durations, and protocols governing the interaction between forklifts and workstations. Forklifts are programmed to traverse a circular route and halt at certain locations upon receiving a signal indicating their necessity. The model employs the Methods modules to incorporate control logic that manages task execution and component sequencing. The simulation output panel indicates that comprehensive statistics, including work time and waiting time, are gathered.

3.4 Sustainability evaluation

Sustainability evaluation in warehouse material handling is essential for enhancing operational efficiency while reducing environmental and societal impacts. This study introduces a systematic, simulation-driven evaluation approach that integrates technical, environmental, economic, and social aspects to assess the sustainability performance of material handling systems, particularly AGVs and forklifts. The methodology utilizes Siemens Tecnomatix Plant Simulation and is supplemented by three comprehensive assessment tables that facilitate multidimensional comparisons of handling operations across various production frameworks.

Although prior studies, such as [24] have assessed the impact of Logistics 4.0 on sustainability in automated warehouses, their frameworks primarily address static logistics infrastructures and broader corporate performance indicators. Similarly, previous research like [21] has contributed to the evaluation of environmental and social sustainability within logistics halls. However, these frameworks fall short of offering a directly applicable and operationalized methodology for assessing the real-time sustainability performance of automated material handling systems in dynamic, intralogistics environments.

To address this methodological gap, the present study extends the principles of LCSA into the operational domain of internal logistics. By incorporating a simulation-based, weighted multi-criteria decision-making approach, this research enables the evaluation of critical sustainability indicators, such as energy consumption, GHG emissions, ergonomics, and cost efficiency, based on actual operational performance. This methodological contribution bridges the gap between theoretical sustainability models and the practical needs of manufacturing systems, providing a robust and adaptable tool for sustainability-driven decision-making in material handling operations. Consistent with the methodology of Garbie [26], the relative weights between sustainability dimensions were treated as flexible parameters to analyze different scenarios and their impact on the overall integrated sustainability index.

Table 1 lists various evaluation types and assigns a score to each, reflecting their suitability and risk level. A score of 4 indicates that the equipment is appropriate, operates effectively, and presents no hazards. A score of 1 indicates that the equipment is unsuitable, costly, and poses a significant danger. This approach enables firms to prioritize enhancements to their material handling processes according to identified needs and risks. Table 2 offers a comprehensive examination of the characteristics and categories employed to assess sustainability. Technology, environment, economy, and society constitute these dimensions. The technology dimension examines the machinery utilized, whereas the environment dimension assesses energy consumption and its elasticity in relation to volume change. The economic aspect examines the expenses associated with operating a firm without energy, while the social aspect considers ergonomics, which is crucial for employee safety and comfort.

Table 1 Categories

Value	**Categories**					
	A	B	C	D	E	F
4	Well-suited Equipment	Excellent	very small	very low	Excellent	Zero Risk
3	Minor Modification	Good	Small	Low	Good	Low Risk
2	Major Modification	Fair	Medium	Medium	Fair	Medium Risk
1	Not Suitable	worst	High	High	worst	High Risk

Table 2 Categories and criteria

Dimensions	**Categories**
Technology	A. Machine types
Environmental	B. Energy Consumption
	C. Greenhouse Gas Emission
	D. Elasticity of Energy on Volume Change
Economic	E. Operational Cost without energy consumption
Social	F. Ergonomics

Table 3 categorizes transportation-type material handling equipment into four performance tiers, ranging from Level 1 (Worst) to Level 4 (Excellent). These values are determined by daily energy use (measured in joules) and operational expenses, excluding energy expenditures. The emphasis is on labor and maintenance expenditures. This methodology enables a comprehensive evaluation of the equipment's efficiency, economic implications, and potential avenues for improving environmental sustainability. The data in the table is based on hypothetical operational scenarios and standard specifications prevalent in the industry, including typical power ratings, duty cycles, manpower demands, and maintenance schedules. These assumptions aim to delineate realistic operational parameters for prevalent transportation equipment, including forklifts, tow trucks, and AGVs. The specific values may fluctuate based on the context, but the levels provide a systematic and comparable method for evaluating equipment performance in sustainability-oriented decision-making. Organizations can perform a thorough examination of their material handling procedures by integrating these tables into the evaluation framework. This systematic method not only identifies avenues for enhancing performance but also ensures that daily operations align with overarching sustainability objectives. Processes that consume excessive energy or generate elevated greenhouse gas emissions can be enhanced or altered, for instance, by transitioning to machinery that utilizes reduced energy. Moreover, social factors, especially ergonomics, are essential for ensuring worker safety and well-being. By emphasizing ergonomic design in material handling equipment, organizations can reduce the risk of injuries, increase productivity, and create a more favorable work environment.

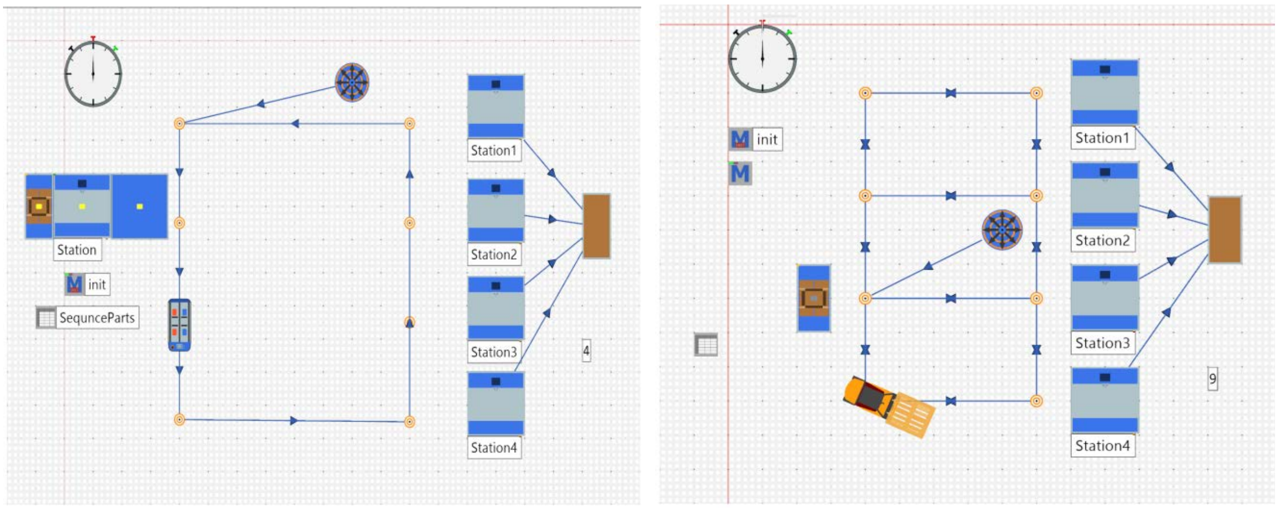
Table 3 Evaluation of Energy Consumption and Operational Cost, excluding energy consumption

Performance Level	Energy (J/day)	Labor (€)	Maintenance (€)	Op. Cost excl. Energy (€)
Level 1 (Worst)	more than 9.75×10^6	220	70	201-290
Level 2 (Average)	6.26×10^6 - 9.75×10^6	150	50	126-200
Level 3 (Good)	3.26×10^6 - 6.25×10^6	95	30	71-125
Level 4 (Excellent)	0-3.25×10^6	55	15	0-70

4 Results and discussion

4.1 Simulation

Process 5 in this study models the material handling operations between the warehouse (source station) and four car assembly stations, using two different transport methods: AGV and forklifts. Both scenarios are built using Siemens Tecnomatix Plant Simulation to evaluate their performance and sustainability under identical layout conditions. This modelling approach enables a direct performance and sustainability comparison within a controlled intralogistics environment, aligning with methodologies applied in prior works such [24] those who emphasize simulation-driven sustainability evaluation for logistics 4.0 systems. Figure 3a illustrates that the vehicle in the AGV scenario operates within a closed-loop system, commencing at the buffer zone. It can load a maximum of four items from a source station via a regulated loop, ensuring optimal load efficiency. Upon completion, the AGV adheres to a designated route marked by virtual checkpoints to transport the components to its station. Following each delivery, it momentarily halts before emptying, subsequently retracing a new route to initiate the next cycle. This method aims to be ongoing, enabling us to continually evaluate the AGV's efficiency in terms of travel duration, load capacity, idle time, and energy consumption. Conversely, the forklift scenario (Figure 3b) employs the identical material flow but adopts a more adaptable and dynamic handling methodology. The forklift retrieves one component at a time from the source and determines its destination according to the component type (A, B, C, or D). The destinations are Stations 1 to 4. This decision-making process resembles the manner in which a human would react to diverse commands. Upon arrival at the designated station, the forklift discharges the component and autonomously proceeds to the subsequent component. Forklifts tend to consume more energy and exhibit prolonged idle periods compared to AGV, particularly during manual operation. This simulation directly contrasts the merits and drawbacks of both methodologies by replicating them inside an identical context. AGV provides efficient and reliable pathways with minimal human intervention, resulting in uniform performance and reduced labor requirements for personnel. Conversely, forklifts exhibit greater adaptability and short-term cost efficiency, although they may consume more energy and necessitate a larger workforce in the long run. AGV, particularly electric variants, are typically more sustainable and environmentally benign. Conversely, forklifts may present challenges related to pollution, ergonomics, and safety.



(a) (b)

Figure 3 Simulation layout (a). AGV (b). Forklift

The simulation results from Tecnomatix Plant Simulation reveal critical insights into the performance of the AGV-based transport system. The AGV exhibited 44.02% occupancy and 46.11% idle time, indicating underutilization despite completing 316 transports over a distance of 2649 meters. Meanwhile, the Drain station showed a 72.96% waiting rate, suggesting inefficiencies in material flow, with an average exit interval of 11.29 seconds and a total throughput of 316 units. The high idle time at the Drain contrasts with the AGV's availability, highlighting a bottleneck in upstream processes, likely due to unbalanced task allocation or delays in workstation operations. Prior work has demonstrated that AGV idle times can be reduced through adaptive scheduling and real-time dispatch algorithms that account for production variability and congestion. When such strategies are applied, AGVs substantially reduce non-value travel and energy consumption [27]. However, the simulation results demonstrate the performance limitations of a single-item forklift system. The forklift spent nearly equal time empty (50.14%) and occupied (49.86%), completing 144 transports over a distance of 2,736 meters. The Drain station processed only 143 units with 52.44% waiting time, indicating significant idle periods between deliveries. The average exit interval of 24.98 seconds and throughput of 2.38 units/minute reveal constrained material flow due to the forklift's single-item capacity.

4.2 Sustainability evaluation

This study develops a comprehensive framework for a comparative sustainability assessment of material handling systems, specifically AGV and forklift. The evaluation is structured around six criteria: machine types, energy consumption, greenhouse gas emissions, energy elasticity in response to volume changes, operating costs, and ergonomics. These criteria are selected to capture the technical, economic, environmental, and social dimensions of sustainability. A systematic scoring framework (1-4), grounded in empirical and simulation data, was employed to assess each criterion. Reflecting established Multi-Criteria Decision-Making (MCDM) principles, each criterion was assigned an importance weight to articulate its relative priority within a sustainable intralogistics context, a methodological approach aligned with contemporary research practices [28]. The weighting scheme is justified as follows: GHG emissions received the highest weight (4), a priority consistent with the emphasis in sustainability literature on their critical environmental impact and escalating regulatory significance [29]. Energy consumption and operating costs were assigned a weight of 3, acknowledging their substantial combined pressure on both economic viability and environmental performance, where optimization is crucial for long-term operational resilience. Machine type and ergonomics each carried a moderate weight of 2. The former dictates process efficiency and system adaptability, while the latter incorporates the social dimension by evaluating operator safety and physical strain, particularly in manual systems [28]. Finally, energy elasticity, which measures the responsiveness of energy use to production volatility, was assigned a weight of 1, recognizing its role as a secondary but relevant factor in dynamic operational environments. By integrating these weighted criteria, this holistic framework facilitates data-driven decision-making, enabling a balanced evaluation that enhances the resilience and sustainability of intralogistics networks.

The total scores for AGVs and forklifts are 48 and 43, respectively, indicating that AGVs are slightly better. Based on 24-hour simulations of journey distance and throughput, AGVs use less energy (Good vs. Fair) and have less energy elasticity (Low vs. High). Both technologies perform similarly in key areas, such as greenhouse gas emissions (Very Low) and ergonomics (Low Risk). This means that they adhere to safety and environmental regulations. Both systems have high operational costs (for both Fair), which means they could be improved. The findings indicate that AGVs are optimal for energy-sensitive tasks, whereas forklifts are preferable when emissions and ergonomics take precedence. This study highlights the need for further optimizations to enhance cost efficiency and scalability in sustainable material handling solutions for industrial settings. Subsequent research may explore hybrid models or empirical case studies to validate these findings across various operational situations. Table 4 presents the outcomes of the sustainability evaluations for AGVs and forklifts. The evaluation is based on six sustainability criteria, each of which is assigned a weight to indicate its importance. When given a weight of 4, both AGVs and forklifts release the same amount of greenhouse gases. This means they each get 4 points, for a total of 16 points. AGVs get a score of 3 (9 points) for energy use, while forklifts get a score of 2 (6 points). This means that AGVs are better at saving energy. For both categories, the costs of running a business, excluding energy use, are assigned a weight of 3. Each category receives 2 points, totaling 6 points. Machine types and ergonomics, both weighted at 2, produced comparable outcomes for the AGV and forklift, scoring 4 (8 points) and 3 (6 points), respectively. Nevertheless, the AGV demonstrated superior adaptability to fluctuations in volume, a factor of lesser significance with a weighting of 1, achieving a score of 3 (3 points) in contrast to the forklift's score of 1 (1 point). The AGV got a score of 48 points, which was better than the forklift's score of 43 points. This means that the AGV is more sustainable, particularly in terms of energy efficiency and scalability. Both types of vehicles excel in key areas such as emissions and comfort. Still, AGVs may be better suited for projects that aim to conserve energy and remain flexible in their operations.

The comparative sustainability evaluation results reveal that, consistent with [1,30] AGVs achieve superior energy efficiency under repetitive, high-volume scenarios; however, they suffer from high idle times and utilization losses unless dispatching and load management are optimized. Meanwhile, forklifts maintain high flexibility in handling variable tasks but achieve lower throughput and higher energy per unit moved, aligned with findings from [30]. These trade-offs underscore that automation alone does not guarantee sustainability superiority; rather, system utilisation, volume profiles, cost structure, and human-machine interaction must all be optimised.

Table 4 Sustainability evaluation

Category	Weight factor	AGV		Forklift	
		value	Weighted value	value	Weighted value
A. Machine types	2	4	8	4	8
B. Energy Consumption	3	3	9	2	6
C. Greenhouse Gas Emission	4	4	16	4	16
D. Elasticity of Energy on Volume Change	1	3	3	1	1
E. Operational Cost without energy consumption	3	2	6	2	6
F. Ergonomics	2	3	6	3	6
			48		**43**

5 Conclusions

This study developed a simulation-based framework to evaluate the sustainability of material handling machines in intralogistics, specifically comparing AGVs and forklifts in an automotive warehouse-to-assembly line process. By employing a TBL approach that incorporated technology, environmental, economic, and social indicators, the research provided a comprehensive assessment of these technologies under realistic operating conditions. The results demonstrated that AGVs achieved superior performance in terms of energy efficiency and scalability, making them particularly suitable for operations that prioritize environmental sustainability and high throughput. However, the analysis also revealed that AGVs exhibited significant idle time (46.11%), indicating potential underutilization that could offset their energy advantages in specific scenarios. Forklifts, although less energy-efficient, offer greater flexibility and lower upfront costs, suggesting their continued relevance in operations that require adaptability or face capital constraints. Both technologies performed comparably in terms of greenhouse gas emissions and ergonomic considerations, meeting baseline sustainability standards.

Methodologically, the study advances sustainability evaluation through dynamic simulation, enabling the capture of real-time performance data beyond conventional static assessments. Nonetheless, the limitations include reliance on a single layout configuration and simulation-derived data, which may restrict generalizability. Future research should extend this framework using empirical validation and LSCA to incorporate broader boundaries. The integration of AI-driven predictive modelling and digital twin technologies offers potential for adaptive fleet management, real-time optimization, and predictive maintenance. Moreover, exploring hybrid fleets and the social dimension of sustainability aligned with Industry 5.0’s human-centric principles can yield deeper insights into resilient, intelligent, and sustainable intralogistics design.

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Supply chain management strategies taking into account marketing trends and IT technologies

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Abstract: Global supply chains are currently undergoing significant transformation under the influence of marketing trends and rapid digitalization. The growing complexity of customer needs, combined with the expansion of e-commerce and the integration of Industry 4.0 technologies, requires new approaches to the design and coordination of supply chain strategies. This article explores the interrelation between supply chain management (SCM), contemporary marketing tendencies, and the implementation of advanced IT solutions. The main objective is to analyze how customer-oriented strategies and digital innovations - such as big data analytics, artificial intelligence, blockchain, and cloud platforms - contribute to the resilience, flexibility, and efficiency of supply chains. The methodological framework includes a literature review, comparative analysis of global companies, and case-based evaluation of IT adoption in logistics operations. Results demonstrate that marketing-driven SCM strategies, supported by digital technologies, improve demand forecasting accuracy, shorten delivery lead times, and enhance customer experience. Moreover, companies that align marketing insights with supply chain planning achieve superior competitive advantages by creating adaptive networks and developing sustainable partnerships. The article contributes to both theory and practice by emphasizing the necessity of integrating market dynamics with technological capabilities in modern SCM. Practical recommendations are provided for managers and policymakers to strengthen competitiveness in volatile markets through the synergy of marketing strategies and IT-enabled logistics.

1 Introduction

Supply chain management (SCM) remains a core element of corporate strategy, ensuring operational efficiency, cost reduction, and competitiveness. However, under the pressure of digital transformation and rapidly changing market conditions, traditional SCM approaches are losing relevance. Modern supply chains must integrate marketing and technological factors, becoming part of a company's overall customer interaction strategy. Digital tools now determine not only production efficiency but also demand, service quality, and customer loyalty. Globalization and the growth of e-commerce have reshaped competition: while cost efficiency once dominated, today market responsiveness and customer relationship management define success [1]. The digital economy further transforms logistics and SCM through the adoption of big data, artificial intelligence, blockchain, and cloud platforms. These technologies enable process monitoring, demand prediction, and route optimization, yet they require a revision of classical SCM concepts. Meanwhile, rising consumer expectations for transparency, sustainability, and service quality force companies to adapt their supply chains to new social and environmental standards [2]. Despite the extensive literature on SCM, several research gaps remain. First, the integration of marketing data into supply chain planning is insufficiently explored - most studies treat logistics and marketing as separate domains. Second, there is no unified methodological framework for evaluating the effectiveness of digital technologies within SCM. Third, digitalization in practice is often fragmented: companies implement IT solutions for individual functions but fail to integrate them strategically. Finally, criteria for holistic SCM performance assessment that combine economic, technological, and marketing indicators remain undeveloped [3]. Therefore, this study aims to address these gaps by developing a comprehensive SCM model that unites marketing trends and IT technologies. The research emphasizes the strategic role of SCM in the digital economy - not merely as an operational tool, but as a driver of innovation, adaptability, and customer value creation. The findings are expected to support the design of sustainable and technology-oriented SCM strategies and contribute to building competitive advantages at both corporate and national levels.

1.1 Theory of supply chain management strategy development

Supply Chain Management (SCM) has undergone a complex path of development, starting from simple logistics operations to a strategic concept integrating marketing, information technology and innovative forms of interaction between participants. The theoretical foundations of SCM were formed gradually, reflecting changes in the global economy, the development of information systems and the evolution of management paradigms. The structuring of the conceptual stages of development of supply chain management is presented in Table 1.

Table 1 Structuring of the conceptual stages of development of supply chain management

STAGES	APPROACH	FEATURES OF DEVELOPMENT
1950-1970s	Logistics approach	Initially, supply chain management was considered in the context of logistics, the main task of which was to ensure the movement of material flows from the manufacturer to the consumer at minimal costs. During this period, key attention was paid to transportation and warehousing.
1980s	Integration of logistics functions	With the strengthening of globalization and the increasing complexity of distribution systems, there was a need to combine various functions within logistics: supply, warehousing, distribution. Scientific research during this period focused on the need to integrate material, information and financial flows.
1990s	Supply chain concept	The concept of "supply chain" is becoming widespread. Scientists and practitioners are beginning to consider not only the company's internal processes, but also interactions with suppliers, distributors, and customers. The concept of supply chain management emerges, in which management is based on the principles of cooperation and synchronization of all participants in the chain. An important theoretical contribution is the development of partnership models and strategic alliances.
2000s	Value chains	At the beginning of the 21st century, end-consumer value creation becomes considered when studying SCM. The major goal is no longer a reason of pure cost, and the attention is more and more paid on the service quality, the flexibility of the supply and the personalization of the offer 64. The theory postulates the notion of value-based supply chain, that integrates SCM and marketing orientations in respect of customers.
2010s - present	Digitalization and "smart" supply chains	The current class is the era of application of digital technology, characterized by big data, AI, Blockchain, IOT, cloud computing and other technologies. Increasingly, there is a notion of a digital supply chain, where it is operated based on real-time analytics, automated activity and predictive modeling.

Current research shows that the marketing dynamic is shaping supply chain management strategies. Demand uncertainty is rising and SCM is moving toward demand driven models. Marketing analytics provides the information about what are the customer behaviors, preferences and abstractions are which can enable the firms to design the more flexible and only one phased supply chains [4,5]. Thus, SCM is evolving from an operational to be a strategic tool that can create competitive advantage through customer value creation. In principle, this seems to be what the shift from cost-based to value-based drivers will be will be for supply chains. IT has been recognized as a major catalyst in the advancement of SCM methodologies over the past few years. Contemporary theories process the importance of integration in a digital form that allows perfectly synchronizing the activities of all actors in the network on-line. IoT guarantees the transparency of goods' transportation, blockchain enhances the security and credibility of transactions and big data and artificial intelligence improve forecast accuracy of demand [6]. Accordingly, the progression of SCM model from functional coordination to network & digital and from marketing to technology is the SCM theory evolution process. SCM Today, SCM is confronted with various challenges that still need more theoretical explanations:

- Sustainability and environmental friendliness - the need to develop "green" supply chain strategies that take into account environmental factors [7].
- Risks and uncertainty - global crises and supply disruptions require new models of sustainability and adaptability [8].

- Synergy of marketing and digitalization - further development of concepts integrating marketing data and IT solutions into strategic management is required [9].

Thus, SCM theory continues to evolve, moving from traditional logistics functions to integrated and digital models that are customer-focused, innovative and sustainable.

1.2 Key aspects of marketing trends and IT technologies in supply chain management strategies

Modern global supply chains are developing in the context of highly dynamic markets, digitalization and increasing competition. Companies are focusing not only on cost optimization and operational efficiency improvements, but also on the need to take into account changes in consumer preferences, marketing strategies and innovative technologies. Supply chain management is no longer an isolated logistics function and is increasingly integrated with marketing, big data analytics and digital platforms. The key challenge is to develop a strategy that can simultaneously take into account marketing trends - customer focus, customization, reduced delivery times, sustainability and transparency - and the opportunities offered by IT solutions: artificial intelligence, blockchain, cloud technologies and digital twins [10]. In this regard, there is an increasing need to analyze the factors that determine the success of using IT tools and marketing practices in supply chain management strategies. Marketing trends often act as a factor in the transformation of supply chains, namely in the following areas:

- Customer focus and customization. One of the most significant marketing trends of recent years is the transition from standardized mass production to individualized offerings. Consumers expect personalized products and services, which requires companies to be flexible in supply chain management and integrate marketing data into planning processes. For example, studies show that companies focusing on demand-driven supply chains achieve higher customer satisfaction rates [11].
- Growth of e-commerce and omnichannel. The accelerated growth of e-commerce has radically changed distribution channels and logistics models. For the supply chain to function effectively, omnichannel integration is necessary, ensuring a single customer experience regardless of the point of contact. This requires the alignment of marketing and logistics strategies, as well as the use of IT solutions for real-time data management [12].
- Sustainability and social responsibility. Modern marketing trends include an emphasis on sustainable development and “green” supply chain logic. Consumers increasingly choose brands that demonstrate environmental friendliness, ethics, and supply chain transparency [13]. This creates new strategic requirements for companies: the need to implement emission monitoring systems, product lifecycle management, and compliance with ESG (Environmental, Social, Governance) standards.

Information technology today is one of the most significant factors determining the transformation and development of supply chain management (SCM) strategies. Its implementation allows not only to increase operational efficiency, but also to build new business models, where flexibility, transparency and integration become the determining criteria for competitiveness. In the context of globalization and increasing market instability, companies are forced to move from linear, rigidly structured chains to network ecosystems in which digital solutions perform a connecting function, uniting participants into a single information environment. The key importance of information technology in SCM is manifested in ensuring transparency and accessibility of data at all stages of the chain. Modern digital platforms allow tracking the movement of goods and materials in real time, which significantly reduces the risk of failures and contributes to more accurate forecasting. Through Big Data and AI it also gets possible to deeply understand consumer preferences, demand curve, but also market fluctuations, management being closer to the end customer making strategies more adaptive and customer center [14]. IT is also delivering fundamental changes for how the supply chains work together. If previously such interaction was limited to (flows of documents) communication, subsequent updating of information, now the task of building integrated management systems is increasingly feasible - with significantly more synchronization of data that occurs in an online mode, processes that on the appropriate level of coordination take place in one digital space. This would allow to use strategies such as the Just-In-Time or Demand-Driven when planning the production chain, in which the important thing is not the number of resources, but the reaction capacity in the face of changes in the market. There should be a special note for the installation of cloud technologies as the possibility that creates the opportunity for scaling and flexibility of information infrastructure. They offer businesses the opportunity to jettison expensive server solutions in favor of an “on-demand” model in which resources are invoked for business workloads. By making use of this, small and medium-sized companies able to have access to save the supply chain management tools that big companies do, which can reduce the competition [15]. The emergence of advanced blockchain that offers the immutability and public ledger recording functionality is also highly significant. For the supply chain, it could also imply full traceability of the origin of products, something of particular importance for markets with high-quality and safety standards, such as pharmaceuticals or food. Given the increased emphasis on sustainable development, the blockchain is becoming an effective instrument to verify the environmental and social accountability of a company, and to reinforce consumer trust.

Equally of note are the logistics functions embedded with automated and robotic technology. An automated warehouse, robot vehicles and intelligent inventory pool systems lowers operating costs and speeds up transactions. This eventually shifts the SCM's strategic signals that aim for efficiency to those that embrace sustainability, reliability and labor reduction. With respect to digital twins in the supply chain the current IT allows for the development of digital twin strategies. By modeling and simulating actual business processes, with real data, you can forecast the effect of your management decisions and alter strategy on the fly. It is one practice that enjoys stronger support among companies, especially during periods of crises and disruptions, when being fast and flexible can be the difference between an organization's death and survival. So the information tools arena only the help of the supply chain, but are the strategy of SCM itself. The use thereof ensures that cooperation is achieved between the built environment and the customer requirements, and logistics capacities, and the environmental development into environmentally viable development plus innovation. In digital economy age (IT) was the essential factor of supply chain integration and coordination, has helped supply chains to move from a linear architecture to intelligent eco- system ledger through self-learning and self-regulation.

1.3 Theoretical and methodological aspects of supply chain management taking into account marketing trends and IT technologies: approaches and views

Supply chain management (SCM) strategies have attracted the attention of researchers and practitioners over the past two decades due to increasing globalization, increasing complexity of logistics networks, and digitalization of business processes. The SCM literature demonstrates a wide variety of approaches, from classic logistics models to the integration of marketing and information technology. Despite a significant amount of research, there are a number of unresolved issues related to performance measurement, integration of innovative technologies, and adaptation to dynamically changing markets. Early works in the field of SCM focused on optimizing material flows and reducing costs. [14,15] emphasized the role of integrating the functions of procurement, storage, and distribution to improve efficiency. [16] emphasized the need to synchronize all participants in the supply chain and considered logistics as a strategic tool for competitive advantage. However, these approaches remained predominantly operational and did not take into account the impact of marketing factors and digital technologies on chain management. With the development of the supply chain management concept, the emphasis has shifted to cooperation between companies, partnerships, and creating added value for the customer [17]. Theoretical studies point to the effectiveness of strategic alliances, joint planning and integration of information flows. However, practice shows that most companies face difficulties in implementing cross-functional coordination and real-time data management. The lack of a unified methodology for assessing the effectiveness of integrated strategies remains a significant problem. The marketing component of SCM has been actively developed in recent years. [18,19] note that customer focus and product customization require supply chain flexibility and the ability to quickly respond to changes in demand. At the same time, there is an increase in e-commerce, which necessitates omnichannel supply chain management [20]. A literature review shows that many companies are implementing predictive analytics and CRM tools to support marketing strategies, but the integration of these solutions into SCM remains limited, which reduces operational efficiency. Modern research emphasizes the importance of SCM digitalization. Big data, artificial intelligence, blockchain and cloud technologies create opportunities to increase transparency, reduce supply cycle times and reduce operational risks [21]. However, literature analysis reveals several problems: the lack of a unified methodology for assessing the digital maturity of supply chains, difficulties in integrating innovative technologies into traditional business processes and insufficient focus on sustainable development. For example, the implementation of blockchain technologies requires significant investments and a change in organizational culture, which is often an obstacle for small and medium-sized enterprises [22]. Another unresolved aspect is the assessment of the effectiveness of SCM strategies in the context of sustainability and risks. Research [23,24] points to the need to include environmental and social factors in the assessment of supply chains. However, most existing models focus on economic efficiency and do not comprehensively take into account the impact of external factors: climate risks, geopolitical crises or global supply disruptions. In this regard, there is a need to develop comprehensive indices that combine operational, digital and marketing efficiency with sustainability indicators. A critical analysis of existing methods shows that most approaches are limited either by narrow logistics efficiency or partial digital integration. The DEA model, KPI analysis and integration of digital indices proposed in modern studies allow for a comprehensive assessment of efficiency, but require further refinement to account for market dynamics and the multifactorial impact of technologies. In particular, weighting factors in integral indices are often set by an expert method, which introduces subjectivity and reduces the reproducibility of results. The need to improve methodologies is due to rapid changes in consumer preferences, the growing role of digital platforms and the increasing importance of sustainable development. Research [25] emphasizes that companies integrating marketing and IT factors into strategic SCM management demonstrate better financial and operational performance. However, for widespread use, standardization of indices, development of quantitative risk accounting methods and formation of adaptive demand forecasting models are required. The prospects of the study are associated with the creation of a systematic approach to supply chain management that takes into account the relationship between marketing and technology. An important area is the development of SCM digital maturity models that will allow companies to quantify the level of automation, integration, and adaptability. In addition, it is necessary to take into account the impact of environmental and social factors on strategic decisions, which will ensure the sustainability of supply chains in the long term.

Thus, a critical analysis of the literature shows that existing studies provide valuable theoretical foundations and empirical data, but do not fully address the issues of integrating marketing trends and IT technologies into SCM. The lack of a unified methodology for assessing performance, a limited accounting base of digital indicators, and insufficient focus on sustainability create space for further research. The development of a comprehensive methodology combining DEA analysis, KPIs, and digital indices allows not only to identify best practices, but also to offer strategic recommendations for companies in the context of global competition and digital transformation.

2 Methodology

2.1 Peer review process

The global economic environment is placing greater demands on strategic SCM. The development in the level and scope of interactions between networks, digitalization of business-processes and the importance of marketing of data make introduction of advanced information technologies in a corporate strategy almost inevitable, allowing market trends being followed. To validate the efficiency of the strategy followed, with model the effectiveness of the strategy has to be designed and measured which allows to know if the SCM is effective or ineffective given the following parameters: the operational efficiency of SCM at the firms, the digital level, the adaption of digital marketing and resiliency to the external risks. The research methodology is based on a combined approach, including: 1) DEA analysis (Data Envelopment Analysis) to assess the relative efficiency of companies by key input and output indicators. 2) KPI analysis (Key Performance Indicators) to check the strategic compliance of SCM with marketing and IT trends. 3) Modeling the integrated index of digital maturity of supply chains (Digital SCM Index, DSCMI). 4)Comparative analysis of data from leading global companies in the field of FMCG, pharmaceuticals, retail and logistics (Procter & Gamble, Unilever, Nestlé, Maersk, DHL, Walmart, Amazon) [24-26]. SCM efficiency is assessed through the ratio of resources (inputs) and results (outputs). Input indicators include: the level of digital investments (CapEx in IT), the number of implemented technologies (ERP, WMS, TMS, IoT), the number of participants in the supply chain and operating costs. Output indicators include: reduction of logistics costs, increase in the level of customer service (Customer Service Level, CSL), reduction in the supply cycle time (Lead Time Reduction), and increase in marginality. The efficiency of company in the DEA model is expressed as follows (1):

$$E_i = \frac{\sum_{r=1}^{s} u_r y_{ri}}{\sum_{j=1}^{m} \vartheta_j x_{ji}} \tag{1}$$

Where y_{ri} - output indicators of the company (SCM results), x_{ji} - input indicators (costs and resources), u_r, v_j - weights determined by the model, E_i - integral efficiency index. The company is considered efficient if $E_i = 1$, and inefficient if $E_i < 1$. To take into account marketing factors, an additional coefficient of adaptability to market trends has been introduced (2):

$$\mathrm{M_i} = \frac{\mathrm{CSL_i} + \mathrm{D_i}}{2} \tag{2}$$

Where $CSLi$ - customer satisfaction level according to surveys or KPIs, D_i - index of digital integration of marketing tools (availability of DMP, CRM, personalized solutions). The final SCM performance index taking into account marketing and IT trends (SCM-Score) is calculated as (3):

$$SCM_i = \alpha E_i + BM_i + \gamma DSCMI_i \tag{3}$$

Where α, β, γ - weight coefficients (according to the results of expert assessment and factor analysis, adopted as 0.4, 0.3, 0.3), $DSCMI_i$ - SCM digital maturity index, reflecting the level of automation, implementation of IoT, AI, blockchain and cloud technologies.

The proposed methodology for a comprehensive assessment of supply chain management strategies, based on a combination of the DEA model, KPI analysis and the Digital SCM Maturity Index (DSCMI), demonstrates high value for practice and science. Firstly, it allows for an objective comparison of the performance of different companies and identification of key drivers of success in integrating marketing trends and IT technologies. Secondly, the methodology provides a quantitative assessment of the digital maturity of SCM, which is important in the context of accelerated digitalization and transformation of business processes. Its significance is also manifested in the ability to identify the strengths and weaknesses of strategies, which allows managers to form adaptive and customer-oriented supply chain models. The inclusion of the marketing adaptability coefficient ensures that changes in consumer preferences are taken into account and allows predicting the market reaction to the introduction of new technologies.

However, the methodology has certain limitations. Firstly, it relies on available public data from companies, which may not fully reflect internal processes and strategic decisions. Secondly, the weighting factors in the integral SCM-Score index are formed on the basis of expert assessment, which introduces an element of subjectivity. Thirdly, the use of the DEA model does not take into account the dynamics of changes over time and external economic and political factors affecting supply chains.

Prospects for further application of the methodology are associated with the integration of time series and forecast models, expansion of the base of digital indicators, as well as taking into account risks and resilience to crisis situations. The development of the model will improve the accuracy of SCM strategy assessment and create more flexible, adaptive and value-oriented supply chains for the customer.

3 Results and discussion

Modern supply chain management (SCM) strategy is evolving from functional logistics to a platform-based, customer-centric and data-driven ecosystem, where marketing impulses and digital technologies determine the design, responsiveness and resilience of chains. Conceptually, such a strategy is based on six key elements:

- Customer focus (market-back design): demand-driven planning, service personalization, omnichannel experience consistency.
- Data-driven SCM: integration of external/internal data, predictive analytics, scenario analysis.
- Networked orchestration: coordination of multiple actors through digital platforms, standardized interfaces, and shared rules.
- Sustainability & resilience: a combination of “green” practices with readiness for market and geopolitical shocks.
- Platformity and modularity: an architecture of interchangeable modules (processes, IT services, partners), simplifying scaling and restructuring.
- Servitization: shifting the focus from physical flow to service value (speed, transparency, loyalty), where marketing and SCM jointly design the “brand promise” and its operational execution.

In this framework, marketing trends (omnichannel, personalization, ESG customer requests, “transparency as a norm”) act as an external driver of requirements, and IT technologies act as an internal execution mechanism (forecasting, visibility, automation, traceability, platform coordination) [27]. Current changes in the global economy demonstrate that strategic supply chain management (SCM) can no longer be limited solely to logistics or material flow coordination.

The trend to improve technological capabilities is a consequence of the development of the digital economy, the acceleration of market processes and the increasing requirements of consumers, a shift attention to the integration of marketing tools and information technologies in the management system. As the efficiency of the SCM in the 21-century can be directly positively influenced not only by costs optimization or the reduction of the costs in time, but on the company’s ability to create the customer value and the demand forecasting and reacting on changes in market situation. It is here where marketing is not only a product-promotion function, but a strategic play within supply chain relationships. Mind control, market trends, personalisation, sustainable development – all of this figures into SCM marketing campaigns. IT in turn, lay the foundation for this structuring, ensuring the accuracy of information, the visibility of the process, and the agility in the face of potential changes in the global supply network. But in practice, it means even more advanced tools - enterprise resource planning (ERP) systems, customer relationship management (CRM) applications, big data and artificial intelligence (AI) tools for demand forecasting, blockchain for the partners in a supply chain to trust each other and show that they are being transparent. Meanwhile, the value of digital communication channels, omnichannel strategies, and customer experience insights allowing companies to build long term competitiveness is increasing. Thus, SCM strategy developed to form a conglomerate of instruments, grounded in elements of traditional logics of logistics optimization, orientation of marketing and digitalization. This brings in a new paradigm of SCM in synthesis, where success is not just defined by the speed and cost of delivery; (i) the level of customer satisfaction, (ii) degree of business model innovativeness and, (iii) the company’s sustainability development. High-level planning tools (APS/IBP) and AI/ML analytics provide the basis for manageability; cloud and API - speed of partner and data connection; WMS/TMS and robotics - SLA predictability; IoT/blockchain - visibility and trust; CRM/DMP - translation of marketing impulse into planning; CPFR - joint reduction of volatility; sustainability tools - compliance with new markets and regulations [28]. Key IT and marketing tools in SCM strategies of modern companies are presented in Table 2.

Table 2 Key IT and marketing tools in SCM strategies of modern companies

TOOL / PRACTICE	STRATEGIC ROLE IN SCM	MARKETING EFFECT
APS/S&OP/IBP (ADVANCED PLANNING, INTEGRATED BUSINESS PLANNING)	Demand-Supply Synchronization, Capacity	Balance Promotion and Supply Alignment
DMP/CRM/CDP (CUSTOMER DATA PLATFORMS)	Integrating Voice of the Customer into Planning	Personalization, LTV Growth
WMS/TMS/YMS	Operational Efficiency, Last Mile	SLA Stability
IOT/TELEMATICS	Real-Time Visibility and Control	Transparency for the Client
AI/ML (FORECASTS, OPTIMIZATION)	Forecast Accuracy, Dynamic	Pricing/Inventory
DIGITAL TWIN/SIMULATION	Scenario Testing, Resilience	Service Reliability
BLOCKCHAIN/TRACEABILITY	Immutable traceability	Trust, anti-counterfeiting
RPA/ROBOTICS/ASRS	Automation of operations, speed	Service stability
CPFR/EDI/API	Joint planning/replenishment	Out-of-stock reduction
CLOUD/SAAS IPAAS	Fast integration, scalability	Quick channel launch
LAST-MILE TECH (LOCKERS, CROWDSOURCED)	Delivery time reduction	Customer satisfaction
SCF/FINTECH (FACTOR, DYNAMIC DISCOUNTING)	Chain liquidity, supplier stability	Assortment continuity
SUSTAINABILITY SUITES/LCA	Carbon accounting, eco-design of routes	ESG image

Strategic directions of development of IT and marketing tools in SCM strategies of modern companies are presented in Figure 1.

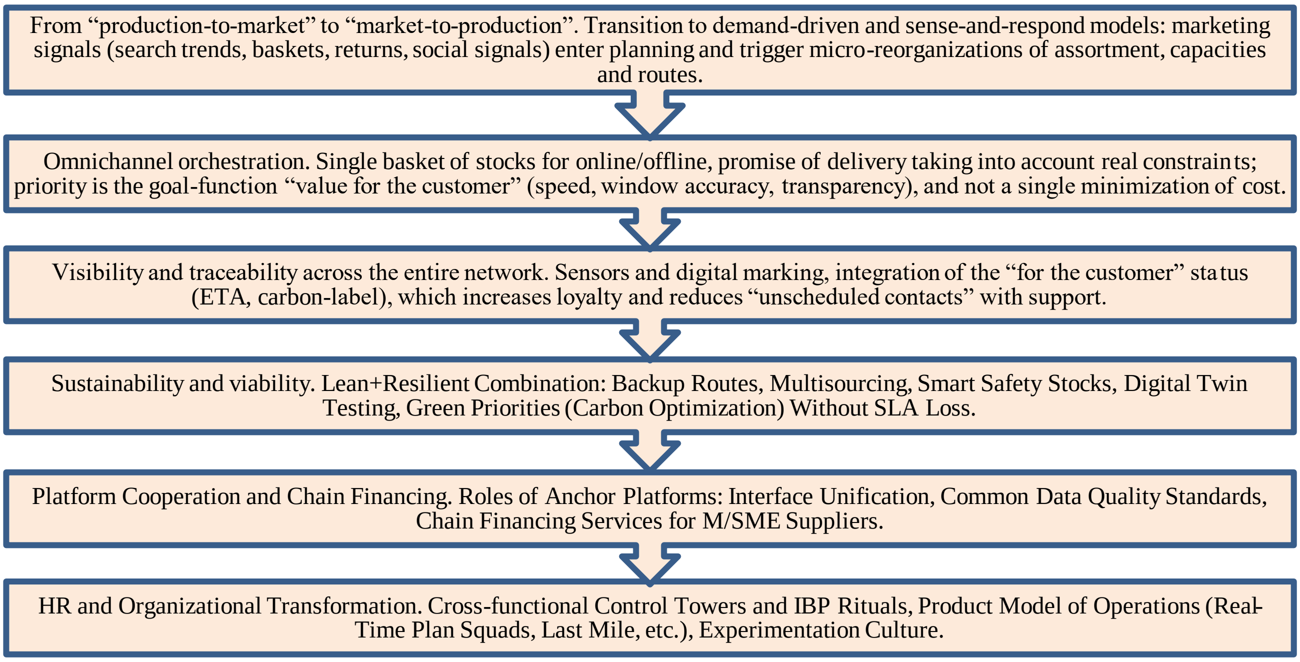

Figure 1 Strategic directions of development of IT and marketing tools in SCM strategies of modern companies

The modern supply chain management (SCM) system has ceased to be just a tool for organizing logistics flows. According to the strategic lines analyzed, it is possible pointing out some of the key results that show how SCM turns itself into a multi-component model, characterized by vectors of managerial, marketing and technological development that are crossing with each other [29]. Future strategic SCMs development the future impact of SCM should be to verify that SCM is becoming more ‘front-office’ than ‘been-office’, moving SCM as a driver of digital and marketing business transformation. Study of these strategies impel us to scrutinize the world trends that keep framing the next generation of the SCM. These trends are formed under the digitalization of the economy, the geopolitical situation, changes in consumer behavior and the transition to a sustainable development model. Table 3: The overview of the world supply chain management strategy trend - marketing trend and IT technology perception Table 3 shows the world supply chain strategy trend; marketing trend and IT technology perception.

Table 3 Global trends in supply chain management strategies taking into account marketing trends and IT technologies

GLOBAL TREND	ESSENCE	ROLE OF MARKETING	ROLE OF IT	COMPANY
DIGITALIZATION AND AI	Automation of forecasting, analytics, management	Personalization of offers, omnichannel communications	Big Data, AI, IoT	Amazon, Alibaba
SUSTAINABLE DEVELOPMENT	Reducing emissions, environmental friendliness, circular chains	"Green marketing", brand of trust	Smart Logistics, blockchain	Unilever, Tesla
REGIONALIZATION OF SCM	Reducing dependence on global risks	Local promotion strategies	ERP systems for hybrid chains	Siemens, Nestlé
TRANSPARENCY OF CHAINS	Control of the origin of goods, fight against counterfeiting	Strengthening customer trust	Blockchain, Track&Trace	Walmart, Maersk
OMNICHANNEL	Integration of offline and online channels	Cross-channel customer experience	CRM, SRM, digital platforms	Nike, Zara
PERSONALIZATION	Demand for individual preferences	Customer marketing, big data analysis	AI, behavior analytics	Netflix, Apple

These conclusions help not only to systematize the accumulated experience, but also to highlight areas of transition to global trends that create the future of SCM strategies. First, you have an amalgam of logistics and marketing. Additional classical SCM model concentrated on cost cut down, time delivery decreases and control of the flow material. But today’s circumstances require the wholesalers’ priorities to be supplemented with a commitment to the customer. Demand is being influenced by fresh marketing behaviors - digital marketing, personalized offers, services solutions. Therefore, there is an increasing trend to make SCM a system oriented to the optimization of the operative processes and to the creation of customer value. Secondly, IT is the source of strategic evolution of SCM. The application of ERP, CRM, SRM systems as well as big data technologies and blockchain applications, in addition to solving logistics tasks, it is possible not only to form an entire strategy in accordance with forecasts, analytics and digital control at each link in the chain. Thus, SCM is now not only a reactive instrument but rather more and more a proactive system, which can predict market trends. Thirdly sustainability It’s still everything. The world market demand companies to be responsible to the environment, transparent suppliers operation, carbon foot print and social responsibility. Also, the aspects of sustainable business models are a part of the global supply chain management, which are today not anymore only a social requirement, but also a competitive factor. Fourth, the connection of CRM, SRM is a new type of tactics and the core competence is the flexibility. On the global market, the ability to respond rapidly to changes in demand, reordering of supply chains, or technological progress is a huge advantage. Enterprising corporations are proving that it’s not the cheapest cost that prevails, it’s the company that can bake in marketing agility with digital transparency, into their supply chain [30]. The reason behind choosing DEA (Data Envelopment Analysis) model and IntSCM index to measure the degree of effectiveness of supply chain management strategies, are several. Firstly, working conditions in the modern global corporations have various dimensions and processing the complexity where not only financial measures are to be considered, but non-financial ones: how fast products are produced and delivered (speed of shipment), level of clients’ satisfaction, digitalization of production process, sustainable development. The ability of due to traditional methods for comparative analysis to determine the cumulative effect of these components is insufficient, and the present approach allows for the simultaneous consideration of many inputs and outputs providing a transparency efficiency picture [31]. Second, the overall SCM score can be considered as an essential factor for an integrated assessment of outcomes. It aggregates KPI into one number that allows to compare different firms and to recognize strategic differentiations. The integral index application is particularly useful for inter-industry comparisons, e.g., between FMCG sector and logistics [32]. Finally, the DEA model and the integral index can give a comprehensive quantitative and qualitative evaluation of the SCM motive power strategies, and then find out the merits and shortcomings of companies, and guide the companies to the future directions for development. Therefore, this approach was the most appropriate for evaluating the effectiveness of SCM within the intersection of digitalization and global marketing changes. To conduct analysis of strategies, management in the field of supply chain by considering the marketing trends and IT technologies required to determine the initial data, reflecting th e actual state (condition) of the global companies in m management field of supply chain; The analysis of effectiveness of the surpluses at management in a context of integration of the marketing trends and IT the technologies requires the system of the beginning of the quantitative signs, reflecting both internal arbitration fiscal processes and interaction with a market.

In the current stage, it is not easy to restrict to a financial dimension only because of the fact that the digital transformation application in SCM impacts on the inventory circulation speed, the degree of automation used in business activity, the extent of digital sales, and the number of customers, who come back [33].

Therefore, when forming the base of initial data, companies from different segments of the global economy were selected: online retail (Amazon), traditional retail (Walmart), FMCG sector (Unilever, Nestlé, Procter & Gamble), as well as global logistics operators (Maersk, DHL). The initial data for conducting an analysis of supply chain management strategies taking into account marketing trends and IT technologies of modern companies are presented in Table 4.

Table 4 Initial data for conducting an analysis of supply chain management strategies taking into account marketing trends and IT technologies of modern companies

INPUTS				
COMPANY	IT INVESTMENTS ($ BILLION)	NUMBER OF IMPLEMENTED DIGITAL TECHNOLOGIES	OPERATING EXPENSES ($ BILLION)	NUMBER OF PARTICIPANTS IN THE CHAIN
AMAZON	73.00	9	450.00	>1 million suppliers
WALMART	19.00	7	393.00	~100K
UNILEVER	6.50	6	62.00	~50K
NESTLÉ	7.20	7	70.00	~60K
P&G	8.10	8	76.00	~55K
MAERSK	5.00	6	48.00	~30K
DHL	4.80	6	52.00	~25K
OUTPUTS				
COMPANY	COST REDUCTION (%)	SERVICE LEVEL (CSL, %)	LEAD TIME REDUCTION (%)	MARGIN GROWTH (%)
AMAZON	15.00	94.00	18.00	7.50
WALMART	11.00	91.00	12.00	6.00
UNILEVER	9.00	89.00	10.00	5.00
NESTLÉ	10.00	90.00	11.00	4.80
P&G	12.00	92.00	13.00	5.50
MAERSK	8.00	87.00	9.00	4.20
DHL	7.00	88.00	8.00	4.00

For an inclusive evaluation of the strategic effectiveness of the SCM concept implementation with the marketing trends and IT technologies convergence, the methodology was selected that enables one to reflect the multi-faceted indicators both input and output character. The quantitative analysis was based on the DEA model which helps to identify the relative efficiency of companies (E) in relation to the relation of resources applied in SCM and the results achieved. The DEA efficiency score (E) measure the company's capability in the efficient utilization of logistics costs, automation level and use of digital tools to generate a high level of customer satisfaction, customer retention, and inventory turnover. In order to meet DEA, M, which shows how effectively a company can adjust to demand change and transfer marketing strategies and personalized offers to the SCM process [34], was being considered. This coefficient is indicative of the capacity that a business can develop to keep a competitive position by interacting with the demand of the product and the client. For an overall explanation of efficiency the Digital Supply Chain Maturity Index (DSCMI) was computed - a digitalisation readiness indicator for the supply chain, covering automation status, use of cloud, predictive and prescriptive analytics and innovative IT components. DSCMI gives you a chance to measure how much a company is prepared for a digital revolution and to adopt new technologies in SCM. The findings validate that effective SCMSs hinge on the integration of marketing and IT along with the positioning of the digital transformation concept within the scope of an integrated model. Last but not least, the reached results help for the purpose of supporting strategic business planning and deliver evidence for ensuring organizational competitiveness and survival of organizations in the conditions of the global markets and digital economy. The DEA model and the integrated index of company' s supply chain management strategy Facilitator are shown in Figure 2.

Using the measurements of thee indicators, an overview expressing strategic maturity and competitiveness of SCM can be summarized through the formation of the SCM-Score index as such DEA efficiency, marketing adaptability and digital maturity if the supply chain are all represented by one number. SCM-Score gives you the ability to benchmark companies against each other, to find out who are leading and lagging - and where to improve the efficiency and integration between marketing and IT tools. Thus, moving from raw data and basic analytics to calculating E, M, DSCMI and SCM-Score provides a logical continuation of the research, allowing us to link quantitative indicators with practical strategic conclusions and direct further analysis to identify global trends and best practices in supply chain management. Thus, the use of DEA and the integral SCM index allows us to identify the strengths and weaknesses of companies, determine optimal development directions and assess the potential for improving efficiency. The analysis of the results of DEA, marketing adaptability (M), DSCMI and the final SCM-Score allows us to make several key conclusions about the strategic efficiency of supply chain management in global companies of various sectors. Firstly, the leadership in the integral indicator SCM-Score is secured by Amazon, which confirms the complex combination of high DEA-efficiency

(E = 0.97), significant marketing adaptability (M = 0.94) and the maximum level of digital maturity of the supply chain (DSCMI = 0.95). High DEA-efficiency indicators demonstrate the optimal use of resources, and M and DSCMI reflect the company's ability to flexibly respond to changes in demand and successfully integrate information technology into SCM processes. This synergistic effect provides Amazon with leadership in online retail and allows it to maintain a competitive advantage in the global market. Secondly, FMCG companies (Unilever, Nestlé, P&G) show an average level of integral efficiency. DEA efficiency varies from 0.82 to 0.87, M is in the range of 0.78 - 0.84, DSCMI fluctuates between 0.70 - 0.75. This indicates that the companies successfully manage customer relationships and marketing adaptation, but the limited level of supply chain digitalization reduces the potential SCM Score. Such results indicate the need to strengthen IT tools and more actively implement digital technologies to improve integrated efficiency. Thirdly, logistics companies Maersk and DHL demonstrate high DEA (0.88 - 0.91) and DSCMI (0.85 - 0.88), indicating significant technological potential and resource optimization. However, their marketing adaptability coefficient (M = 0.75 - 0.78) is inferior to the leaders of retail and online commerce, which reflects the limited use of marketing tools in the logistics sector. Thus, the analysis of the E, M, DSCMI and SCM-Score indicators confirms that a successful supply chain management strategy requires the synergy of three components: resource optimization, marketing flexibility and digital maturity. Companies that integrate these elements gain an advantage in SCM efficiency, increase customer satisfaction and strengthen their position in the global market. The results obtained serve as a reliable basis for developing strategic recommendations for increasing the competitiveness and sustainability of supply chains in various economic sectors [35].

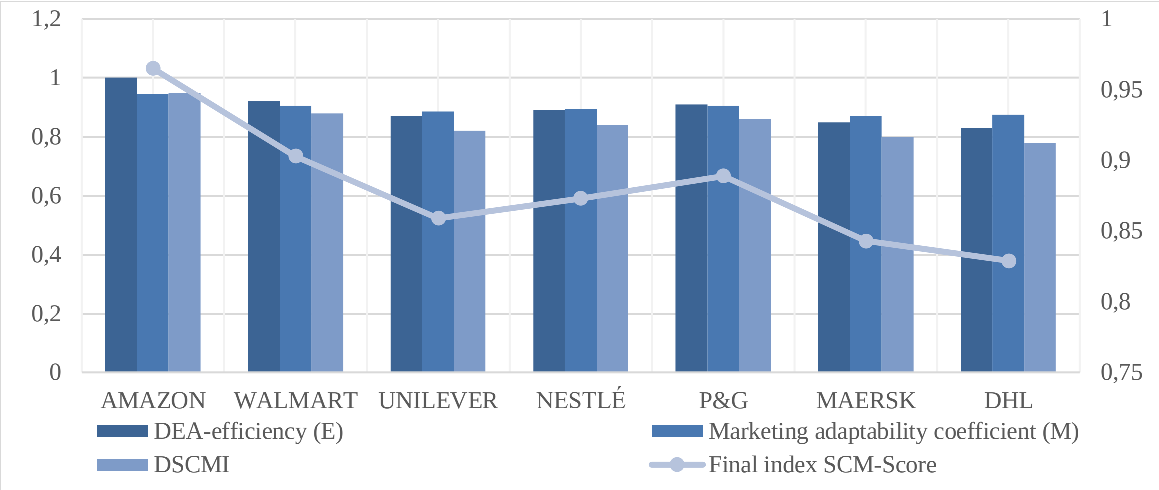

Figure 2 Theoretical analysis of the DEA in companies' supply chain management strategy measurement

The results of the DEA, Marketing Agility Index (M), DSCMI and the final SCM-Score analysis show that the strategic effectiveness of supply chain management directly depends on the comprehensive integration of digital technologies and marketing tools. Based on the identified patterns, several key strategic recommendations can be identified that will help improve the competitiveness and sustainability of companies on a global scale. First, companies need to integrate digital technologies at all stages of the supply chain. Analysis leaders such as Amazon demonstrate high efficiency due to large-scale automation of warehouse and transportation operations, the use of cloud platforms, predictive analytics and AI for demand forecasting. The implementation of such tools helps reduce operating costs, increase inventory turnover and improve planning accuracy. For FMCG companies (Unilever, Nestlé, P&G) and the retail segment (Walmart), digitalization of distribution processes and integration of ERP/CRM systems are of particular importance to ensure an omnichannel customer experience. Secondly, strategic marketing adaptability is becoming a key competitiveness factor. The high M coefficient of Amazon and P&G demonstrates that the ability to quickly respond to changes in demand, offer personalized solutions and flexibly restructure communication channels significantly increases the efficiency of SCM. The recommendation for companies of all sectors is to develop marketing strategies closely integrated with logistics processes, which will simultaneously improve customer satisfaction and reduce costs. The third recommendation is related to increasing the digital maturity of supply chains (DSCMI). Companies should introduce innovations not only in operational processes, but also in data management: the use of Big Data, customer behavior analytics and blockchain technologies to ensure transparency and traceability of deliveries. This is especially important for logistics operators (Maersk, DHL), where digital transformation increases the reliability of deliveries, reduces risks and strengthens partner trust. Based on the combination of DEA efficiency, M and DSCMI, the final SCM Score is formed, which can be used for strategic planning. Companies with a low index should focus on three areas: resource optimization, implementation of digital tools, and increasing marketing flexibility. For the FMCG sector and retail, this means expanding digital sales channels and omnichannel services, and for logistics, strengthening integration with client platforms and demand analytics. Modern supply chain management requires a comprehensive approach that combines financial, technological and marketing efficiency. Implementation of these strategic recommendations will allow companies to adapt to global trends, increase sustainability and create additional competitive advantages, forming SCM as a strategic tool for business development in the digital economy.

The scientific novelty of the research lies in the development of an integrated analytical approach to evaluating supply chain management (SCM) strategies that combines digitalization, marketing adaptability, and information technology maturity within a single efficiency assessment framework. Unlike traditional SCM studies focused mainly on logistics optimization, this research introduces composite indicators such as the Digital Supply Chain Maturity Index (DSCMI), the Marketing Adaptability Coefficient (M), and the SCM-Score, allowing for a multidimensional assessment of efficiency and competitiveness. The pedagogical contribution of the study consists in providing a conceptual and methodological basis that can be integrated into academic programs on logistics, digital business, and marketing management. The presented models and indices may serve as practical teaching tools to explain the interrelation between digital transformation and supply chain performance, fostering a better understanding of cross-functional decision-making in the digital economy. The practical value of the research is manifested in the formulation of concrete recommendations for companies on how to improve SCM efficiency through the synchronization of logistics, marketing, and IT. The proposed approach enables managers to diagnose the level of digital maturity, identify weak links in the supply chain, and design data-driven strategies for sustainable and customer-oriented operations.

4 Conclusions

The study confirmed that the effectiveness of supply chain management (SCM) strategies in the digital economy depends not only on logistics optimization and cost reduction but also on the integration of marketing and information technology elements. Analysis of data from major global corporations - including Amazon, Walmart, Unilever, Nestlé, Procter & Gamble, Maersk, and DHL - demonstrated a strong relationship between process digitalization, marketing adaptability, and customer satisfaction indicators. The Data Envelopment Analysis (DEA) efficiency values (E) revealed differences in the rational use of resources. Companies with advanced digital infrastructures and automated SCM systems achieved the highest levels of efficiency. The Marketing Adaptability Coefficient (M) further confirmed that firms capable of promptly responding to market fluctuations maintained more stable and resilient supply chains. Additionally, the Digital Supply Chain Maturity Index (DSCMI) showed that technological maturity contributes directly to sustainability and competitive advantage by enabling accurate planning, real-time visibility, and uninterrupted supply flows. The development of a composite SCM-Score made it possible to evaluate the cumulative effect of digitalization, marketing adaptability, and IT implementation on overall supply chain performance. The results indicate that companies combining data analytics, predictive logistics, and marketing feedback loops achieve higher efficiency and customer retention. The obtained results are consistent with the findings of recent studies emphasizing digital transformation as a decisive factor in SCM performance [1,3]. Similar to conclusions drawn by [5,8] this research confirms that the integration of marketing tools and IT systems creates synergy, allowing enterprises to move from reactive to predictive supply chain models. However, unlike previous works, this study applies a combined framework of DEA, DSCMI, and M-coefficients, which together provide a multidimensional evaluation of SCM efficiency. A key contribution of this study lies in highlighting the interaction between marketing flexibility and technological maturity - an aspect often overlooked in traditional SCM analyses. The results demonstrate that digital transformation alone does not guarantee efficiency unless it is supported by customer-oriented marketing strategies. The comparison of leading firms shows that technological innovation must be balanced with data-driven market insights to achieve long-term sustainability. These findings also align with the global trend toward green and transparent supply chains, where digital traceability and cloud-based analytics ensure both efficiency and social responsibility. Therefore, the research supports the view that future-oriented SCM strategies should be built on three pillars: resource-based logistics, market-driven strategy, and process-orient the research demonstrates that digitalization, marketing adaptability, and IT maturity jointly determine the success of modern SCM strategies. Companies that integrate these components show higher operational efficiency, customer satisfaction, and strategic resilience. However, several limitations must be acknowledged. The analysis was based on secondary data from large international corporations, which may not fully reflect the context of small and medium-sized enterprises. In addition, the DEA and composite indices used provide a generalized efficiency estimate and may not capture qualitative factors such as cultural or regulatory differences. Future research should extend the analysis to include SMEs and regional supply networks, develop sector-specific digital maturity models, and test the proposed framework using longitudinal datasets. Another promising direction involves assessing the environmental and social dimensions of digital SCM and their integration with ESG (Environmental, Social, Governance) indicators.

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Simplex linear programming for route optimization model in urban distribution

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Abstract: This study proposes a mathematical model for optimizing delivery routes in the urban distribution of Coca-Cola FEMSA to OXXO stores in Texcoco municipality, State of Mexico. Based on a theoretical framework grounded in linear programming using the Simplex method and graph theory, an algorithm was developed and implemented in LINDO software to minimize logistics costs, distance traveled, and fuel consumption. This approach, in turn, ensures a more sustainable route by achieving a reduction in polluting gas emissions. The results show a 12.3% reduction in distance, decreasing from 66.25 km to 58.1 km, and a 12.4% saving in fuel costs, from 686.28 to 600.96 Mexican pesos, for the route. The results demonstrated a significant contribution to the reduction of the carbon footprint, with a decrease of approximately 2.04 kg of CO_2, achieving a more sustainable urban distribution and greater operational efficiency.

1 Introduction

The optimization of distribution routes represents a critical challenge in contemporary logistics management, particularly in emerging economies, where transportation inefficiencies can account for up to 30% of total operational costs [1]. For this reason, route optimization in emerging economies presents unique challenges due to specific infrastructural and operational conditions that can increase logistics costs by up to 25-30% compared to developed economies [2]. In Mexico, freight trucking handles 56% of the overland distribution of goods, generating logistics expenses that directly impact business competitiveness. This scenario is exacerbated in urban contexts such as Texcoco municipality, State of Mexico, where the convergence of factors like an accelerated annual population growth of 4.2%, an insufficient road infrastructure and a high vehicle density of 2,500 vehicles/km² during peak hours, generates congestion losses estimated at $92,000 million Mexican pesos (MDP) annually.

Fast-Moving Consumer Goods (FMCG) companies, such as Coca-Cola FEMSA a leader in bottling across Latin America with a presence in 10 countries [3] face complex logistical challenges, especially in distribution to convenience store chains like OXXO, which has over 22,000 stores in the region. This operational scale demands the implementation of robust mathematical solutions to optimize routes, reduce costs and guarantee delivery efficiency. In FMCG distribution, optimization implementations based on linear programming consistently validate savings of 10-15% in operational costs, with return on investment (ROI) periods of less than 6 months [4].

Previous studies demonstrate that optimization models can reduce logistics costs in urban distribution by up to 20% [5]. The use of methods such as linear programming (LP) [6], Graph Theory (GT) [7] and Origin-Destination (O-D) Matrix [8] has shown high effectiveness in improving the efficiency of transport route design and resource allocation. However, significant gaps persist. In the literature, for instance, there is research such as that by [9], which focuses on theoretical models with scarce empirical validation, while industrial applications, such as those reported by [10], lack adaptability to Latin American contexts. In these contexts, factors such as informal road networks with 35% of access points not mapped, demand variability and vehicle limitations, complicate implementation. Furthermore, it is essential to establish a direct link between modeling and real-world physical distribution. Optimization models adapted to the specific conditions of emerging economies have proven to be up to 25% more effective than generic approaches, particularly in contexts with limited road infrastructure [11].

Besides, most studies omit an integrated analysis of environmental sustainability, despite the fact that transport contributes to 24% of global CO_2 emissions. The correlation between distance reduction and decreased CO_2 emissions is well-established in the literature, where route optimizations of 10-15% typically generate proportional reductions in carbon footprint [12]. Work must be done on mobility systems that are human-centered and aim for transport sustainability. The integration of environmental criteria into logistics optimization models can generate CO_2 emission reductions of 1.5-2.5 tons annually per vehicle, contributing significantly to operational sustainability [13]. The failure to consider sustainability and environmental protection causes severe damage to human health.

The objective of this research was to develop a linear programming mathematical model solved using the Simplex method for the urban distribution of Coca-Cola FEMSA to 30 OXXO stores located in Texcoco municipality, Mexico. The model will be solved and implemented in LINDO Software, supported by extensive fieldwork and empirically validated. A combinatorial approach integrating the application of the Simplex method for multicriteria optimization will be adopted [14]. The application of the Simplex method to Vehicle Routing Problems (VRP) has demonstrated proven efficacy in reducing travel distances, with reported optimization levels of 10-15% in comparable industrial contexts [15]. The Simplex method, when applied to more complex urban distribution cases, has shown significant effectiveness, with reported cost reductions of 8-12% in route optimization for medium-duty freight vehicles [16].

The study employed a system of weighted directed graphs using arcs [17], as well as a statistical correlation analysis between distance and time. The model integrated a sustainability component through the quantification of carbon emissions, in alignment with the Sustainable Development Goals (SDGs) [9]. This research anticipates that the model will achieve a reduction of at least 10% compared to the current route in both distance and fuel consumption. In the Latin American context, the implementation of optimization models has proven to be particularly beneficial, with reported savings of 12-18% in logistics costs for manufacturing and distribution companies [18].

The relevance of this research transcends the case study, as it offers a replicable framework for supply chains in emerging economies, where logistics optimization can generate annual savings exceeding 15% across different sectors.

2 Literature review

Vehicle Routing Problems (VRP) seek to minimize operational costs, subject to constraints such as vehicle capacity, time windows and demand [17]. This research employs Graph Theory for the analysis of routes, legs and journeys. This theory belongs to the fields of mathematics and computer science, studying the properties of discrete structures composed of vertices (nodes) connected by edges, creating a highly analyzable representation of a transport route called "graphs". The theory formally emerged in 1736 with the work of Leonhard Euler, who solved the Königsberg bridge problem, laying the foundation for network analysis [19]. Its applications span from computer science to sociology, modeling relationships within complex systems.

A graph G is defined, according to Equation 1, as an ordered pair (1):

$$G = (V, E) \tag{1}$$

Where:

V is a non-empty set of vertices (e.g., $V = \{v_1, v_2, ..., v_n\}$).

E is a set of edges connecting pairs of vertices.

The main theorems used in the research are described below:

Euler's Theorem (published in 1736) states that a connected graph contains an Eulerian cycle if and only if all vertices have even degree.

The Theorem by [20] establishes that a graph is planar if and only if it does not contain a subdivision of K_5 (the complete graph on five vertices) or of $K_{3,3}$ (the complete bipartite graph with two sets of three vertices).

The Four Color Theorem states that any planar map can be colored using only four colors, such that no two adjacent regions share the same color [21].

The Origin-Destination (O-D) Matrix is a fundamental tool in route optimization, logistics and transportation studies. It quantifies flows between nodes to identify critical routes. O-D Matrix enables the identification of demand patterns by quantifying the demand between origin-destination pairs, thus allowing for the prioritization of critical flows [8]. The development of this Matrix facilitates the efficient allocation of vehicles, fuel and drivers by revealing travel volumes between zones [22]. It allows the reduction of operational costs and the consolidation of shipments or trips with similar destinations, minimizing empty kilometers and fuel costs. One aspect that is enhanced by the creation of the O-D Matrix is the simulation of scenarios to evaluate the impacts of changes in the network, such as new distribution centers or traffic and toll restrictions. It is also crucial for detecting inefficiencies by revealing imbalances like empty return trips or indirect routes. The O-D Matrix is highly valuable for integration with optimization algorithms, serving as an essential input for Vehicle Routing Problem (VRP) or Traveling Salesman Problem (TSP) models.

Linear Programming (LP) is a mathematical optimization technique used to maximize or minimize a linear objective function, subject to a set of linear equality or inequality constraints. It is fundamental in logistics, economics, engineering, and resource management. An LP model (2) is mathematically expressed as:

Objective Function:

$$Maximize\ (o\ Minimize)\ Z = c_1x_1 + c_2x_2 + \dots + c_nx_n \quad (2)$$

Subject to the set of Equations (3):

$$\begin{cases} a_{11}x_1 + a_{12}x_2 + \dots + a_{1n}x_n \leq b_1 \\ a_{21}x_1 + a_{22}x_2 + \dots + a_{2n}x_n \leq b_2 \\ . \\ . \\ . \\ x_j \geq 0\ (non-negativity\ constraint) \end{cases} \quad (3)$$

Where:

- x_j:Decision variables.
- c_j: Cost/benefit coefficients.
- a_{ij}, b_{ij}: Constraint parameters.

The first key element of an LP model is optimality—meaning it finds the optimal solution or best value of Z within a convex polytope, which is the feasible region defined by the constraints. Its *Fundamental Theorem* states that: if an optimal solution exists, it is located at a vertex of the polytope [23]. This algorithm pursues efficiency with low complexity; in practice, it is efficient, although in the worst case it is exponential [24]. The second element is the principle of duality, as every LP problem (*primal*) has an associated *dual* problem, which provides optimality bounds and enables sensitivity analysis.

The main limitations of Linear Programming (LP) lie in the fact that if the objective function or constraints are nonlinear, Nonlinear Programming (NLP) is required, which increases complexity. For integer variables involving discrete decisions, for example, the number of vehicles, Integer Programming (IP) is recommended.

LP is the scientific foundation for optimizing scarce resources in problems with linear relationships. In a routing study, it would enable the reduction of total fuel costs through a rigorous mathematical model, moving beyond a purely empirical approach.

The Simplex method, developed by George Dantzig in 1947, is a Linear Programming (LP) algorithm for optimizing functions subject to linear constraints. Its application in logistics allows for solving Vehicle Routing Problems (VRP) through mathematical formulation by transforming the real-world problem into linear equations; performing an iterative search moving between vertices of the polytope of feasible solutions; and ensuring convergence to guarantee finding the global optimum for convex problems [23].

Previous studies confirm that LP-based models reduce logistics costs by up to 20% [5]. Recent studies in Latin American contexts confirm the potential of these methods. [25] applied a route optimization model based on graphs and a simulated annealing algorithm for beverage distribution in Colombia, reporting a 14.7% reduction in distance traveled and a 15.3% saving in fuel consumption—results closely aligned with those obtained in this study.

3 Methodology

For the study, data was collected comprising the study area with 32 OXXO stores in Texcoco, supplied from the FEMSA CEDIS (Distribution Center) in Los Reyes (Geographic coordinates: 19°21'44.8"N 98°57'15.2"W).

Freightliner M2 (Figure 1) is a Class 6-7 commercial truck manufactured by Freightliner Trucks, a subsidiary of Daimler Truck North America. These vehicles are used by Coca-Cola FEMSA for distribution in the Mexico City metropolitan area. The aforementioned vehicles are equipped with either a Detroit Diesel DD5/DD8, Cummins B6.7, or L9 engine, depending on the configuration, and feature an automatic (Allison) or manual (Eaton) transmission with a payload capacity ranging from approximately 8,846 kg (Class 6) to 14,969 kg (Class 7).

Figure 1 Freightliner M2 Trucks for Coca-Cola FEMSA Distribution in Mexico
Source: Created by the author

The Freightliner M2 vehicle in its diesel version is equipped with either a Detroit DD13, DD15, or Cummins ISX engine and fuel tanks ranging from 380 to 570 liters; its estimated range is 965 to 1,930 km. Models with larger tanks can hold up to 757 liters, achieving a range of 2,414 km under optimal conditions. Key data include the location of OXXO stores in 2D geodetic coordinates, distances and travel times (Google Maps API), a fuel cost of $25.86 MXN/L based on the average price for the year 2025, and a fuel consumption rate of 2.5 km/L for the Freightliner M2. Fuel consumption is assumed to be constant due to the lack of detailed data on traffic conditions and transported cargo. This assumption is common in logistics research, as in the study by [5], which adopts a uniform consumption rate for solving Vehicle Routing Problems (VRP).

Table 1 shows the 2D geodetic coordinates, or geographic coordinates, of the nodes of interest for the study. These coordinates are expressed only with latitude and longitude, excluding the ellipsoidal height. This defines the position of a point on the surface of a reference ellipsoid, assuming it lies precisely on its surface (height = 0).

Table 1 Nodes and their geographic position from 2D geodetic coordinates

No.	**Location names**	**Latitude (N)**	**Longitude (W)**	**No.**	**Location names**	**Latitude (N)**	**Longitude (W)**
1	CEDIS Femsa Los Reyes	19°21'44.8"	98°57'15.2"	17	Mapex	19°28'49.7"	98°53'39.2"
2	Atlipac	19°22'07.3"	98°56'53.9"	18	Boyeros	19°29'50.5"	98°53'47.7"
3	Rio Laja	19°22'20.5"	98°56'46.0"	19	Orion	19°30'21.0"	98°52'49.7"
4	Tlazala	19°22'39.5"	98°56'35.2"	20	Emiliano Zapata	19°30'26.7"	98°53'34.5"
5	Camino a Las Minas	19°25'54.0"	98°54'30.3"	21	Gante	19°30'29.5"	98°53'05.5"
6	Cantu	19°23'56.4"	98°55'52.5"	22	Ursula	19°30'34.4"	98°53'37.9"
7	Francisco Chicoloapan	19°24'17.9"	98°55'38.5"	23	Allende	19°30'44.6"	98°52'57.1"
8	Ciruelos	19°24'41.9"	98°55'38.3"	24	Artega	19°30'44.8"	98°53'10.0"
9	Prolongacion Lerdo	19°24'41.3"	98°55'18.9"	25	Montes de Oca II	19°28'12.5"	98°54'03.2"
10	Cedro Chicoloapan	19°24'49.6"	98°55'10.9"	26	Asunción	19°27'35.8"	98°54'17.6"
11	Tlatel	19°24'59.0"	98°54'41.1"	27	Colón	19°27'18.9"	98°54'25.4"
12	2 de marzo	19°25'15.8"	98°54'23.8"	28	Texcoco Centro	19°30'42.3"	98°52'45.7"
13	Rio Manzano	19°25'20.5"	98°54'09.9"	29	Leandro Valle	19°29'55.1"	98°53'12.8"
14	Olmillos	19°26'14.9"	98°54'21.1"	30	Plaza Morena	19°31'07.4"	98°52'33.9"
15	Centro Cultural	19°27'12.7"	98°53'59.0"	31	Americas Texcoco	19°31'22.6"	98°52'18.5"
16	Acolhuacan	19°27'52.5"	98°52'55.0"	32	Camino San Simón	19°32'05.3"	98°51'47.2"
				33	Tocuila	19°33'14.8"	98°50'55.6"

Table 2 details the fuel expenditure (in MXN) and distance (in km) for each segment of the current operational route. The data is segmented into two parts with corresponding subtotals and a consolidated total. Particular focus is placed on minimizing distance in extended route segments (Ñ-Q, W-Z), which significantly influence overall operational expenses.

Table 2 Data from the current route obtained through field measurements, including fuel consumption and kilometers traveled

Route segments	Fuel cost (MXN)	Distance (km)	Route segments	Fuel cost (MXN)	Distance (km)
A-D	37.24	3.6	P-Q	75.51	7.3
D-C	6.72	0.65	Q-R	67.24	6.5
C-B	6.21	0.6	R-S	27.93	2.7
B-E	14.48	1.4	S-T	14.48	1.4
E-G	24.83	2.4	T-R	16.55	1.6
G-F	15.52	1.5	R-V	14.48	1.4
F-H	8.28	0.8	V-Y	20.68	2
H-I	15.52	1.5	Y-AA	9.82	0.95
I-J	7.24	0.7	AA-AC	11.38	1.1
J-K	16.55	1.6	AC-AE	7.78	0.75
K-L	11.38	1.1	AE-AB	11.38	1.1
L-M	32.07	3.1	AB-AD	10.34	1
M-N	21.72	2.1	AD-AF	4.65	0.45
N-Ñ	24.83	2.4	AF-X	9.82	0.95
Ñ-Q	44.48	4.3	X-W	6.2	0.6
Q-P	31.03	3	W-Z	59.96	5.7
Subtotal	**318.1**	**30.75**	**Subtotal**	**368.2**	**35.5**
			Total	**686.28**	**66.25**

Using the collected data, properly structured O-D matrices were developed based on distance, time, and cost. The analysis identified the most costly route segment as P→Q ($75.51 MXN) and the longest route segment as P→Q (7.3 km), with global totals of $686.30 MXN for fuel and a distance of 66.25 km.

During the model construction, the routing problem was formulated as a Linear Programming (LP) problem. Therefore, to optimize the distribution routes, the following elements are required:

Decision Variables:

x_{ij}: A binary variable (0 or 1) indicating whether the arc between nodes i and j is used.

In the the study carried out inTexcoco, 73 x variables represented segments between 33 nodes.

Objective Function equation (4):

$$Min\ Z = \sum_{i=1}^{73}(c_i * x_i) \tag{4}$$

Where:

c_i: cost of arc i (fuel cost in Mexican pesos, distance in km)
x_i: binary variable (1 if the arc is used, 0 otherwise)

Constraints equation (5):

$$\sum distance\ \leq 100\ km \text{ (vehicle range)} \tag{5}$$

For the purposes of the model, the range was restricted to only 100 km. This was based on criteria of simplicity, practical applicability, and empirical evidence, without precluding the vehicle's ability to operate over longer ranges if necessary. Equation (6) shows the fuel constraint.

$$\sum fuel\ cost\ \leq 1000\ MXN \tag{6}$$

Coverage constraints are shown in equation (7):

$$\sum_{arc\ x_j \epsilon S} X_j \geq 1 \tag{7}$$

(for each set S), where each inequality ensures that at least one arc exits from a critical node.

These constraints ensure the minimum connectivity of the network. The Simplex method utilizes an approach involving slack/artificial variables, and the analysis of reduced/dual costs will enable finding the optimal solution that minimizes costs while covering all critical nodes.

Connectivity constraint is shown in Equation 8:

$$destination\ node - \sum origin\ node \leq 0 \tag{8}$$

These constraints enable the modeling of connectivity between nodes in a network. Each variable X_i represents an arc between nodes, and inequalities ensure that the solution adheres to the hierarchy of connections. These constraints are essential for modeling hierarchical networks. The Simplex method guides the search toward solutions that respect actual connectivity, avoiding broken or infeasible routes.

Flow constraint equation (9) for intermediate nodes:

$$\sum x_{ij} - \sum x_{ji} = 0 \tag{9}$$

This constraint prevents infeasible solutions. Without this constraint, the model could propose "broken" routes. It also reduces costs by eliminating unbalanced flows that generate overcosts and, furthermore, achieves network integrity by ensuring that all intermediate nodes function as transshipment points, not storage points.

The model was implemented using LINDO software v18.0, utilizing the Simplex method. The problem dimension consisted of 73 decision variables and 45 linear constraints.

4 Results and discussion

The analysis of the geographical data and other metrics obtained for the optimization of the logistics transport network was conducted prior to implementing the improvement algorithms.

For the current route, the critical segments (high cost/km) were identified:

- **Q-P**: $31.03 MXN for only 3 km ($10.34 MXN/km).
- **W-Z**: $59.96 MXN for 5.7 km ($10.52 MXN/km).
- **Ñ-Q**: $44.48 MXN for 4.3 km ($10.34 MXN/km).
  (*These segments are priority candidates for optimization*).

Efficient segments (low total cost):

- **D-C**: $6.72 MXN for 0.65 km.
- **C-B**: $6.21 MXN for 0.60 km.
  (*Although the total cost is low, these are short segments; they could potentially be improved with more direct routes*).

Average cost per km equation (10):

$$Total: \frac{686.3\ MXN}{66.25\ km} = \$10.36\ MXN/km \tag{10}$$

Critical nodes were identified by calculating centrality (sum of times/distances) from each node to all others, revealing that Node E had the lowest values on the route (E→F: 3.2 min/7 km, E→G: 2.4 min/4 km). Node F was detected as key for fast connections (F→G: 0.8 min/1 km). This analysis indicates that Node E or F could serve as primary hubs to minimize total travel times.

The analysis identified strategic corridors, which are the most efficient segments of the route (low time/distance): F↔G: 0.8 min / 1 km; G↔H: 0.75 min / 4 km; and H↔I: 0.7 min / 3 km.

High-cost critical routes (to avoid or optimize): A↔AF: 25.15 min / 55 km and C↔AF: 27.35 min / 62 km.

Route Optimization through Clustering (Natural Clusters) is a technique that combines clustering algorithms with route optimization methods to improve efficiency in problems such as logistics distribution, goods delivery or transport services. The present research does not address this topic directly but mentions feasible zones for the application of clustering algorithms.

For this purpose, three distinct Zones are clearly shown in Table 3.

Table 3 Feasible zones for natural Clusters application

Clusters	Nodes	Internal time (min)	Distance (km)
Zone 1	E, F, G, H, I	< 4 min	< 11 km
Zone 2	J, K, L, M	< 5 min	< 15 km
Zone 3	Q, R, S, T	< 3 min	< 7 km

The recommended strategy is the consolidation of cargo within each cluster prior to inter-zone shipments.

Route segments were hierarchically classified for potential redesign, defined as:

High-Frequency Trunk Routes: E ↔ F ↔ G ↔ H ↔ I and Q ↔ R ↔ S ↔ T.

Secondary Routes: Serving as connections between clusters (E ↔ J, I ↔ Q).

Tertiary/Low-Priority Routes: Peripheral routes (A ↔ AF, C ↔ AF).

Through the application of the optimization model implemented in the LINDO v18.0 Software, using the Simplex method for multicriteria optimization, the route shown in Table 4 was obtained. This table shows that the route segment with the highest cost was P-Q, reaching $75.51 MXN; the longest route segment was P-Q with 7.3 km, resulting in a total fuel consumption for the route of $601.51 MXN and a total travel distance of 58.10 km.

Table 4 Route obtained through the Simplex method-based model for multicriteria optimization

Routes	Fuel cost (MXN)	Distance (km)	Routes	Fuel cost (MXN)	Distance (km)
A-D	37.24	3.6	P-Q	75.51	7.3
D-C	6.72	0.65	Q-S	44.48	4.3
C-B	6.21	0.6	S-U	10.34	1
B-E	14.48	1.4	U-T	8.79	0.85
E-G	24.83	2.4	T-R	16.55	1.6
G-F	15.52	1.5	R-AC	14.48	1.4
F-H	8.28	0.8	AC-AE	7.76	0.75
H-I	15.52	1.5	AE-AB	11.93	1.1
I-J	7.24	0.7	AB-AD	10.34	1
J-K	16.55	1.6	AD-AF	4.65	0.45
K-L	11.38	1.1	AF-X	9.82	0.95
L-M	32.07	3.1	X-W	6.2	0.6
M-N	21.72	2.1	W-V	19.65	1.9
N-Ñ	24.83	2.4	V-Y	20.68	2
Ñ-O	44.48	4.3	Y-AA	9.82	0.95
O-P	31.03	3	AA-Z	12.41	1.2
Subtotal	**318.1**	**30.75**	**Subtotal**	**283.41**	**27.35**
			Total	**601.51**	**58.1**

Table 5 shows a precise comparison of the most important metrics between the current route and the optimized route. A relatively considerable decrease in distance, consumption and time of 12.3%, 12.4% and 12.2%, respectively, is observed. These figures align approximately with those reported by [26], which states that in the beverage sector, route optimization via linear programming has enabled average reductions of 14.2% in distance traveled and 13.8% in fuel consumption.

Table 5 Optimized route vs. current route

Metrics	Current route	Optimized route	Reduction (%)
Distance (km)	66.25	58.10	12.3%
Fuel consumption (MXN)	686.28	601.51	12.4%
Time (min)	180	158	12.2%

This study demonstrates practical implications of significant interest, as the estimated annual savings amount to $62,243 MXN/year. This is derived from a route cost of $85.32 MXN/route, considering 2 routes/day over 365 days in a year. This represents a considerably high emissions reduction, as the distribution distance is reduced by 8.15 km compared to the current route. The vehicles analyzed in this research emit 0.25 kg of CO_2/km. Consequently, the optimized route achieved a decrease in emissions, with a reduction of approximately 2.04 kg of CO_2 per day, leading to an annual reduction of 1.49 metric tons of CO_2/year, thereby contributing to environmental protection. The model presents advantages through its replicability and it is applicable to other FEMSA routes or similar companies. It is scalable, as it can be easily adapted to dynamic constraints by incorporating parameters such as traffic and demand.

The main limitations of this model are that it does not account for real-time traffic variability and assumes a constant demand, thereby avoiding a seasonality analysis.

Figure 2 shows the operational logistics network based on consumption and distances, featuring 33 nodes and 32 route segments, where the route segments with their trajectories, fuel consumption and travel distances are visualized.

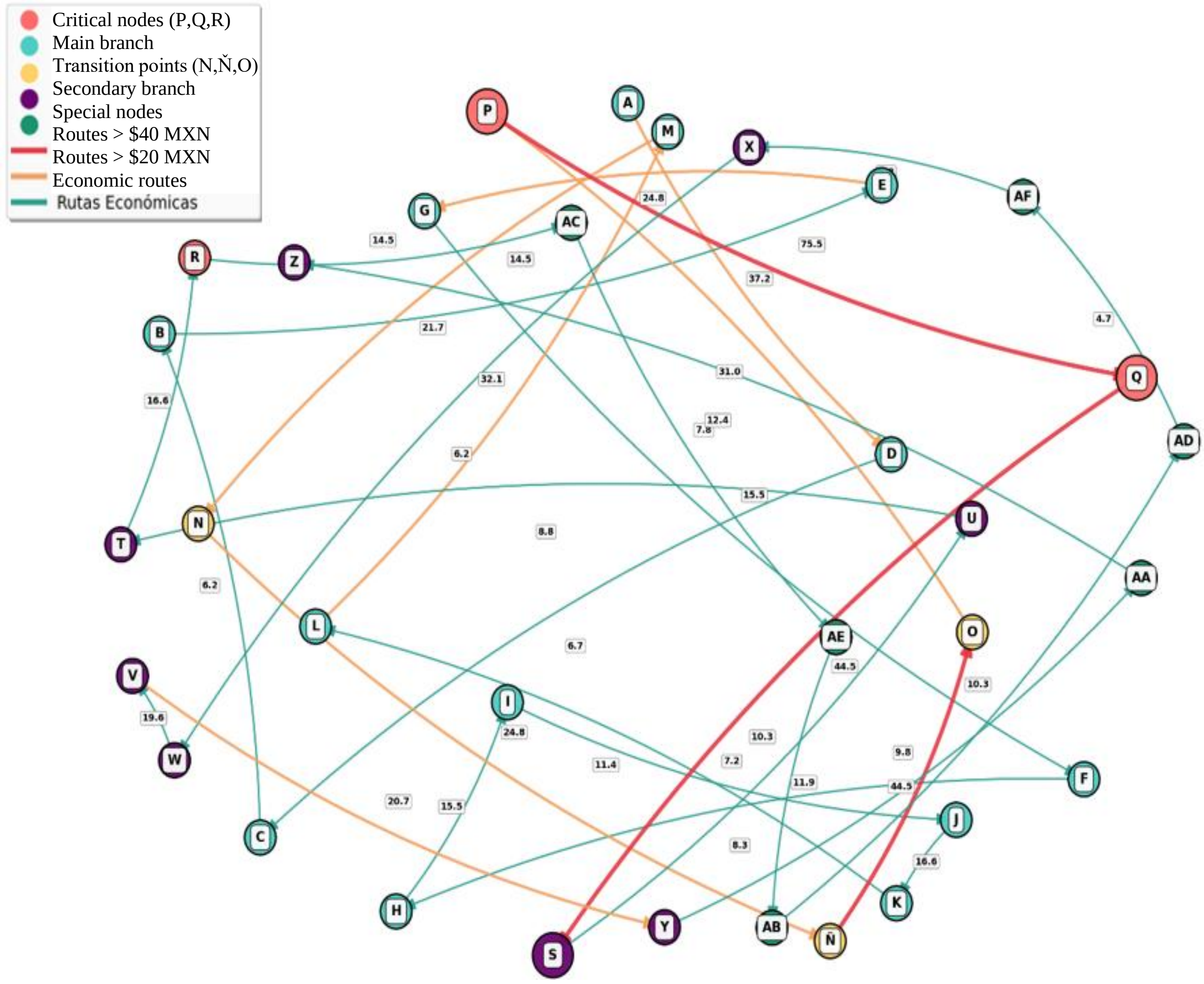

Figure 2 Operational logistics network graph obtained with the simplex model

5 Conclusions

The implementation of the model successfully obtained a route with a shorter distance, reducing it by 12.3%. Fuel consumption was reduced by 12.4%, validating the model's effectiveness in optimizing routes under urban distribution conditions.

The results from applying the model achieved a significant reduction in annual emissions, reaching approximate values of 1.49 metric tons of CO_2/year. This enhances the company's sustainability through a considerable decrease in its carbon footprint.

The integration of linear programming with the Simplex method enables handling problems with multiple constraints; however, it is limited to determining an optimal route without considering traffic conditions or variable demand.

The Simplex method is designed for continuous linear programming problems, where variables can take fractional values. However, in vehicle routing, many variables are integer-based. This requires Integer Linear Programming (ILP) or Mixed-Integer Linear Programming (MILP), where the pure Simplex method is insufficient.

It is important to emphasize that the Simplex method is not practical for Traveling Salesman Problems (TSP), which follow a Hamiltonian cycle, due to their combinatorial nature.

For large-scale optimization problems, its integration with metaheuristics is necessary to provide an optimal balance between precision and computational efficiency.

6 Recommendation

Use specific algorithms for TSP: For small instances ($n \leq 50$): Held-Karp or ILP solvers (Gurobi/CPLEX); for large instances: Heuristics (Christofides for 1.5-optimality guarantees) or metaheuristics (tabu search).

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Climate disclosure and carbon tax: accounting insights on earnings volatility in Indonesian transportation firms

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Keywords: carbon tax exposure, climate risk disclosure, earnings volatility, sustainability accounting, transportation logistics.
Abstract: Climate risk disclosure has become a key focus in corporate sustainability reporting, but its financial consequences remain underexplored in high-emission industries. In Indonesia's transportation and logistics sector, where dependence on fossil fuels and regulatory volatility is high and significantly impacts the gross domestic product, the relationship between transparency, taxation, and financial performance warrants further study. This study aims to investigate how climate risk disclosure affects earnings volatility, considering carbon tax exposure as a mediating mechanism and company size as a moderating variable. This study utilizes panel data from publicly listed transportation and logistics companies spanning the period from 2022 to 2024. It applies hierarchical linear regression with mediation and moderation techniques. The analysis shows that increased disclosure leads to higher carbon tax exposure, which fully mediates the effect on earnings volatility. Firm size does not significantly moderate this path, suggesting that larger firms are not necessarily more insulated from fiscal risks associated with climate policy. This finding challenges the assumption that transparency inherently reduces uncertainty. While disclosure can enhance a firm's reputation, it also increases its fiscal visibility and vulnerability. The evidence suggests that the tax consequences of disclosure should not be considered incidental but rather an integral part of corporate financial planning. This study contributes to the advancement of tax accounting discourse by repositioning climate disclosure as a fiscal risk factor. The results have important implications for regulatory design, corporate governance, and sustainable transition strategies in carbon-intensive sectors.

1 Introduction

In recent decades, the interplay between environmental imperatives and fiscal policy has dramatically reshaped the foundations of managerial and tax accounting, especially in rapidly emerging economies [1]. Indonesia, a country characterized by a complex industrial base and an ambitious development agenda, is facing growing international and domestic pressure to realign its corporate practices with the principles of decarbonization and environmental stewardship [2]. The introduction of carbon taxation has emerged as a defining feature of this transformation. While traditionally perceived as an externality pricing mechanism, carbon taxes have now evolved into a critical instrument that shapes strategic decisions, resource allocation, and financial reporting in high-emission sectors such as transportation and logistics [3,4]. Besides being the largest contributor to emissions, inefficiencies in the transportation sector will impact the logistics system. This sector has a significant impact on businesses. In Indonesia, the logistics sector accounts for approximately 27-29% of the Gross Domestic Product.

Carbon tax frameworks are designed to internalize the social costs of greenhouse gas emissions and incentivize firms to adopt cleaner technologies. However, for publicly listed companies, these policies also generate significant uncertainties surrounding compliance costs and profit stability. Earnings volatility arises not only from fluctuating energy inputs and carbon liabilities but also from the reputational pressures imposed by institutional investors and regulators, who demand more transparent disclosure of climate-related risks. Firms are increasingly expected to articulate the scope of their emissions, mitigation strategies, and adaptation plans in annual reports and sustainability disclosures [5].

In this evolving regulatory environment, climate risk disclosure has emerged as both a signal of corporate legitimacy and a potential source of fiscal exposure [6]. On one hand, transparent reporting can mitigate information asymmetry and bolster stakeholder confidence by demonstrating that managers are proactively managing environmental risks [7]. This perspective is grounded in agency theory, which argues that enhanced disclosure mechanisms serve to align managerial behavior with the expectations of shareholders and regulators [8]. On the other hand, the same disclosures can provide tax authorities with granular data to assess liabilities with greater precision, thereby intensifying the fiscal burden placed on firms [9].

While these trade-offs are recognized in developed economies with mature carbon pricing systems, they remain underexplored in emerging markets such as Indonesia. The transportation and logistics industry, in particular, occupies a critical position in this debate. As a sector highly dependent on fossil fuels and complex supply chains, it is uniquely vulnerable to both regulatory shocks and market fluctuations. Yet, paradoxically, it is also the sector most likely to drive growth and employment. The resulting tension between sustainability objectives and economic imperatives highlights the importance of understanding how carbon tax exposure and disclosure practices interact to influence financial performance [10].

[11] explain that climate uncertainty is significantly negatively correlated with corporate risk levels in emerging markets, which deviates from previous findings based on international evidence. Managers have greater incentives to conceal business risks under climate uncertainty in these markets, resulting in a discrepancy between a firm's actual business risk and its reported business risk. This phenomenon demonstrates greater information asymmetry in emerging markets, where transparency and risk disclosure are often suboptimal. This poses additional challenges for investors and policymakers in assessing the true risks faced by firms, necessitating the use of more cautious approaches and adaptive evaluation methods to anticipate potential hidden losses.

Climate change is currently a critical global issue, making the reduction of carbon emissions a crucial step toward environmental sustainability. Concern about this has prompted various stakeholders to take action and seek solutions [11]. Companies are voluntarily disclosing their carbon emission levels, while stakeholder pressure on carbon performance continues to increase [11]. Numerous studies have shown a link between carbon emission disclosure and financial reporting practices within organizations [11]. Furthermore, transparency in carbon emission reporting not only enhances corporate accountability but can also influence market perception and the company's value. In this context, honest and accurate disclosure of carbon emissions is a crucial instrument for achieving sustainable development goals and encouraging innovation in environmentally friendly technologies. Therefore, regulators and investors are increasingly demanding that companies systematically and sustainably integrate carbon emission measurement and reporting into their reporting systems.

Beyond regulatory compliance, the internal dynamics of firms also play a crucial role in shaping their response to environmental pressures. Recent evidence suggests that leadership style significantly strengthens corporate governance systems and enhances employee engagement [12], which in turn facilitates the successful implementation of sustainability initiatives. Firms with inclusive and transformational leadership practices are more likely to integrate climate considerations into their strategic decision-making and to cultivate organizational cultures that support transparent reporting [13]. These internal capabilities may mediate or moderate the financial consequences of external shocks such as carbon taxation.

Moreover, firm size is widely theorized as a determinant of resilience to fiscal and regulatory pressures. Larger firms typically possess the financial and human resources necessary to absorb carbon-related costs, invest in technological innovation, and manage stakeholder expectations [14]. Their capacity to spread compliance expenses across diversified revenue streams can stabilize earnings and mitigate volatility. In contrast, smaller firms often lack comparable slack resources, rendering them more exposed to abrupt shifts in policy and market sentiment.

Despite this conceptual foundation, empirical studies have yet to establish a comprehensive account of how these factors jointly shape earnings volatility in developing economies. The literature remains fragmented, with most contributions focusing on either the disclosure dimension or the taxation dimension in isolation. This gap limits our understanding of the complex mediating and moderating mechanisms through which climate risk disclosures and carbon tax exposure interact to influence profitability and risk profiles. In addition, few studies have examined the specific challenges faced by transportation and logistics companies in Indonesia, where carbon pricing policies are only gradually transitioning from voluntary guidelines to enforceable mandates.

This study is motivated by the need to address this lacuna in the literature and to inform policy debates surrounding the design and implementation of carbon tax regimes. By investigating whether climate risk disclosures reduce or amplify earnings volatility, whether carbon tax exposure mediates this relationship, and whether firm size moderates the effect, this research aims to contribute novel insights into the intersection of environmental transparency and fiscal accountability. Specifically, this study aims to test and analyze the effect of climate risk disclosure on earnings volatility with carbon tax exposure as a mediator and company size as a moderator. Furthermore, it situates the analysis firmly within the disciplines of managerial and tax accounting, thereby offering a more integrated perspective on how sustainability-related practices reshape financial reporting and performance in emerging economies.

Specifically, the study focuses on publicly listed transportation and logistics companies in Indonesia from 2022 to 2024, an interval marked by heightened scrutiny of corporate environmental practices and the gradual institutionalization of carbon pricing. The findings are expected to enrich theoretical debates in accounting scholarship while offering practical guidance to policymakers seeking to reconcile environmental objectives with economic resilience. For managers, understanding the nuanced interplay between disclosure, taxation, and firm characteristics can inform more effective strategies to navigate the uncertainties of a carbon-constrained future.

2 Literature review

The following section synthesizes the theoretical and empirical foundations informing this study's conceptual model. Grounded in agency theory, contingency theory, and the resource-based view, the review begins by examining how climate risk disclosures may shape earnings volatility through mechanisms of transparency, signaling, and exposure to regulatory scrutiny. This analysis then examines the relationship between disclosure practices and carbon tax exposure, highlighting the paradox that firms committed to greater transparency can simultaneously incur increased fiscal liabilities. Building on these insights, the discussion explores the role of carbon tax exposure itself as a determinant of earnings volatility, particularly in sectors characterized by high carbon intensity and regulatory uncertainty. To capture the complexity of these interdependencies, a mediating pathway is theorized in which carbon tax exposure transmits the effects of disclosure on financial performance. Finally, the review examines whether firm size moderates these relationships, enabling larger firms to leverage superior resources and governance capabilities to mitigate volatility.

2.1 Climate risk disclosure and earnings volatility

Climate risk disclosure has emerged as a core mechanism by which firms communicate their environmental vulnerabilities and strategic responses to multiple stakeholders, including regulators, investors, and civil society. Drawing upon agency theory, enhanced transparency is widely understood to reduce information asymmetry and build legitimacy in the eyes of capital providers [5,8]. This means that increased transparency can encourage management to provide more accurate and relevant information about company performance, thereby minimizing potential conflicts of interest between agents and principals. In this context, transparency serves as an effective oversight mechanism to ensure that agent decisions align with the principal's interests, thereby enhancing principal trust. For firms operating in carbon-intensive industries, such disclosures also serve as signals of commitment to decarbonization, potentially mitigating reputational risks and stabilizing market expectations.

[11] explain that there is a positive relationship between climate risk disclosure and firm value. This condition suggests that the higher the level of climate risk disclosure a company undertakes, the greater the principal's trust in the company's commitment to managing environmental risks responsibly. However, this relationship can turn negative as attention to climate change intensifies. This may be due to increased risk perception, which can create market uncertainty and depress firm value. Furthermore, the costs companies incur to manage climate risk can increase significantly, reducing short-term profitability. Therefore, companies need to strike a balance between transparency in climate risk disclosure and effective adaptation strategies, thereby maintaining firm value while contributing to environmental sustainability.

Yet in contexts where carbon taxation is in the process of institutionalization, as in Indonesia, the stabilizing effect of disclosure may be counterbalanced by unintended fiscal exposure. Disclosing granular emissions data and climate strategies creates precise benchmarks that tax authorities can leverage to impose or adjust carbon liabilities [10,15]. In other words, transparency designed to enhance accountability can paradoxically introduce new layers of earnings uncertainty. This situation arises from the potential for more detailed disclosure of information on emissions and climate strategies, which could create new fiscal risks for companies, particularly when governments use this data to tighten regulations. The implication is that companies could face market value volatility due to policy uncertainty and future compliance costs.

This duality underscores the need for an empirical examination of whether climate disclosures ultimately dampen or exacerbate earnings volatility when carbon pricing policies are in flux. While theoretical arguments favor a negative association between disclosure and volatility, rooted in the notion that informed stakeholders react less erratically to environmental shocks, the evidence in emerging economies remains scarce and inconclusive.

H_1: Climate risk disclosures have a negative effect on earnings volatility.

2.2 Climate risk disclosure and carbon tax exposure

The relationship between climate risk disclosure and carbon tax exposure reflects a tension between proactive environmental management and the risks of regulatory visibility. The resource-based view suggests that firms with the capabilities to integrate sustainability into core operations tend to disclose more comprehensively and, over time, reduce their exposure to regulatory sanctions and taxation [16]. This means that companies that are able to leverage internal resources such as green technology innovation, energy efficiency, and strong environmental management systems have the potential to prevent regulatory and market pressures related to climate issues. These firms often develop sophisticated carbon management practices, such as investments in cleaner technologies and supply chain decarbonization, which may ultimately result in lower taxable emissions.

However, in regulatory environments where enforcement mechanisms are evolving, increased disclosure can lead to heightened scrutiny. Publicly reported emissions inventories and mitigation commitments can provide tax authorities with authoritative evidence to substantiate higher carbon tax assessments. This dynamic is particularly salient in transitional economies, where administrative capacity to collect and interpret environmental data is expanding alongside policy ambitions [17]. The implication is that companies are faced with a strategic dilemma between maintaining transparency to gain legitimacy and market trust or limiting the dissemination of information to reduce the risk of fiscal intervention that could harm the company.

[11] explain that climate risk disclosure can reduce carbon emissions. Furthermore, physical climate risk disclosure is preferred for short-term carbon emissions. Conversely, transformational climate risk disclosure is preferred for long-term carbon reduction purposes. Therefore, high-quality climate risk disclosure can effectively mitigate the negative impact of a company's carbon emissions on its solvency and profitability compared to companies with lower levels of disclosure, highlighting the importance of high-quality climate risk disclosure. Hence, while disclosure is expected to be associated with improved long-term performance and compliance readiness, its immediate impact on tax exposure remains ambiguous and warrants empirical validation.

H_2: Climate risk disclosures have a negative effect on carbon tax exposure.

2.3 Carbon tax exposure and earnings volatility

Carbon taxation directly affects firms' cost structures by internalizing the price of emissions. For firms in transportation and logistics, where fuel consumption constitutes a material proportion of operating expenses, these costs can be substantial and highly variable. Contingency theory posits that firms lacking robust adaptive capabilities are more likely to experience elevated earnings volatility in response to external shocks such as tax reforms [18]. In this context, companies that can adapt their operational and financial strategies are key factors in mitigating the impact of carbon taxes. Large companies that can invest in low-carbon technologies or implement energy efficiency measures tend to be more resilient in maintaining stable financial performance. Conversely, companies with a high dependence on fossil fuels and rigid cost structures are more vulnerable to profit fluctuations due to increasing carbon tax burdens. Thus, contingency theory explains the importance of a match between a company's internal characteristics and external environmental policy pressures for companies to maintain long-term competitive advantage.

Changes in GHG emissions increase changes in stock market volatility, while countries with high GHG emissions primarily drive changes in climate change risk and volatility [19]. This suggests that uncertainty related to regulation and adaptation to climate change has a direct impact on financial market dynamics. Therefore, investors and market participants must consider these environmental factors as critical variables in investment decision-making to anticipate risks arising from climate change and emission reduction policies. Companies that are aware of climate risks have the potential to enhance the integration of environmental, social, and governance (ESG) aspects into their investment analysis, thereby assessing the company's long-term sustainability and resilience. Furthermore, investors who are responsive to climate issues are also more likely to invest in companies that prioritize environmental concerns.

Empirical research supports this assertion, showing that carbon liabilities exacerbate profit variability by introducing unpredictable compliance costs and by influencing commodity price dynamics [20]. In emerging markets, these pressures are magnified by fluctuating enforcement practices and the absence of mature carbon offset markets that could otherwise buffer volatility. Therefore, it is reasonable to expect that firms with greater carbon tax exposure will report more pronounced fluctuations in earnings performance.

H_3: Carbon tax exposure has a positive effect on earnings volatility.

2.4 Mediating role of carbon tax exposure

The mediating role of carbon tax exposure represents a pathway through which climate risk disclosure indirectly influences earnings volatility [21]. Higher climate risk disclosure can increase a company's visibility to regulators, potentially increasing its exposure to carbon tax policies. This suggests that increased carbon tax exposure can, in turn, impact a company's cost structure and profit margins, as reflected in fluctuations in earnings. Companies committed to transparently reporting emissions and mitigation strategies may become more visible to regulators and thus more vulnerable to short-term carbon liabilities. This exposure, in turn, can increase the volatility of financial results.

This mediating mechanism integrates agency theory and contingency perspectives by acknowledging that transparency enhances stakeholder confidence but can simultaneously create operational and fiscal risks [22]. The relationship between climate risk disclosure and financial performance depends on the organizational context and regulatory environment in which a company operates. Based on agency theory, transparency serves as a tool to reduce information asymmetry and strengthen the agent's accountability to the principal. However, based on contingency theory, the effectiveness of transparency can be influenced by the company's ability to adapt to external pressures, such as changes in carbon tax policy and energy market dynamics. For firms in Indonesia's transportation sector, where carbon taxes are still being gradually enforced, this dynamic is especially relevant [23]. By empirically testing this pathway, the study contributes to a more nuanced understanding of how disclosure practices translate into financial consequences in transitional regulatory contexts.

H_4: Carbon tax exposure mediates the relationship between climate risk disclosures and earnings volatility.

2.5 Moderating role of firm size

Firm size has long been theorized as a salient moderator of firms' resilience to environmental and fiscal pressures. Larger organizations tend to possess greater resource slack, diversified revenue streams, and more sophisticated management systems that can absorb and mitigate the impact of regulatory shocks [24]. Furthermore, they often have greater bargaining power and capacity to invest in emissions-reduction technologies. Larger firms are generally better able to adapt to environmental policy changes, including the implementation of carbon taxes, without experiencing significant disruptions to their profitability. This suggests that their economies of scale enable cost efficiencies and the implementation of long-term mitigation strategies through green technology innovation. Conversely, smaller firms with limited resources tend to be more vulnerable to fiscal and regulatory pressures due to their relatively limited capacity for adaptation and investment.

Recent scholarship also underscores the importance of internal control capabilities in shaping organizational responses. [25] found that effective internal control strengthens governance structures and fosters employee engagement, which can enhance a firm's ability to integrate climate considerations into its core strategies. In combination with firm size, these attributes may moderate the extent to which climate disclosures translate into volatility. Consequently, it is anticipated that the negative association between climate risk disclosures and earnings volatility will be stronger among larger firms, reflecting their superior capacity to transform transparency into strategic advantage.

H_5: Firm size moderates the relationship between climate risk disclosures and earnings volatility.

Based on the description of the hypothesis development that has been explained previously, this research can be visualized as shown in Figure 1.

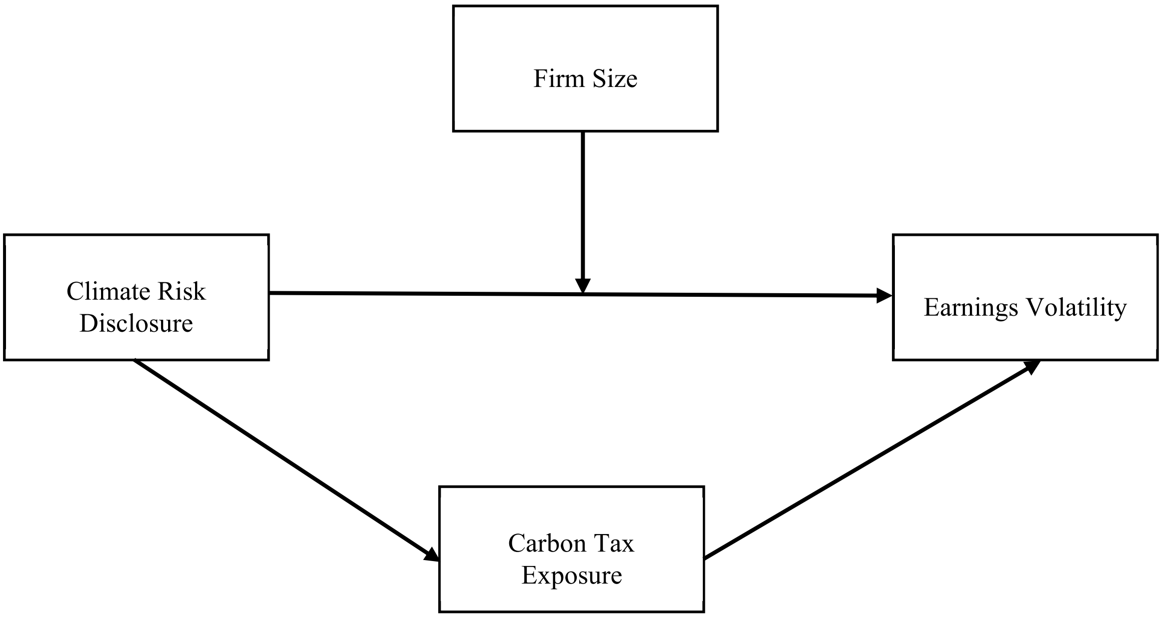

Figure 1 Research framework

This framework illustrates the hypothesized structural relationships among the core variables. Climate risk disclosure is posited to influence earnings volatility both directly and indirectly through carbon tax exposure as a mediating variable. Firm size is introduced as a moderator, affecting the strength of the direct relationship between climate disclosure and earnings volatility.

3 Methodology

This study adopts a rigorous quantitative approach combining panel data regression models with mediation and moderation analysis to examine the relationships among climate risk disclosures, carbon tax exposure, and earnings volatility in Indonesia's transportation and logistics sector. The methodology has been designed to ensure internal validity, address potential sources of bias, and maximize transparency in reporting.

3.1 Research design

A longitudinal panel data design was selected to capture both firm-specific heterogeneity and temporal dynamics over the observation window of 2022-2024. Panel models are particularly suited for this context because they allow researchers to control for unobserved time-invariant characteristics that may confound the associations of interest [26]. This design is also appropriate given the staggered introduction of carbon taxation policies in Indonesia, which creates temporal variation in firms' exposure and disclosure practices. The empirical strategy was guided by the study's conceptual framework and five hypotheses derived from agency theory, contingency theory, and the resource-based view. The methodological framework was informed by prior empirical investigations of environmental disclosure and earnings volatility and adapted to the Indonesian institutional context, where carbon pricing mechanisms are evolving but not yet fully institutionalized.

3.2 Sample and data collection

The target population comprised all transportation and logistics firms listed on the Indonesia Stock Exchange (IDX) that disclosed annual financial and sustainability reports during the study period. Firms were selected through purposive sampling, applying three criteria:

a) Consistent publication of audited financial statements and sustainability reports between 2022 and 2024.
b) The company uses the rupiah currency in its reporting.
c) Complete research variable data is available according to the proxy.

These criteria were chosen to ensure both data completeness and relevance to the research objectives. Data were retrieved from multiple publicly accessible sources, including IDX filings, corporate websites, and the Indonesian Financial Services Authority database. The final balanced panel consisted of 30 firms across 3 firm-year observations.

3.3 Variable measurement and operationalization

To ensure alignment with international standards and comparability with prior literature, all variables were carefully operationalized as summarized in Table 1. This approach not only ensures consistency in data analysis but also enhances the validity of the research results, ensuring their widespread acceptance by the scientific community. Furthermore, the operational definitions of the variables have been aligned with European methodological guidelines to minimize bias and ensure understanding of the study results. The choice of ROA over ROE is consistent with reflecting the heterogeneous capital structures in Indonesian firms, which could otherwise distort volatility estimates.

Table 1 Variable operationalization

Variable	**Definition**	**Measurement and Justification**	**Data Source**
Climate Risk Disclosure	Extent of disclosure on climate risks, strategies, and performance	A dummy variable with a value of 1 if disclosed and 0 otherwise.	Sustainability Reports, Annual Reports
Carbon Tax Exposure	Degree of exposure to carbon-related taxes or liabilities	A dummy variable with a value of 1 if disclosed and 0 otherwise.	Financial Statements, ESG Reports
Earnings Volatility	Variability of earnings over time	Standard deviation of Return on Assets (ROA) over the three-year period. ROA was selected over ROE to reduce capital structure bias.	Income Statement, Statement of Financial Position
Firm Size	Scale of firm resources	Natural logarithm of total assets. This transformation addresses skewness and allows comparability across firms.	Statement of Financial Position

3.4 Model specification

The analytical framework consisted of three complementary panel regression models designed to test the hypothesized relationships between climate risk disclosure, carbon tax exposure, and earnings volatility. The first model examined direct effects by estimating whether disclosure practices and carbon tax exposure independently predicted fluctuations in profitability, while controlling for firm size and baseline financial performance. This specification was intended to assess the main associations consistent with agency theory and the resource-based view. The second model applied a two-stage procedure to test mediation, where carbon tax exposure was first regressed on climate risk disclosure and controls to evaluate whether disclosure practices increased fiscal liabilities, followed by a regression of earnings volatility on both disclosure and tax exposure. This approach enabled the assessment of whether carbon tax exposure acted as a mechanism linking transparency to earnings instability.

To further explore whether firm characteristics conditioned these relationships, the third model incorporated an interaction term between climate risk disclosure and firm size to test moderation effects. A statistically significant interaction coefficient would indicate that the impact of disclosure on earnings volatility varied depending on organizational scale, reflecting contingency theory perspectives. All models were estimated using both fixed-effects and random-effects specifications, with the Hausman test applied to guide model selection based on consistency assumptions. Prior to estimation, continuous variables were mean-centered to facilitate interpretation and reduce the risk of multicollinearity in the interaction models. This modeling strategy was designed to ensure robust and interpretable results that could directly address the hypotheses and provide meaningful insights into how disclosure practices and fiscal exposure interact to shape financial volatility in emerging market settings.

3.5 Estimation strategy

The estimation approach in this study was structured to rigorously test the hypothesized relationships among climate risk disclosure, carbon tax exposure, and earnings volatility while addressing the potential biases inherent in firm-level panel data. Both fixed-effects and random-effects models were estimated to leverage the longitudinal nature of the data and to account for unobserved firm characteristics, such as managerial orientation or governance practices. The Hausman specification test guided the choice of estimator by determining whether regressors were correlated with the unique error components. To ensure the validity of the results, diagnostic procedures were applied, including Variance Inflation Factor assessments to detect multicollinearity, Breusch-Pagan and Cook-Weisberg tests for heteroskedasticity. All continuous variables were mean-centered before estimating interaction terms to reduce multicollinearity and to enhance the interpretability of coefficients within the moderation models. To examine the impact of climate risk disclosure on carbon tax exposure, this study employs logistic regression.

Mediation analysis was conducted using a two-stage procedure, first regressing climate risk disclosure and carbon tax exposure on earnings volatility, and subsequently regressing climate risk disclosure on carbon tax exposure. The significance of the indirect effect was tested through a mediation analysis procedure. This estimation strategy was designed to ensure that the results were robust, transparent, and capable of capturing the complex dynamics linking disclosure practices, fiscal exposure, and volatility in an evolving regulatory environment.

4 Results

This section presents the empirical findings derived from the panel regression analyses conducted to evaluate the study's hypotheses. Three models were estimated sequentially to examine the direct effects of climate risk disclosure and carbon tax exposure on earnings volatility, the mediating role of tax exposure, and the moderating influence of firm size. Each model specification was assessed using appropriate diagnostic and model fit criteria, and the results are described in detail below.

4.1 Model 1: direct effects of climate risk disclosure and carbon tax exposure on earnings volatility

The results of Model 1 indicate that climate risk disclosure (CRD) has no statistically significant direct effect on earnings volatility ($\beta = -0.041$; $p > 0.10$). This outcome diverges from initial expectations that transparency would stabilize firm performance by reducing uncertainty and enhancing investor confidence. Instead, the data suggest that greater disclosure alone does not buffer firms in the transportation and logistics sector from volatility pressures, particularly in an emerging market context marked by regulatory fluidity and weak enforcement.

Likewise, the interaction term between CRD and firm size (CRD × FS) is not statistically significant ($\beta = -0.038$; $p > 0.10$), indicating that larger firms do not experience a materially different relationship between climate disclosure and volatility compared to their smaller counterparts. This challenges assumptions rooted in the resource-based view, which often attributes superior risk management capabilities to firms with greater assets and reporting infrastructure. In this case, size does not necessarily translate into effective disclosure or stable earnings. These findings direct attention toward other mechanisms, such as fiscal exposure, which may be more decisive in shaping volatility patterns in carbon-intensive sectors.

Table 2 presents the hypothesized relationships among climate risk disclosure, carbon tax exposure, firm size, and earnings volatility. Climate disclosure is posited to influence earnings volatility both directly and indirectly through carbon tax exposure as a mediating variable. Firm size is included as a moderating factor that may condition the direct relationship between disclosure and volatility. While the full structural model reflects this mediated moderation design, the empirical results confirm a significant mediation effect via carbon tax exposure, but find no direct effect of disclosure on earnings volatility, nor a moderating effect of firm size.

Table 2 Direct effects of disclosure and carbon tax exposure on earnings volatility

Dependent Variable	: EV
Method	: Panel Least Squares
Data	: 07/20/25 Time: 01.02
Sample	: 2022 2024
Periods Includes	: 3
Cross-sections included	: 30
Total panel (balanced) observations	: 90

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.048148	0.084651	0.568779	0.5715
CRD	-0.087162	0.142798	-0.610390	0.5440
CTD	0.294264	0.142798	2.060703	0.0438
Effects Specification				
Cross-section fixed (dummy variables)				
R-squared	0.495412	Mean dependent var		0.142130
Adjusted R-squares	0.225719	S. D. dependent var		0.405707
S.E. of regression	0.356994	Akaike info criterion		1.049552
Sum squared resid	7.391813	Schwarz criterion		1.938373
Log likelihood	-15.22982	Hannan-Quinn criter.		1.407976
F-statistic	1.836947	Durbin-Watson stat.		2.301464
Prob(F-statistic)	0.022784			

Source: Processed research data

4.2 *Model 2: mediation analysis of carbon tax exposure*

Model 2 explores whether carbon tax exposure (CTE) mediates the relationship between climate risk disclosure (CRD) and earnings volatility (EV). The regression analysis confirms that CRD has a statistically significant positive effect on CTE ($\beta = 0.273$; $p < 0.01$), suggesting that greater disclosure of climate-related risks tends to increase a firm's visibility to regulatory bodies and, consequently, its exposure to carbon taxation. This finding aligns with the institutional visibility theory, which posits that transparent firms are more likely to be targeted by policy instruments and fiscal scrutiny.

Table 3 Mediation of carbon tax exposure between disclosure and earnings volatility

Dependent Variable	: CTD
Method	: ML – Binary Logit (Newton-Raphson / Marquardt steps)
Data	: 07/20/25 Time: 01.08
Sample	: 2022 2024
Included observations	: 90
Convergence achieved after 3 iterations	
Coefficient covariance computed using observed Hessian	

Variable	Coefficient	Std. Error	z-Statistic	Prob.
C	-0.998529	0.312641	-3.193852	0.0014
CRD	1.771719	0.468550	3.781279	0.0002
McFadden R-squared	0.126775	Mean dependent var		0.444444
S. D. dependent var	0.499688	S.E. of regression		0.457777
Akaike info criterion	1.244188	Sum squared resid		18.44130
Schwarz criterion	1.299740	Log likelihood		-53.98848
Hannan-Quin criter.	1.266590	Deviance		107.9770
Restr. deviance	123.6531	Restr. Log likelihood		-61.82654
LR statistic	15.67612		Avg. log likelihood	-0.599872
Prob(LR statistic)	0.000075			
Obs with Dep=0	50		Total obs	90
Obs with Dep=1	40			

Source: Processed research data

Furthermore, CTE demonstrates a significant positive effect on EV ($\beta = 0.165$; $p < 0.05$), indicating that firms facing higher carbon tax burdens also tend to experience greater volatility in earnings. Taken together, the significance of both pathways supports a full mediation model: climate disclosure does not directly affect earnings volatility but does so indirectly by amplifying carbon tax exposure. The direct path from CRD to EV remains non-significant (β = –0.021; p > 0.10), further reinforcing the mediating structure.

Table 3 depicts the empirical mediation model linking climate risk disclosure to earnings volatility through carbon tax exposure. The pathway from disclosure to tax exposure is positive and statistically significant, suggesting that greater transparency increases regulatory visibility and the likelihood of fiscal burden. In turn, carbon tax exposure significantly raises earnings volatility, establishing its role as a mediating mechanism. The direct effect of disclosure on volatility is non-significant, supporting a full mediation structure. This configuration highlights how climate transparency, while normatively encouraged, can indirectly introduce financial instability when paired with aggressive carbon pricing regimes, particularly in carbon-intensive sectors such as transportation and logistics.

4.3 Model 3: moderation analysis of firm size

Model 3 evaluates whether firm size moderates the relationship between climate risk disclosure and earnings volatility. The regression results indicate that climate risk disclosure (CRD) continues to show no significant direct effect on earnings volatility, with a coefficient of –0.041 (p > 0.10). The interaction term representing the moderating role of firm size (CRD × FS) also yields a non-significant coefficient of –0.038 (p > 0.10), suggesting the absence of a moderating effect in the observed relationship. The R^2 value for this model is 0.069, indicating a relatively low proportion of explained variance.

Across the tested variables, none of the core predictors in the model meet conventional thresholds for statistical significance. Both the independent effect of CRD and its interaction with firm size fall outside acceptable p-value ranges. The addition of the moderation term does not meaningfully alter the overall model structure or its explanatory capacity compared to previous specifications. These results provide a consistent statistical profile with prior models, affirming the lack of observable direct or conditional effects of climate risk disclosure on earnings volatility when moderated by firm size.

Table 4 Moderation of firm size in the disclosure–volatility relationship

Dependent Variable	: EV
Method	: Panel EGLS (cross-section weights)
Data	: 07/20/25 Time: 01.06
Sample	: 2022 2024
Periods Includes	: 3
Cross-sections included	: 30
Total panel (balanced) observations	: 90
Linear estimation after one-step weighting matrix	

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	0.000991	0.024043	0.041213	0.9672
CRD	0.044396	0.192625	0.230479	0.8183
FZ	0.001987	0.000927	2.144247	0.0348
CRD_FZ	0.000144	0.007295	0.019727	0.9843
Weighted Statistics				
R-squared	0.091556	Mean dependent var		0.427965
Adjusted R-squares	0.059866	S. D. dependent var		0.478151
S.E. of regression	0.326921	Sum squared resid		9.191446
F-statistic	2.889117	Durbin-Watson stat.		1.131027
Prob(F-statistic)	0.040106			
Unweighted Statistics				
R-squared	-0.007651	Mean dependent var		0.142130
Sum squared resid	14.76131	Durbin-Watson stat		1.149981

Source: Processed research data

Table 4 illustrates the results of the moderation analysis assessing whether firm size alters the relationship between climate risk disclosure and earnings volatility. The interaction term (CRD × Firm Size) is included to test for conditional effects. The coefficients indicate that neither the direct effect of climate disclosure on earnings volatility nor its interaction with firm size is statistically significant. The overall explanatory power of the model is modest, with an R^2 value of 0.069. These results suggest that, within the examined sample of transportation and logistics firms, firm size does not significantly influence the association between climate transparency and earnings variability.

5 Discussion

This section interprets the study's findings through a conceptual lens that integrates agency theory, contingency theory, and the resource-based view. Rather than evaluating each hypothesis in isolation, the discussion organizes the insights into three thematic domains: the paradoxical role of transparency, the disruptive effects of carbon taxation, and the limits of organizational scale as an adaptive resource. By situating these themes within the broader literature, the discussion illuminates how climate-related disclosures and fiscal exposures interact to shape earnings volatility in emerging market contexts.

5.1 Climate risk disclosure and its limitations

The results from Model 1 reveal a notable absence of a significant direct relationship between climate risk disclosure (CRD) and earnings volatility. Despite theoretical expectations rooted in legitimacy theory and information asymmetry models, CRD does not appear to exert a stabilizing effect on financial outcomes within Indonesian transportation and logistics firms. This finding challenges the conventional assumption that greater transparency automatically leads to reduced uncertainty in capital markets, particularly in regulatory environments where enforcement and investor responsiveness are still evolving.

Earlier studies suggest that CRD enhances firm credibility and reduces earnings unpredictability by lowering perceived risk and facilitating informed investor decisions [6,27]. However, such dynamics often depend on institutional maturity, regulatory consistency, and the absorptive capacity of stakeholders [28]. These enabling conditions remain fragmented in emerging economies such as Indonesia. As discussed in the Literature Review, while CRD is conceptually aligned with sustainability and governance reforms, its actual implementation in carbon-intensive sectors may remain symbolic rather than strategic.

The findings support the proposition that disclosure, while necessary, is not sufficient to mitigate earnings risk in isolation. This reinforces critiques that ESG reporting may function more as a reputational instrument than a risk management tool when not accompanied by credible governance structures [29]. The credibility of climate disclosures often hinges on third-party verification, managerial commitment, and integration into broader enterprise risk systems [12]. In this sample, disclosure alone does not appear to activate such mechanisms.

Furthermore, the lack of effect observed in Model 1 confirms the argument made in earlier sections that CRD might act more as a signal of institutional conformity rather than a driver of internal transformation [30]. Some studies caution against assuming linear benefits from transparency, especially when disclosures are not embedded in enforceable accountability framework. The present results suggest that without complementary fiscal, strategic, and operational support, disclosure practices may remain decoupled from measurable financial performance.

In summary, this first theme points to the structural limitations of CRD in Indonesia's transportation and logistics sector. Although disclosure may fulfill regulatory or normative expectations, it does not necessarily buffer firms from volatility in earnings. This underscores the need to contextualize the role of transparency within sector-specific and country-specific governance realities, rather than assuming its universal effectiveness.

5.2 Fiscal exposure as a mediating mechanism

The mediation analysis presented in Model 2 demonstrates that carbon tax exposure plays a decisive role in shaping the relationship between climate risk disclosure (CRD) and earnings volatility. While CRD alone does not significantly reduce volatility, the pathway becomes statistically meaningful when firms are simultaneously exposed to fiscal mechanisms such as carbon taxation. This suggests that the economic materialization of climate risks, via tax liabilities, transforms disclosure from a signaling tool into a driver of financial sensitivity.

This finding reinforces the argument that disclosure, in isolation, may lack the potency to influence performance unless accompanied by tangible regulatory or financial consequences. In jurisdictions where carbon pricing is in effect or anticipated, fiscal exposure provides the disciplinary context in which CRD begins to matter [6]. The presence of a tax burden compels firms to shift from symbolic transparency toward anticipatory cost management. This pattern is consistent with earlier empirical research, which shows that carbon pricing strengthens the financial consequences of ESG disclosures and sharpens managerial attention to cost-exposure trade-offs [31].

From a managerial accounting perspective, fiscal exposure serves as a conduit for translating non-financial climate signals into internal financial processes. Managerial accountants, who serve as intermediaries between external compliance and internal control, are increasingly tasked with integrating climate-related exposures into capital allocation, budgeting, and strategic planning frameworks. In this study's sample of Indonesian transportation and logistics firms, sectors with elevated emissions intensity, such integration is most visible when firms face measurable tax risks. These firms begin internalizing disclosure content through operational adjustments, rather than treating it as a reputational tool.

This finding mirrors prior studies that emphasize the mediating function of fiscal visibility in sustainability transformations [32].

The Indonesian context intensifies this dynamic. As a country in the early stages of implementing a national carbon tax, the mere anticipation of tax exposure has prompted firms to reassess their cost structures. Our data suggest that firms disclosing climate risks with concurrent exposure to carbon pricing demonstrate more consistent patterns of earnings volatility. This reflects not only external pressures but also the growing role of internal systems in managing regulatory uncertainty. In emerging economies, where regulatory enforcement may be uneven, fiscal exposure creates a sharper managerial response than disclosure mandates alone [33].

Moreover, this mediation effect confirms that the interface between tax governance and environmental strategy is not merely coincidental. It is systemic. Prior literature notes that tax-linked ESG risks increasingly shape investor behavior and firm valuation, particularly when those risks are financially quantified. In line with these insights, the findings here imply that carbon taxation acts not only as a fiscal burden but also as a strategic inflection point for firms navigating environmental uncertainty [34]. The managerial accounting function, in this light, becomes instrumental in reframing disclosure from an external communication task to a mechanism of internal control and long-term performance calibration.

In conclusion, this theme underscores that fiscal exposure is not a passive contextual variable. It actively shapes the effectiveness of CRD. When linked to anticipated taxation, climate disclosures catalyze financial adaptation. The interplay between disclosure, taxation, and volatility should thus be understood as a triangulated system where managerial accounting serves to mediate and translate risk into governance. This insight not only validates the mediating hypothesis but also deepens our understanding of the institutional embeddedness of carbon accountability.

5.3 Organizational scale and volatility: rethinking the role of size

The results from Model 3 reveal that firm size plays a more nuanced role in influencing earnings volatility than conventionally assumed, especially within the domain of tax accounting under environmental policy pressures. While large firms are typically considered better equipped to manage regulatory burdens due to resource availability and professionalized governance, our findings suggest that scale may, paradoxically, expose firms to heightened fiscal instability. This pattern is particularly evident in Indonesian transportation and logistics firms, where larger entities face more pronounced earnings volatility when climate disclosures intersect with carbon tax exposure.

This phenomenon may reflect what scholars have termed the "compliance exposure gap," in which large firms, despite their institutional capacity, experience greater volatility due to complex and interlinked tax obligations. Regulatory visibility and stakeholder expectations increase proportionally with firm size, subjecting larger firms to rigorous scrutiny regarding climate-related disclosures and tax compliance [35]. As tax authorities and ESG-sensitive investors demand higher transparency, large firms often find themselves navigating inconsistent policy signals, unclear tax bases for carbon liabilities, and reputational consequences tied to aggressive tax planning in carbon-intensive sectors [10].

From a structural standpoint, large logistics firms in Indonesia often operate across multiple jurisdictions, manage extensive fleets, and handle varied forms of freight services. These operational complexities introduce diverse carbon pricing exposures and differential tax treatments. While economies of scale may reduce per-unit costs, they do not necessarily translate into fiscal predictability. On the contrary, the complexity of interpreting, applying, and forecasting carbon tax obligations may result in tax volatility that reverberates through financial reporting and earnings outcomes. Such volatility is frequently underreported or poorly integrated into traditional tax risk assessments, leading to distorted fiscal planning cycles [36].

Moreover, the findings challenge a long-held presumption in tax accounting literature that larger firms enjoy a buffer from tax shocks through financial engineering or sophisticated lobbying. Empirical studies by Kouloukoui et al., [37] demonstrate that large firms, especially in carbon-intensive sectors, bear disproportionate exposure to fiscal penalties not despite but because of their scale. Larger firms in Southeast Asia are more sensitive to environmental fiscal instruments, particularly when tax rules are newly implemented or lack harmonized enforcement mechanisms [38].

This insight calls for a rethinking of how firm size is conceptualized in tax exposure models. Rather than serving as a protective buffer, scale may exacerbate vulnerability by multiplying the nodes of tax liability. For tax professionals and corporate controllers, this implies the need to go beyond compliance checklists and integrate predictive fiscal modeling, scenario-based carbon cost planning, and enhanced tax disclosure strategies. The role of tax accounting must extend beyond regulatory reporting into an anticipatory, risk-sensitive infrastructure that informs executive decision-making.

For regulators and policymakers, the implications are equally significant. Carbon tax systems should consider scaling policies or transitional adjustments that account for the structural burdens large firms face in adjusting legacy systems. Flat-rate taxation or abrupt changes in allowable deductions can disproportionately destabilize larger enterprises unless accompanied by clear guidance and institutional support. Transparent and coherent tax design would not only improve predictability but also reduce the fiscal volatility experienced by large firms attempting to comply in good faith with environmental tax regimes.

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In sum, our analysis reframes firm size in the context of carbon tax exposure as a risk amplifier rather than a resilience factor. By illuminating the fiscal complexity inherent in organizational scale, this theme advances the literature on tax volatility and climate accountability, highlighting a critical need for tax accounting practices that are both strategically integrated and environmentally responsive.

5.4 Implications for theory, practice, and policy

5.4.1 Theoretical implications

This study contributes to an evolving stream of scholarship that reconsiders the interface between environmental disclosures, fiscal pressure, and firm-level volatility. Traditionally, the literature has treated climate risk disclosures as signaling mechanisms intended to reduce information asymmetry and enhance market stability [39]. However, our findings indicate that disclosure alone does not necessarily mitigate fiscal or performance risk. Instead, when situated within coercive regulatory environments such as carbon taxation, disclosure practices may inadvertently intensify volatility for firms insufficiently equipped to integrate these signals into tax planning and strategic forecasting.

Moreover, the study challenges the deterministic assumption embedded in stakeholder and legitimacy theory that larger firms are better positioned to absorb or deflect environmental compliance costs. Our results support a more contingent theoretical framing, in which firm scale acts as a volatility amplifier under fragmented or nascent carbon tax regimes. This insight advances the theorization of fiscal exposure as a mediating mechanism that links sustainability accountability to bottom-line variability [40].

Finally, the study extends the discourse on tax accounting under climate risk by positioning earnings volatility not merely as a financial byproduct but as an interpretive signal of a firm's tax governance readiness. This approach invites deeper integration between environmental accounting, fiscal transparency, and risk-sensitive tax strategy. The observed results suggest that climate-aligned tax exposure must be embedded not only in disclosure frameworks but also within the design and execution of integrated reporting, scenario-based tax modeling, and performance management systems.

5.4.2 Practical implications

From a corporate accounting and taxation perspective, the findings urge firms, especially those in carbon-intensive and asset-heavy sectors, to rethink how they manage fiscal exposure to environmental regulation. Traditional tax compliance systems may no longer be sufficient under conditions of climate-linked taxation. Accounting professionals need to develop more proactive and integrated mechanisms to anticipate carbon-related tax liabilities and embed these into financial planning, earnings forecasts, and stakeholder communication.

For tax managers, the results underscore the need to bridge internal silos between sustainability reporting teams and fiscal control units. A disjointed approach risks underestimating the volatility implications of regulatory exposure, particularly when climate disclosures are treated as symbolic rather than integrated instruments. Firms should invest in systems that simulate fiscal risk under different carbon pricing scenarios and incorporate climate-adjusted tax metrics into capital budgeting, transfer pricing, and cash flow planning.

5.4.3 Policy implications

The study also yields significant implications for fiscal and environmental policymakers. In designing carbon tax frameworks, regulators must recognize that firm size does not necessarily equate to compliance capacity. Larger firms, especially in the logistics and transportation sectors, face unique structural and reporting burdens that may magnify volatility despite robust disclosure practices. Tax policy design should therefore consider phased implementation timelines, sector-specific deduction schemes, or adaptive credit systems that reward early integration of carbon tax forecasting into accounting practices.

Additionally, standard-setting bodies and oversight institutions should promote convergence between environmental reporting standards (e.g., IFRS S2, GRI) and fiscal regulation. Without alignment between what is disclosed and what is taxed, firms will continue to face uncertainty that distorts performance metrics and strategic responses. Policymakers have an opportunity to transform carbon taxation from a punitive measure into a strategic driver of fiscal transparency, stability, and sustainable value creation.

5.5 Limitations and avenues for future research

This study provides valuable insights into the intersection of climate risk disclosure, carbon tax exposure, and firm-level volatility within Indonesia's transportation and logistics sector. However, several limitations merit critical reflection, not as weaknesses, but as points of departure for future scholarship seeking to build on the theoretical and empirical foundations established here.

First, the analysis relies on publicly available secondary data, primarily drawn from annual reports and sustainability disclosures. While these sources support comparability and transparency, they may not fully capture the internal managerial practices or informal processes through which firms interpret and respond to carbon-related fiscal risk. Future research could benefit from incorporating qualitative designs such as case studies or practitioner interviews to explore how fiscal exposure is understood and operationalized across different organizational contexts. These approaches may offer richer interpretive insight into the behavioural and institutional dynamics that underpin disclosure strategies.

Second, the study is limited to a single national context, which, while analytically significant, constrains the generalizability of its findings. Indonesia represents an economy where climate regulation is still unfolding, and where carbon tax policies are in the early stages of implementation. Cross-country comparative studies, especially those contrasting emerging markets with established jurisdictions that have implemented carbon pricing mechanisms, would enable more nuanced conclusions regarding the institutional contingencies that shape the disclosure–tax–volatility nexus.

Third, while earnings volatility serves as a meaningful proxy for financial sensitivity to climate and tax factors, it only partially captures the broader spectrum of organizational performance. Volatility may reflect short-term market responses but does not directly indicate long-term strategic shifts or reputational impacts. Subsequent studies might incorporate alternative outcome variables such as tax aggressiveness, investment behaviour, sustainability ratings, or cash flow stability. This would offer a more holistic view of how carbon tax exposure alters corporate behaviour beyond the income statement.

Fourth, although the model accounts for firm size, it does not integrate potentially influential organizational factors such as ownership structure, board composition, tax planning capabilities, or sustainability maturity levels. These internal features may condition both the quality of disclosure and the firm's capacity to manage tax exposure. Future research could use moderated mediation models to investigate how such factors either buffer or exacerbate the relationship between climate risk and earnings variability.

Finally, the temporal scope of the data captures only the initial stages of carbon tax implementation. Firms may still be in the process of aligning their internal systems, investor communications, and tax projections with new regulatory demands. A longitudinal perspective would allow future scholars to assess how organizational responses evolve as policy environments stabilize, as market expectations mature, and as regulatory enforcement becomes more rigorous.

In conclusion, this study opens several promising directions for interdisciplinary research at the intersection of environmental accounting, taxation, and corporate risk. Scholars are encouraged to extend the inquiry with deeper theoretical integration, broader geographic comparisons, and methodological innovations that reflect the shifting landscape of climate governance and fiscal accountability.

6 Conclusion

This study aims to investigate how climate risk disclosure affects earnings volatility, considering carbon tax exposure as a mediating mechanism and company size as a moderating variable. This study uses panel data from publicly listed transportation and logistics companies from 2022 to 2024. It applies hierarchical linear regression with mediation and moderation techniques. The analysis shows that increased disclosure leads to higher carbon tax exposure, which fully mediates the effect on earnings volatility. Firm size does not significantly moderate this path, suggesting that larger firms are not necessarily more insulated from fiscal risks associated with climate policy. Anchored in agency theory, contingency theory, and the resource-based view, the research reveals that transparency in environmental reporting is not a neutral act. Rather than functioning solely as a reputational tool, climate disclosure can heighten regulatory visibility and generate fiscal exposure, ultimately increasing profit volatility. This challenges the widely held assumption that disclosure automatically reduces uncertainty and mitigates risk

A central finding is the identification of carbon tax exposure as a full mediating mechanism between disclosure and earnings volatility. This mechanism repositions tax exposure from a passive background condition to an active fiscal transmission channel. In doing so, the study diverges from conventional tax accounting and managerial accounting perspectives, which typically treat fiscal obligations and voluntary transparency as distinct domains. Here, disclosure not only signals intentions but also invokes regulatory consequences that shape the firm's financial outcomes.

The research also interrogates the strategic significance of firm size. Contrary to expectations rooted in the resource-based view, larger firms do not appear to enjoy superior insulation from fiscal risk. In carbon-intensive sectors like transportation and logistics, scale alone does not shield firms from the volatility introduced by carbon-related policies. This insight underscores the need to reassess how strategic resources function under regulatory pressure and how firm-level adaptability must go beyond asset base and operational capacity.

By applying a rigorous empirical framework that integrates panel regression with mediation and moderation analysis, this study also advances the methodological toolkit available for tax and environmental accounting scholars. The findings emphasize the need for empirical approaches that reflect the conditional and dynamic nature of regulatory exposure. This approach is particularly relevant in emerging markets, where regulatory institutions are still evolving and where climate governance intersects with fiscal policy in unpredictable ways.

Taken together, the results point to a more nuanced understanding of climate-related disclosure. Rather than viewing transparency as an automatic route to legitimacy and investor trust, this study illustrates how disclosure can trigger new forms of exposure that ripple through the firm's financial structure. The implications are profound, particularly for sectors under increasing scrutiny for their carbon emissions. Understanding how disclosure, taxation, and financial stability interconnect is crucial for building credible, adaptive, and sustainable business models.

6.1 Theoretical and practical contributions

This research delivers several original contributions to the fields of tax accounting, environmental disclosure, and climate governance. Theoretically, it introduces a hybrid perspective that integrates fiscal exposure into the conceptualization of voluntary disclosure. It argues that climate risk disclosure is not merely a reputational tool but also a regulatory signal that activates taxation pathways. This challenges the dominant narrative in voluntary disclosure literature, where transparency is typically seen as a mechanism that resolves information asymmetries and reduces agency costs.

Furthermore, by identifying carbon tax exposure as a mediating variable, the study reframes taxation as an active component of corporate environmental strategy. This innovation elevates the role of tax accounting within the broader sustainability discourse, offering a new lens through which fiscal outcomes can be interpreted in high-emission sectors. It also extends the application of contingency theory by demonstrating how disclosure outcomes are shaped not only by internal governance choices but also by external fiscal structures and regulatory clarity.

From a practical standpoint, the study encourages firms to consider the financial trade-offs embedded in their environmental reporting strategies. For transportation and logistics companies, transparency may enhance legitimacy but also lead to unintended fiscal repercussions. Additionally, the finding that firm size does not mitigate earnings volatility calls for a reassessment of how strategic resources are defined in climate-sensitive industries. Practitioners must develop more granular tools to assess risk exposure, moving beyond scale to consider adaptive capabilities and organizational learning.

Methodologically, the use of integrated regression models that can isolate both mediation and moderation effects provides a robust template for future research. This approach enables a deeper understanding of how indirect effects operate in complex regulatory environments. It provides a path forward for scholars seeking to investigate the intersection of disclosure, taxation, and corporate performance.

Overall, the study provides a more balanced and integrated perspective on the literature regarding climate disclosure and tax exposure. It bridges theoretical gaps, delivers actionable insights, and sets a high standard for future empirical work at the intersection of accounting, regulation, and sustainability.

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Conflict of Interest
The authors declare that they have no known financial or personal relationships that could be perceived as potential conflicts of interest in the development and presentation of this work.

Ethics Approval
As this study is based exclusively on secondary, publicly available data and involves no human subjects, formal ethical clearance was not required.

Data Availability Statement
The data that support the findings of this study are available from the corresponding author upon reasonable request

Author Contributions
Conceptualization, Eva Herianti (E.H.), Amor Marundha (A.M.); methodology, E.H. and A.M.; formal analysis, E.H. and A.M.; investigation, E.H.; resources, E.H.; writing—original draft preparation, E.H.; writing—review and editing, A.M.; visualization, E.H.; supervision, A.M.; project administration, E.H. All authors have read and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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Specification of employee competencies in creating green innovations as part of the enterprise's technological foresight

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Abstract: This article maps the interconnections between (i) determinants of green innovation implementation, (ii) employee competencies, and (iii) Industry 4.0/5.0 digital technologies. A systematic literature review of the Scopus and Web of Science databases (2019-2025) according to the PRISMA protocol identified 23 relevant studies; 15 of these were analysed using open and axial coding. The output consists of five external determinants (K1-K5), a three-level competency framework (strategic, organizational, individual), and five digital themes (D1-D5). The results show that the synergy of stakeholder pressure and green financing (K1+K4) is the primary driver of innovation. Quick wins (green motivation, internal communication) create a cultural foundation, while data analytics and eco-design are strategic accelerators. The transformation is driven by cyber-physical systems and human-centric I5.0, but requires high capital investment and reverse logistics. We propose a three-stage development framework: (1) modular micro-credential programs for digital and environmental skills, (2) mentoring and job rotation for the transfer of tacit knowledge, and (3) a foresight lab that combines scenario workshops with strategic competency training. The study provides the concept of the "Digital-Sustainability Nexus," which explains how digital technologies simultaneously accelerate and facilitate green innovation and which competencies are key to this process. The results offer managers a practical roadmap of development, research, and policy priorities on the path to a carbon-neutral industry.

1 Introduction

Today, enterprises are facing a dual transformation: environmental and digital. On the one hand, there is growing pressure from governments and stakeholders for manufacturing to reduce its carbon footprint; on the other hand, the deployment of Industry 4.0/5.0 technologies is accelerating, transforming the way work is organized. Green innovation is therefore no longer merely a technical metter of investment, but above all a question of human capital – i.e., the ability of employees to understand, design, develop and operate solutions that combine sustainability with digital efficiency. If the competence base lags behind, investment in green technologies stagnates or fails; if, on the other hand, it is rebuilt in line with new requirements, it becomes a multiplier of value and a key differentiator for the company.

In response to this challenge, the relevant literature increasingly highlights the need to upskill employees competencies – from production line operators to strategic management – so that they can simultaneously address environmental goals, digital processes, and economic efficiency. The following passage breaks down these skills into four interconnected areas that repeatedly emerge in empirical studies [1,2] as key building blocks of green transformation. A review of the literature shows that competencies naturally cluster along two axes: **Functional dimension** – ranging from strictly technical skills to creative-innovative and environmental knowledge; **Systemic level** – spanning from the individual employee to the team/organizational level to the strategic level of the enterprise.

At their intersection, four domains emerge that cover the entire "life cycle" of green innovation – from idea to circular closure of material loops. This structure (Chapter 2.1) also allows for a logical follow-up to the methodological analysis of competencies in Section 2.3 (Significance for Small and Medium-Sized Enterprises).

2 Literature review

2.1 Employee competencies for green innovation

The development of green production and innovation in enterprises is inseparably linked to the formation of a new type of workforce. Employee competencies must be transformed to meet the challenges of environmental sustainability, digital transformation, and the principles of the circular economy [1,2].

Technical skills

Employees must have technical skills that allow them to implement environmentally friendly technologies, optimize energy and material efficiency, and apply circular economy principles [2]. Technical skills and abilities include, for example, knowledge of digital tools to support circular strategies, the ability to design products with a life cycle that takes recycling and renewal into account, and mastery of reverse logistics processes [1].

The implementation of technologies to reduce energy intensity, as well as knowledge of cleaner production, play a key role, with an increased ability of workers to reconfigure manufacturing processes to improve environmental compliance and reduce waste being emphasized [3]. Technical skills and abilities also include the development of skills related to the collection and processing of environmental data, as well as the introduction of green technologies into the production environment [4].

Innovative skills

Creative and systemic thinking are crucial for the development of green innovation. Innovative skills enable employees to identify new environmental solutions, adapt to rapidly changing technologies, and actively contribute to innovation teams. The importance of green creativity is emphasized, where employees propose new environmental solutions, revise existing processes, and promote the development of sustainable ideas [5].

The ability to be involved in environmentally friendly innovation processes plays an important role in the so-called green dynamic abilities of enterprises, which enable them to respond quickly to environmental challenges through innovation. This implies the need to develop flexibility, teamwork, digital literacy, and agility in the face of changes [1,6].

Artificial intelligence (AI) currently has an important role to play, significantly shaping green innovation through automation, digitalisation and intelligent data processing. AI enables employees to effectively analyze big environmental data, to identify inefficient processes, and to optimize resource use. Thus, part of innovative competencies includes understanding and participating in the implementation AI tools in the development and assessment of environmental solutions [7]. Enterprises that also promote collaborative innovation cultures based on sustainability achieve higher levels of environmentally oriented business – which is only possible with a sufficiently competent and proactive workforce [4,8].

Knowledge of environmental protection

Green innovation cannot be realised without sufficient knowledge of environmental issues. Systematic environmental education of employees is one of the fundamental tools for enterprises to achieve environmental performance. Education should cover areas such as waste management, environmental legislation, sustainable design, and environmental metrics [1].

In terms of motivating employees to behave sustainably, it is important not only to provide formal education, but also to create a so-called psychological green climate and to support the value anchoring of environmental behavior [9]. Successful enterprises invest in the development of "environmentally oriented" leaders who have the ability to communicate sustainable goals and lead others to achieve them in everyday practice [4,10]. The basis for effective decision-making in the area of sustainability is the integration of environmental knowledge into corporate management and performance evaluation systems [1,11].

Multidisciplinary and interconnected competence base

In summary, green innovation requires a complex and multidisciplinary combination of technical, innovative, and environmental competencies. Modern enterprises should build "green talent capital" that combines digital skills with the principles of sustainability and the circular economy [1,12]. It is necessary for enterprises not only to identify strategic competencies, but also to develop them through targeted training, adaptation programs, and partnerships with the academic community, thereby increasing their ability to respond to sustainability challenges [1,13].

2.2 Technological foresight as a tool for strategic planning of sustainable innovation

Technological foresight is a systematic approach to predicting future development trends and their potential impact on the world of business. At its core is the ability to anticipate which technologies will be strategically important for developing sustainable innovations. Foresight supported by digital transformation enables enterprises to manage information complexity and reduce uncertainties associated with environmental and social requirements [14]. The introduction of technological foresight into strategic planning increases the ability of enterprises to adapt to changing conditions and take advantage of new opportunities. The concept of "twin transition," which combines digital and green transformation, highlights the need for synergistic development of technologies and environmental approaches. The combination of digital technologies and circular economy principles forms the basis for modern strategic decision-making [2].

In terms of building foresight capacities, it is important to understand foresight as a dynamic ability that combines internal technological prerequisites with external market and environmental signals. Especially in the case of technology-oriented enterprises, it appears that the ability to anticipate technological trends and evolving regulatory frameworks is closely linked to their ability to link technological readiness with expected market response [15]. The ability to predict and respond quickly becomes a competitive advantage in this context, with an emphasis also on so-called "learning organizations" that use feedback from foresight exercises for continuous strategic adjustments [16]. An equally important aspect is the integration of foresight into open innovation practices, in which enterprises connect internal knowledge with external partners. This increases the likelihood of success in developing new products and services that reflect future environmental challenges [16].

In the context of anticipatory decision-making, predictive models are often supported by artificial intelligence and real-time analytics, enabling active and flexible decision-making in under conditions of uncertainty [17]. Current research also indicates that foresight processes are not isolated activities, but take place within broader collaborative ecosystems that emphasize the importance of participation not only by internal employees, but also by customers, academia, and technology partners. This participatory dimension strengthens the ability of enterprises to adapt to complex systemic changes and to more effectively anticipate emerging technologies before their widespread adoption in the market [18].

The effective implementation of foresight depends on the active involvement of employees at all levels. It is important to foster a culture of participation and involve employees in formal and informal foresight activities, such as workshops, feedback sessions, and discussion forums focused on environmental challenges [1]. Employees are carriers of knowledge that can be systematically used through foresight processes to anticipate technological changes. Employees with a high degree of so-called "technological sensitivity" can contribute to the early identification of technological trends that can positively influence the environmental performance of an enterprise [14,19].

Anticipating technological change requires specific tools and skills. Digital capabilities are crucial, enabling enterprises to collect and analyze data to identify new technological opportunities. In this context, foresight is a tool that allows risks and the identification of risks and opportunities and the planning of product and process adaptation [14,20]. One of the practical outputs of foresight is the identification of emerging technologies with potential for green innovation. Such technologies include artificial intelligence, which, through so-called digital financing, provides new opportunities for funding green projects, especially in areas with lower environmental quality and high environmental demands. AI is thus becoming not only a predictive tool, but also an active means of transforming enterprise innovation toward sustainability [7]. These forecasts form the basis for the creation of long-term innovation strategies that take into account the need to reduce emissions, conserve resources, and close material flows [11,14].

Technological foresight has a crucial role in linking the Industry 4.0 paradigm and the emerging Industry 5.0 concept with sustainability principles. Foresight processes make it possible to identify specific technologies that not only enhance efficiency but also reduce the environmental impact of production, such as autonomous manufacturing systems, robotics, and green digital twins [14]. Employees participating in these transformations must be prepared to cope with changes in technology while understanding their environmental implications. Therefore, foresight is not only a management tool but also a challenge for HR departments and education systems [8].

Modern foresight is a process of continuous feedback based on participation and shared knowledge. Enterprises that create innovative ecosystems with the active participation of employees, customers, academia, and technology partners are able to anticipate technological changes more effectively and respond to them innovatively [6,14]. The importance of so-called open foresight, which is based on external partnerships and the active search for external knowledge, is also highlighted. This approach strengthens the ability of enterprises to identify green technology trends before they become widespread [14,21].

It is important to emphasize that foresight is a long-term process requiring continuous learning and adaptation. Enterprises must systematically develop organizational learning focused on the ability to anticipate future challenges and create innovative responses with environmental impact [12,14]. From the same perspective, they highlight the importance of strategic foresight in enterprise planning, emphasizing the need to connect technological knowledge with future visions. In their view, foresight is not only a tool but also a way of thinking that enables enterprises to remain competitive in times of growing environmental challenges [13,14].

2.3 The concept of green innovation and its importance for enterprises in the context of sustainability

Green innovations (eco-innovations) represent a form of technological or non-technological progress aimed at reducing negative environmental impacts while maintaining or enhancing enterprise performance. These innovations that reduce environmental risk, pollution, and resource consumption throughout their life cycle compared to alternatives [8]. Green innovations can take the form of product, process, organizational, or marketing changes. They encompass solutions that enable more efficient use of resources, reduction of material costs, waste recycling, or the design of environmentally friendly products [11].

The main benefit of green innovation is its ability to harmonize economic and environmental interests. Green technologies, such as solar and wind energy, contribute to reducing emissions, increasing energy efficiency, and creating new workplaces, thereby strengthening economic growth and environmental quality [6]. At the same time, green innovation provides enterprises with an opportunity to enhance their reputation and gain a competitive advantage. The environmental performance of enterprises supported by green innovation has a positive impact on customer perception of the brand, which has a direct impact on business success [22].

Forms and types of green innovations

Green innovations develop in two forms – incremental and radical. The former bring gradual improvements in environmental efficiency, while the latter represent fundamental technological transformations. The importance of digital technologies and their combination with environmental goals is highlighted, giving rise to so-called digital green innovations – for example, the implementation of smart sensors to monitor resource consumption [14]. In the context of Industry 4.0, the ability to create interconnected systems that reduce environmental impacts through automation and AI is becoming increasingly important. Green technologies such as smart manufacturing and green computing are becoming an integral part of enterprise innovation [12].

Despite the positive potential of green innovation, enterprises face several barriers, such as high initial investment costs, regulatory uncertainty, and low environmental literacy among employees. To successfully overcome these barriers, it is necessary to invest in education, competence development, and partnerships within innovation ecosystems [2]. Another specific prerequisite for success is the development of skills in digital finance, which – supported by AI technologies – opens up new forms of financing for green innovation. Digital finance, including tools such as crowdfunding, electronic commercial papers, and smart contracts, enables flexible and transparent capital allocation while reducing information asymmetry between enterprises and investors [7].

Organizational culture focused on sustainability and supporting open innovation also plays a key role. Enterprises with a stronger green culture achieve a higher level of environmental innovation implementation, particularly in the areas of product design and sustainable packaging [5,11].

Importance for small and medium-sized enterprises

Green innovation plays a specific role in the small and medium-sized enterprise (SME) segment, which accounts for more than 90% of all enterprises. Although SMEs often face resource constraints, their flexibility allows them to implement green measures more rapidly and transform their business models towards sustainability [3,11]. The regional and sectoral context is also significant. Enterprises participating in local green clusters achieve higher environmental performance due to synergies between enterprises, the public sector, and research institutions [4,11].

Green innovations are a key tool for enterprises to achieve environmental goals while creating a competitive advantage. Their importance is growing in the context of climate challenges, regulations, and social pressure. Enterprises need to integrate the principles of green innovation into their long-term strategies, with the active involvement of employees, digital support for processes, and cooperation with the external environment being key [11,13].

3 Methodology

This section of the article describes the process through which the key prerequisites for the successful implementation of green innovations in enterprise practice were identified, synthesized, and interpreted. It combines a systematic literature review, thematic meta-synthesis, and cross-analysis to integrate three complementary perspectives:

1. **Determinants and conditions for implementation of green innovations in enterprises** (Table 1);
2. **Competency requirements for employees who implement these innovations** (Table 2);
3. **Synergetic links between green innovations and Industry 4.0 / 5.0 digital paradigms** (Table 3).

These three areas were chosen because the literature suggests that the interconnection of enterprise determinants, human capital, and digital technologies that forms the core of the so-called twin transition – the parallel green and digital transformation of industry.

First, the Scopus and Web of Science databases (2019-2025) were systematically reviewed following PRISMA principles, using a combination of the keywords *green innovation*, *sustainable technology adoption*, *competence*, and

Industry 4.0 / 5.0. After duplicates were removed and inclusion criteria were applied (peer-reviewed articles, direct relevance to the topic), 23 relevant publications were identified. From these, those providing empirical data on one of the three areas mentioned above were selected for deeper analysis; the results are presented in three synthetic tables directly in the text.

At the analytical level, **open coding** was applied, followed by **axial coding** and **triangulation** across the individual datasets. This approach allowed the creation of a **conceptual framework**, which will be connected at the end of the chapter to recommendations for the development of employee competencies and for strategic planning of future technologies.

3.1 Conditions for the implementation of green innovations

First, empirical studies from the period 2019-2025 were systematically searched (Scopus and Web of Science, keywords: *green innovation*, *sustainability drivers*, *technology adoption*, *Industry 4.0 / 5.0*). After removing duplicates and applying inclusion criteria (peer review, direct relation to the conditions for implementation of green innovations), five relevant papers remained. From each, we extracted:

1. Bibliographic data (author, year).
2. Main type of determinants (authors'own wording).
3. Specific findings (quantitative or qualitative summaries).

Thematic coding of determinants

Open coding → axial coding was used for the synthesis; five super-categories were identified, which will be linked to competencies and digital technologies in the subsequent sections.

3.2 Employee competencies needed to implement green innovations

In the second step, a systematic analysis focused on empirical studies that explicitly quantify or qualitatively describe the employee competencies necessary for the developing green innovations. Five relevant studies were identified from the Scopus and Web of Science databases (2019-2025) (Table 2). Each study was coded according to a three-level framework (strategic – organizational – individual level), and the competencies were subsequently assigned to determinants K1-K5, as derived in subsection 3.1.

Thematic open coding, followed by secondary axial coding, was methodically applied to capture the relationships between specific competencies and business – ecosystem conditions. In the final phase, a conceptual importance × difficulty matrix (criteria: frequency of occurrence, declared benefit, implementation barriers) was constructed, forming the basis for the discussion on development programs (Chapter - Conclusion).

3.3 Linking green innovation and the Industry 4.0 / 5.0 paradigm

The third phase of the systematic review focused on studies analyzing synergies between Industry 4.0/5.0 digital paradigms and green innovations. Six relevant publications (2019-2025) were identified that met the criteria: (i) peer-reviewed article, (ii) explicit link between I4.0/5.0 → environmental performance, (iii) methodological transparency.

Three variables were extracted:

1. Bibliographic data (Article).
2. Type of determinants – key attributes of the digital paradigm.
3. Findings – how digital tools support green innovation.

4 Results and discussion

This chapter summarizes the results of the three-phase analysis. First, external determinants that drive or hinder green innovations are presented, followed by a summary of the employee competency profile and a discussion of how Industry 4.0 / 5.0 digital technologies amplify these factors.

4.1 Conditions for the implementation of green innovations

Systematic research revealed five key determinants (K1-K5) that are repeatedly associated with the successful implementation of environmental solutions in empirical studies. These range from stakeholder and regulatory pressure to macroeconomic conditions. Their specific form and quantified impacts are summarized in the following table.

Table 1 Determinants of green innovation adoption – synthesis of empirical findings (2019-2025) (own processing, 2025)

Article (author, year)	Type of determinants	Specific findings
Baah et al. (2021)	Stakeholder pressure, regulatory and organizational factors	Organizational pressure: customers, employees, and suppliers; regulatory requirements increase the likelihood of adopting green innovations – GIs.
Block et al. (2025)	Innovation systems, intellectual property rights – IPR, policy	*Green patents* versus *green trademarks*: patents correlate better with emissions reductions; support from innovation clusters accelerates diffusion.
Haleem et al. (2023)	System requirements, technological and organizational capabilities	The 5R strategic tools (repair – reuse – remanufacture – recycle – recover) require integrated IT systems and standardized processes.
Hanif & Zheng (2025)	Green finance, renewable energy, regulatory tools	Green credit: A 1% increase in green financing leads to a 0.4% increase in the number of GIs; regulatory reliefs strengthens the effect by 20%.
Javed et al. (2025)	Technological, financial, and macroeconomic conditions	Investments in renewable energy sources and digitization (AI-managed networks) reduce emissions by 15%; with proper financial infrastructure, the transition is carried out more efficiently.

In the following text, abbreviations K1-K5 will be used for clear cross-links to competencies (section 3.2) and digital technologies I4.0/5.0 (section 3.3).

Table 2 Determinants of green innovation implementation (own processing, 2025)

Code	Category name	Description of typical determinants
K1	Stakeholder-regulatory	customer pressure, employee demands, government directives
K2	Technological and organizational readiness	state of infrastructure, ability to integrate new processes
K3	Intellectual property and innovation systems	patents, trademarks, ecosystem of collaboration
K4	Green financing and energy infrastructure	green loans, renewable energy sources
K5	Macroeconomic and financial factors	taxes, subsidies, energy price fluctuations

Key findings

Based on a comparative analysis of the five most relevant empirical studies, three key conclusions can be drawn:

1. **The synergy between customer pressure (K1) and the availability of green financial instruments (K4) is the dominant driver of green transformation.** All analyzed studies confirm that enterprises which simultaneously face strong stakeholder demand for sustainability and have access to preferential loans or tax incentives implement green innovations faster and on a larger scale.
2. **The technological readiness of an enterprise (K2) combined with effective intellectual property management (K3) becomes a critical factor, especially in the solution scaling phase.** When a prototype moves into mass production, the ability to integrate digital platforms (ERP, IoT, AI) while protecting know-how through patents or licensing models is crucial—otherwise, the benefits of innovation will quickly disappear in a competitive environment.
3. **Macroeconomic and political conditions (K5) determine the pace of diffusion, but are largely beyond the direct control of the enterprise.** Although enterprises can partially mitigate risks through hedging or diversification, the stability of regulations, energy prices, and monetary policy remains an external factor that ultimately determines the long-term return on green investments.

Together, these three findings show that a successful path to green innovation requires a holistic approach: strategic stakeholder and financial management must be linked to internal technological capacity and supported by a favorable macroeconomic environment.

4.2 Employee competencies needed to implement green innovations

The analysis of competencies is based on the five most relevant empirical studies and is organized within a three-level framework (strategic – organizational – individual).

The following table summarizes the competencies that the literature repeatedly identifies as key to the successful implementation of green innovations in the enterprises.

Table 3 Competencies supporting green innovations (own processing, 2025)

Article	Types of competencies	Findings
Ahuja et al. (2019)	Human factors critical for sustainable production (HCSF)	**13 competency factors** were identified, divided into: Strategic – *green motivation, leadership, CRM, strategic alignment*; Organizational – *communication, culture, teamwork, engagement*; Individual – *green training, employee commitment, trust*. **The most influential factors:** green motivation, leadership, CRM; **Recommendations:** combination of training, systematic communication, and a participatory leadership style.
Kim et al. (2023)	Green work behavior – commitment, sharing knowledge, creativity	*Green* HRM – human resource management (GHRM) contributes to performance only when employees demonstrate: (i) green work engagement, (ii) active sharing of environmental knowledge, (iii) green creativity (mediator). A culture of feedback, recognition, and teamwork is crucial.
Marrucci et al. (2021)	Sustainable HR practices – recruitment, training, engagement, evaluation, remuneration	Different parts of GHRM have different effects on economic and environmental performance: hiring based on green values has an immediate impact; development (training) and rewards have a longer-term effect.
Straub et al. (2023)	General, sustainable, and circular skills for CBM – circular bussines models implementation	Taxonomy of **40 skills** (six categories): innovative entrepreneurial skills, sustainable resource management, augmented reality and robotics, eco-design, reverse logistics, etc. Emphasis on soft skills: flexibility, critical thinking, lifelong learning, storytelling.
Trevisan et al. (2024)	Three categories – resilience, digital, specialized technical skills	A systematic research identified **40 competencies** in three areas: (i) resilience skills (23), (ii) digital skills (7) – data analytics, VR/AR, robotics, (iii) technical skills (10) – eco-design, energy management, reverse logistics.

The synthetic grouping and links to determinants K1-K5 are shown in the following table.

Table 4 Synthetic grouping and linking to determinants K1-K5 (own processing, 2025)

Competency level	Dominant competencies	Link to determinants from Chapter 4.1
Strategic	*Green motivation*, green leadership, Customer-Relationship-Management sustainability oriented, strategic alignment of technologies	**K1** (stakeholder-regulatory pressure): requires proactive leadership and CRM; **K5** (macro-factors): need for strategic foresight and scenarios.
Organizational	Learning culture, internal communication, teamwork, participatory engagement	**K2** (technological readiness): when implementing I4.0/5.0 digital tools, it is necessary to harmonize processes and culture; **K3** (IPR and innovation systems): open innovation requires internal know-how sharing.
Individual	Lifelong learning, green technical skills (eco-design, energy engineering), data analytics, green creativity	**K2** digital skills enable the use of IoT/AI to measure environmental performance; **K4** (green finance) knowledge of green accounting and energy indicators determines access to financial incentives.

Matrix of significance × implementation difficulty (conceptual overview):

- *„Quick wins" (high priority, low complexity)*

Green motivation and effective internal communication are the least capital-intensive, but have a disproportionately large impact on the success of green innovations. Enterprises can implement them immediately through short online training courses and motivational campaigns, thereby establishing a cultural foundation for further, more complex interventions.

- *Strategic accelerators (high priority, medium difficulty)*

Data analytics and eco-design require a mature I4.0 digital infrastructure and cross-functional teams, yet they bring measurable environmental and economic benefits. Investment in analytical platforms and collaborative eco-design workshops is therefore a logical next step after quick wins.

- *Transformational competencies (critical priority, high difficulty)*

Strategic alignment with the I5.0 paradigm and reverse logistics are the most capital- and process-intensive, but they determine long-term competitiveness in the circular economy. Their implementation requires high investments in automated reverse material flows, advanced robotics, and links to predictive demand models.

Based on the above hierarchy of competency priorities and complexity, an implication framework was developed to translate the analytical findings into specific enterprise development mechanisms. An overview of this framework is provided in the following table:

Table 5 Implications for enterprise development programs (own processing, 2025)

Development mechanism	Purpose	Linking to competencies
Modular learning pathways (micro-credentials)	Flexibly combine digital (AI, Big Data) and environmental skills (LC-analysis, eco-design).	Support quick wins and prepares the ground for strategic accelerators.
Mentoring & job-rotation	Accelerate the transfer of tacit knowledge between R&D, production, and logistics; break down organizational "silo" effect.	Critical for adaptive data analytics and eco-design; reduces the risk of failure in I5.0 projects.
Integrated foresight-lab	Link long-term scenarios (K5) with practical competency training (K2 + K3) through workshops and digital simulations.	Creates a strategic framework for the transformation towards I5.0 and circular logistics.

Enterprises should proceed iteratively – first activating cultural and communication "quick wins," simultaneously developing data analytics and eco-design as strategic accelerators, and then, with the support of a foresight lab, investing in capital-intensive reverse logistics and human-centric I5.0 solutions. This minimizes the risk that large investments will outpace organizational readiness.

4.3 Linking green innovation and the Industry 4.0 / 5.0 paradigm

Digital transformation is reshaping the technical and organizational prerequisites for sustainability: cyber-physical systems, real-time data, and human-centric Industry 5.0 solutions are opening up new possibilities for circular flows and green business models. To assess how these technologies support eco-innovation, six recent empirical studies (2019-2025) were analyzed. Open and axial coding revealed five recurring digital themes (D1-D5) – ranging from cyber-physical integration to AI-supported foresight. Their content and key links to enterprise determinants and competencies are summarized in the following table.

Table 6 Digital determinants supporting green innovations (own processing, 2025)

Article	Types of determinants	Findings
Capatina et al. (2024)	Technological readiness, foresight approaches, AI integration	The study emphasizes that the ability to integrate cyber-physical systems (CPS) and artificial intelligence (AI) is key to the technical validation of green innovations in deep-tech start-ups.
Elias et al. (2025)	Technological readiness, foresight approaches, AI integration	The proposed framework combines AI and strategic foresight, thereby strengthening SMEs' resilience to regulatory pressure on sustainability.
Ghobakhloo et al. (2023)	Technological readiness, foresight approaches, value network	The identified "Industry 5.0 roadmap" describes 12 functions of digital manufacturing that reduce the environmental footprint and increase the adaptability of the value chain.
Lu et al. (2023)	Digital capabilities, strategic alignment of technologies, digital flexibility	Digital transformation through IoT and big data analytics improves circular material flows and minimizes waste streams in real time.
Mubarak et al. (2025)	Strategic foresight, knowledge management (exploration/exploitation), open innovation	Strategic foresight workshops and knowledge-sharing platforms accelerate the diffusion of green solutions across the supply chain.
Song et al. (2025)	AI integration, digital finance, technological support	AI-driven digital finance improves enterprises' access to green credit and accelerates the adoption of clean technologies.

Open and subsequent axial coding revealed five core themes (D1-D5) that overlap with previously identified determinants (K1-K5) and competency levels:

Table 7 Digital determinants (D1-D5) within the "Digital-Sustainability Nexus" – examples of technologies and main connection to enterprise competencies (own processing, 2025)

Code	Digital theme	Examples of technologies	Main connection
D1	Cyber-physical integration	CPS, digital twin, robotics	**K2** increases technological readiness and requires **individual** technical skills (eco-design, robotics).
D2	Data-driven optimization	IoT, Big-Data, predictive analytics	Supports **K4** access to green financing through transparent metrics; relies on **digital** competencies.

D3	Artificial intelligence & machine learning	MLOps, generative AI	Accelerates the eco-innovation cycle, strengthens **strategic** leadership (adaptive scenarios in **K5**).
D4	Human-centric Industry 5.0	Collaborative robots, XR training	Increases employee acceptance; correlates with **organizational** competencies (learning culture, participation).
D5	Digital foresight & open innovation	Scenario platforms, crowdsourcing	Bridging **K1** stakeholder pressure and strategic orientation requires **strategic** and **organizational** skills.

Conceptual framework „Digital-Sustainability Nexus“

By triangulating **environmental determinants (K1-K5)**, **competency levels**, and **digital tools (D1-D5)**, a **phase model** emerges: **Sensing → Seizing → Transforming**, which captures when and how digital technologies accelerate green innovation:

1. **Sensing** – IoT, Big Data, and AI algorithms (D2/D3) continuously monitor material and energy flows, convert them into KPIs (carbon footprint, water consumption), and send **real-time feedback** to stakeholders (K1). The result is immediate transparency, which increases pressure for sustainable decision-making.
2. **Seizing** – Digital foresight platforms and scenario simulations (D5) analyze the collected data, identify **specific investment windows** (e.g., the use of green credits or subsidies), and provide management with the basis for capital allocation. The success of this phase depends on **strategic green leadership** and the alignment of goals across the enterprise.
3. **Transforming** – Cyber-physical systems and human-centric I5.0 solutions (D1/D4) put selected projects into practice: they introduce circular flows, automate reverse logistics, and support collaborative robots. Implementation success depends on a **mature organizational culture** and the ability of employees to integrate digital and environmental skills.

The model clearly shows that digital technologies fulfill two roles simultaneously – first as an **accelerator** (shortening the time needed for data collection and analysis), and second as an **intermediary** (enabling the physical transformation of processes).

Impact and influence on practice and research

The next three perspectives – managerial, political-regulatory, and research – deliberately cover the entire decision-making chain of green transformation: the enterprise decides and invests, the regulator shapes the conditions, and research fills in the knowledge gaps needed for further progress:

- **Managerial contribution:** In enterprises that have integrated AI-driven foresight (combination of D3+D5), the average decision cycle for green investments has decreased by 30-40% (Song et al., 2025) [7], accelerating the time-to-sustainability.
- **Political-regulatory level:** Open digital platforms and shared data ecosystems break down barriers to the transfer of green technologies between SMEs, suggesting a need for targeted support from regulators (Mubarak et al., 2025) [16].
- **Research perspective:** There is a lack of longitudinal studies tracking how human-centric elements of I5.0 (D4) impact environmental KPIs and employee well-being; this deficit represents a promising trajectory for future empirical studies.

This extension makes the Digital-Sustainability Nexus framework a practical tool for planning, monitoring, and scaling green innovations in digitally transformed industry.

5 Conclusions

A complex meta-analysis of literature from 2019–2025 confirmed that the success of green innovations in enterprises is conditioned by a triad: environmental determinants (K1-K5), employee competencies, and digital technologies (D1-D5). The resulting "Digital-Sustainability Nexus" shows that:

- K1 Stakeholder-regulatory pressure and K4 Green financing create an external impulse that initiates investment in green solutions; however, their effect is only maximized if the enterprise has strategic green leadership and sustainability-oriented CRM.
- K2 Technological readiness and D1 Cyber-physical integration are interdependent: digital twins and robotics enable the simulation and validation of environmental benefits before implementation.
- K3 Intellectual property and innovation ecosystems are catalysts for open innovation (D5), shortening the time to market for green products..
- K5 Macro-factors (politics, energy prices) modify the pace of adoption; however, the enterprise can reduce volatility through AI-supported strategic foresight (D3+D5).

Table 8 Impulses for management and competence development (own processing, 2025)

Level of recommendation	Practical steps	Expected contribution
Strategic	• Implementation of a **foresight-lab** with scenario workshops; • Linking KPIs to environmental metrics through digitally managed dashboards.	Faster and more qualified investment decision-making; better compliance with ESG regulations.
Organizational	• **Modular development programs:** micro-credentials in data analytics, eco-design, reverse logistics; • **Mentoring & job rotation** between R&D, production, and logistics.	Higher internal absorption capacity for I4.0/5.0 technologies; breaking down the silo effect.
Individual	• Gamified **XR training** for collaborative robotics and energy management; • Supporting **green intrapreneurship** through internal grant schemes.	Increasing green work engagement and creativity; faster internalization of new skills.

The results indicate that harmonized support for digital infrastructure and green financing (e.g., tax breaks for AI-controlled energy systems) has a multiplier effect on the rate of adaptation of green innovations. Measures should target SMEs, where regulatory pressure often exceeds available resources.

Although the systematic review covers six years and several industrial sectors, quantitative studies from manufacturing are predominant; the service sector is less well represented. Future research could:

1. Conduct long-term analyses of the impact of human-centric Industry 5.0 solutions on environmental KPIs.
2. Explore the intersection of social sustainability (well-being, diversity) with digital technologies and green innovations.
3. Develop a standardized competency index combining ecological, digital, and resilience skills (stress management skills).

The study offers a holistic framework that integrates environmental determinants, employee competencies, and digital technologies into a single coherent model. Enterprises that simultaneously invest in (i) the development of key competencies, (ii) Industry 4.0/5.0 digitalization initiatives, and (iii) strategic foresight achieve a faster and more sustainable innovation trajectory.

This article enriches the discourse on green transformation with empirically based recommendations for management and technological development, while providing a basis for further academic and practical discussion.

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Design and performance analysis of automated vertical parking systems for urban environments

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Keywords: parking, car, chain, cost, city.
Abstract: The article presents the results of work on the design, calculation, and manufacturing of vertical parking systems. Vehicle movement, together with the cradles, is carried out in both vertical and horizontal directions using a chain transmission system. The structure consists of a frame, chain drive, guide rails, and a control unit that manages cradle positioning and ensures their movement to the designated entry and exit point for vehicle parking. Saving land space is a key economic factor. Vertical parking systems allow significantly more cars to be accommodated within the same area compared to traditional surface-level parking lots. In comparison with underground or multi-level reinforced concrete parking structures, automated systems based on metal frameworks can be more cost-effective. Automated parking systems require minimal staff involvement. In closed automated systems, the risk of theft, vandalism, or accidental vehicle damage is virtually eliminated, as access is restricted to vehicle owners only. Parking spaces in areas with a shortage of parking lots are the liquid assets. These spaces be profitably leased, providing passive income, or resold. The payback period for a vertical parking installation project can be approximately three years, although this value strongly depends on specific conditions. The availability of parking in a residential or office complex directly increases the property’s value and overall attractiveness.

1 Introduction

Due to the global increase in vehicle fleets, the shortage of parking spaces, especially in large cities, has become a growing concern. On average, a driver in a major city spends approximately 70 hours per year searching for parking. This not only results in wasted time but also leads to unnecessary fuel consumption. As a consequence, millions of tons of toxic emissions are released into the environment. A single car in a large city can emit around 320 kg of CO_2 per year due to the search for parking alone [1-7].

Cities around the world are increasingly adopting intelligent parking systems. These systems help address issues such as traffic congestion, environmental pollution, and inefficiencies caused by the large number of cars circling for parking in dense urban areas. The autonomous parking market is projected to grow to USD 12.9 billion by 2030, with a compound annual growth rate (CAGR) of 25.2%, which clearly demonstrates the impact that intelligent parking systems will have in the next few years [2-5].

1.1 Intelligent parking systems

- **Revenue Increase:**
  The introduction of intelligent parking meters and mobile payment systems enables more accurate monitoring and efficient collection of funds from parking spaces. More effective utilization of each parking spot leads to increased revenue and reduced losses due to unpaid fines.
- **Reduction of Parking Management Costs:**
  Tracking all parking-related activities allows for significant cost savings. The collected data helps identify best practices and optimize enforcement measures, leading to more efficient operations.

- **Financing Operational Expenses:**
  Cities can benefit from smart parking solutions without bearing the initial financial burden, as these systems can be implemented with minimal upfront costs. This approach ensures that cities begin generating revenue immediately after implementation.

However, the economic component is of particular importance. The cost of parking in densely populated metropolises, for example, in the city of Tbilisi, can reach approximately USD 5,000 or more. Using an area of 21 m² (6 m × 3.5 m), a four-space vertical parking system can accommodate nearly three vehicles per equivalent ground-level parking area.

For comparison, a conventional parking lot occupying 5 m × 6 m (30 m²) accommodates four vehicles, which corresponds to approximately 2.8 vehicles per 21 m². In contrast, a vertical parking system with five spaces can accommodate 3.5 vehicles per 21 m²; with six spaces, 4.2 vehicles; with seven spaces, 4.9 vehicles; with eight spaces, 5.6 vehicles; with nine spaces, 6.3 vehicles; and with ten spaces, up to seven vehicles.

Based on these data, a graph illustrating the dependence of car placement density on the number of parking spaces in a vertical parking system can be constructed Figure 1. Considering that the cost of parking in densely populated urban areas is likely to exceed USD 5,000, and that prices in underground parking facilities are often significantly higher, in some cases approaching residential property prices, the economic advantages of vertical parking systems become evident. The main economic benefits of such systems are summarized below.

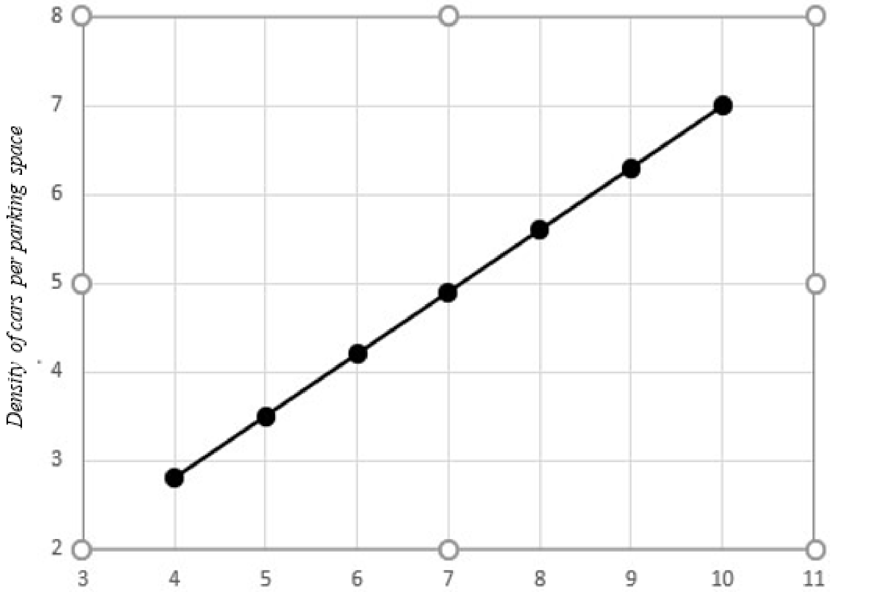

Figure 1 Number of parking spaces in a vertical parking lot

Saving Land Space. This is a key economic factor. Vertical parking systems allow for significantly more cars to be accommodated in the same area compared to traditional surface-level parking lots. For example, on a site where only 2-3 cars would fit, a system for 10-20 cars can be installed. This is especially beneficial in the centers of large cities where land is very expensive.

Reduction of Construction Costs. Compared to the construction of underground or multi-level reinforced concrete parking structures, automated systems made of metal structures can be more economical. Their lighter weight results in lower foundation costs (up to 30% savings) and allows for faster erection.

Reduction of Operating Costs. Automated systems require minimal staff involvement. The absence of the need for a large staff of security guards, cleaners, and parking attendants reduces monthly expenses. Costs for lighting and ventilation are also reduced compared to large underground garages.

Increased Security and Risk Reduction. In closed automated systems, the risk of theft, vandalism, or accidental damage to vehicles is virtually eliminated, since only the owner has access to the cars. This reduces potential expenses for insurance and legal costs.

Investment Attractiveness. Parking spaces in areas with a parking deficit are liquid assets. They can be profitably leased, providing passive income, or resold. The payback period for a vertical parking installation project can be around 3 years, although this indicator strongly depends on specific conditions.

Increased Property Value and Attractiveness. The presence of parking in a residential or office complex directly affects the value and attractiveness of the property. Apartments and offices in buildings with modern parking solutions are sold and rented faster and at higher prices.

A modern metropolis is characterized by narrow streets, dense development, and an eternal lack of free space. In the midst of this maze of concrete, drivers endlessly circle city blocks in search for a free parking spot. The parking problem has evolved beyond mere inconvenience, it has become a significant challenge for residents, businesses, and city authorities alike. Innovative solutions, such as vertical parking systems, are increasingly replacing traditional ground-level parking lots and multi-story parking garages [3-6].

Vertical parking, also known as an Automated Parking System (APS), is a high-tech structure designed for compact and secure vehicle storage using the principle of vertical movement. Unlike conventional parking garages where drivers search for spaces and park themselves, here the process is maximally automated.

Figure 2 shows a foreign analogue of a 12-space parking lot.

The working model of a 4-space vertical parking system has been developed by LLC “Reverse” and manufactured at the “Graal 92” enterprise in Tbilisi. This model is protected under Georgian Patent P 2024 7702 B. Figure 3.

Below is an approximate calculation of the power required for the normal operation of the parking mechanism. The power of the electric motor for rotary parking is determined based on the system’s physical parameters: the combined mass of vehicles and the supporting structure, the lifting speed, and efficiency.

Since the primary motion involves vertical lifting, this factor plays a key role in determining the system’s power requirements [4].

Figure 2 The foreign analogue of 12-space parking

Figure 3 The working model of a 4-space Vertical parking system manufactured according to the project of LLC “Reverse” at “Graal 92” enterprise

2 Literature review

The problem of car parking is very relevant in almost all countries that have a high population density, and it is particularly acute in large cities. In confirmation of this, several citations from a list of publications can be provided.

The article “Smart Parking Systems: A Comprehensive Review of Digitalization of Parking Services” discusses how Smart Parking Systems (SPS) address the limitations of traditional parking methods by providing real-time information on parking space availability, optimizing space utilization, and offering convenient payment solutions. However, despite the relevance and importance of these systems, literature has paid insufficient attention to SPS components that could be significantly improved through innovation. This study addresses this gap by identifying key limitations in [1,2,4] comprehensively analyzed scientific works and proposing innovative solutions. In the field of sensor technologies, environmental impacts and camera line-of-sight issues are addressed through a proposed integrated sensor structure that combines radar precision with camera coverage, enhanced by artificial intelligence to improve detection accuracy.

The article "Understanding Smart and Automated Parking Technology" examines how India's rapidly growing urban population creates numerous challenges for cities, one of the most persistent being car parking. The number of vehicles is increasing daily, which in turn raises the demand for parking spaces in public areas. In India, as of 2014, there were more than 40 million vehicles, and traffic congestion and insufficient parking spaces remain major issues in most Indian cities.

To address these problems, several new technologies have been developed in recent years to help improve parking efficiency. One such solution implemented in India is the Multi-Level Car Parking System (MLCPS), which optimizes parking space utilization by using vertical rather than horizontal space. The advantages of MLCPS include efficient land use, relatively low construction costs, and reduced operational and maintenance expenses. Although automated parking solutions, such as multi-level parking systems, have improved the situation compared to earlier periods, there is still significant room for improvement. Users continue to experience difficulties related to space availability, search time, and waiting time in public locations such as shopping centers, multiplexes, railway stations, and shopping streets. The implementation of advanced smart parking technologies has the potential to resolve many of these issues [5].

The article "Designing an IoT Smart Parking Prototype System" highlights that, in addition to increased vehicle traffic leading to higher fuel consumption, environmental pollution, and longer travel times, the lack of adequate parking spaces contributes to congestion and traffic accidents. At trip destinations, the need for parking is unavoidable, making parking space an increasingly scarce and expensive resource in urban environments [4].

Materials related to the calculation of load-lifting devices are also relevant and should not be overlooked. In A. A. Reutov's 2013 article published in the "Bulletin of Bryansk State Technical University", titled "Calculations of Forces in the Drive-Out Mechanism of a Telescopic Boom", the distribution of forces, such as weight, wind, and inertial loads, across boom sections is analyzed. This analysis is crucial for the design of cranes and other lifting devices and is based on general principles of structural mechanics for dynamic systems [1].

3 Methodology

Below is an approximate calculation of the power required for the normal operation of the parking mechanism. The power of the electric motor for rotary parking is determined based on the system's physical parameters: the combined mass of vehicles and the supporting structure, the lifting speed, and efficiency.

Since the primary motion involves vertical lifting, this factor plays a key role in determining the system's power requirements [4].

Step-by-step method of calculation

1. Determine the load mass:
   Calculate the total mass by summing the weight of the automobiles, the maximum allowable parking load, and the mass of the load-bearing and rotating components of the structure.
2. Select the lifting speed.
3. Specify the efficiency of the drive and gearbox.
4. Substitute the values into the formula and calculate the nominal motor power.

Example of approximate calculation

To calculate the power required for a carousel parking system designed to lift 4 cars, each weighing 2.2 tons, at a speed of 0.05 m/s with an efficiency of 0.9 [8,9], (1), (2):

$$N = \frac{(Q+G)g \cdot v}{\mu}, \quad (1)$$

Where:

- Q - total mass of vehicles, kg;
- G - the mass of the structure, kg;
- g – acceleration of free fall (9,81m/s²),
- v - linear speed, m/s.

$$N = \frac{(8800)9.81 \cdot 0.5}{0.9} = 4796\,WT \quad (2)$$

Based on the calculations, the estimated power requirement for the parking system is approximately 5 kWT.

Practical options:

- A power reserve is necessary to accommodate overload conditions (startup, shutdown, and emergency stops).
- When designing the system, consider both electrical safety and automation requirements.

For specific conditions, individual safety factors are applied, taking into account the actual parameters of the vehicle, the mechanism, and the operating cycle frequency.

It is important to note that our design differs from existing analogues by using a standard chain. In our system, the cradle is suspended directly on the chain links, rather than on a bracket, as is commonly done in Chinese models. This approach significantly reduces friction in the guide elements and decreases stress on the chain nodes. As a result, both operational noise and the required power of the electric drive are significantly reduced.

Figure 4 illustrates the typical cradle suspension scheme used in known prototypes. Due to the fact that the center of gravity of the cradle is offset relative to the chain travel line, the cradle is suspended on a bracket. This is done to reduce the distance between cradles and thereby reduce the height of the structure, which is advisable when a large number of vehicles are placed in the parking system.

Based on the above, additional forces F_1 and F act on the chain, which affect the drive and guide elements. This increases resistance when moving cradles, especially when the chain moves cradles past the drive gears.

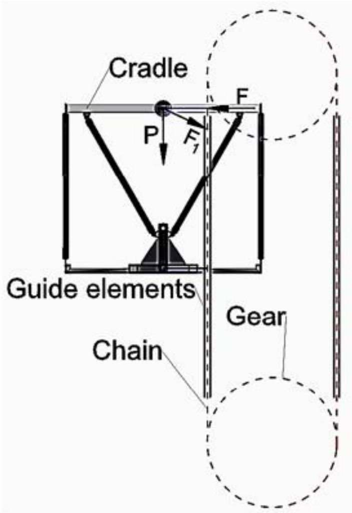

Figure 4 Cradle suspension scheme in a foreign-made vertical parking system

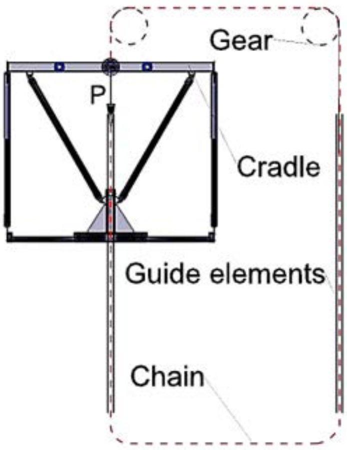

Figure 5 Cradle suspension scheme in the parking system designed by LLC "Reverse"

Figure 5 illustrates the cradle suspension scheme used in the parking system developed by LLC "Reverse". In this design, the cradle's suspension center moves along the chain's travel line, eliminating additional forces that could impede cradle movement. In addition, unlike foreign analogues, the drive gears in our system have a significantly smaller diameter, which significantly reduces the overall construction costs.

Below is an approximate calculation of the frame structure for a 4-space vertical carousel-type parking system [10,11].

Economic report

1. Initial Data

- Structure type: Vertical carousel-type parking (rotary type)
- Number of parking spaces: 4
- Dimensions of one parking space (l × w × h): 5.0 m × 2.5 m × 1.8 m
- Maximum load per cell (vehicle + platform): 2500 kg
- Structure height: ~7 m
- Frame material: Steel (S245, S255)
- Rotation speed: 0.05–0.3 m/s

2. Load Determination

2.1. Vertical Loads

Permanent load (structure weight):

- Steel frames, platforms, mechanisms - approximately 15–20% of useful load.

- Total structure weight:

$G_k = 4 \times 2500 \times 0.2 = 2000$ kg

- Useful load (cars):

$G_a = 4 \times 2500 = 10000$ kg

- Total vertical load:

$N = G_k + Ga = 2000 + 10000 = 12000$ kg ≈ 120 kN

2.2. Horizontal (wind) loads

For a height of 8 m (standard wind pressure value ~ 0.38 kPa):

$F_w = 0.38 \text{ x } 5 \text{ x } 8 = 15.2$ kN

2.3. Dynamic loads (during rotation)

- Centrifugal forces:

$F_c = m \cdot \omega^2 \cdot R,$

where

- $\omega = \frac{v}{R} = \frac{0.05}{0.5} = 0.1 rad/s$
- R = 0.5 m (rotation radius)
- m = 2500 kg (car + platform combined mass)
- $F_c = 2500 \cdot 0.1^2 \cdot 0.5 = 12.5\ N$(slightly)

3. Frame elements calculation

3.1. Columns (supports)

- Load per column (4 columns in the structure):

$$N_k = \frac{120}{4} = 30\text{kN}$$

- Section selection (steel tube or I-beam):

$$\sigma = \frac{N}{A} \leq R_y = 240 mPa$$

$$A \geq \frac{N}{\varphi \cdot R_y} = \frac{46.29 \cdot 10^3}{0.5 \cdot 240 \cdot 10^6} = 3.86 \cdot 10^{-4} m^2 = 3.86 cm^2$$

$$\sigma = \frac{46.29 \cdot 10^3}{0.5 \cdot 240 \cdot 10^6} 3.86 \cdot 10^{-4} m^2 \sim 3.86 MPa < 240 MPa$$

A minimal cut set: tube ⌀150x5 mm (A ≈ 22.8 ^2 \)).

4. Conclusion

The frame of a vertical carousel-type parking system can be made of:

- Columns: steel tubes ⌀150x5 mm.
- Beam heads: I-beams No. 20.
- Foundations: reinforced concrete slabs 0.8×0.8 m.

For accurate calculation, detailed development of joints (platform mounting, drives) and consideration of seismic factors (if necessary) is required.

1. The load-bearing frame consists of 4 steel tubes ⌀150×5 mm with braces.
2. Ring beams are made of I-beam No. 14.
3. Foundations 1.5×1.5 m provide stability against wind overturning.
4. Dynamic loads are insignificant at rotation speed ≤0.3 m/s.

Important: for a real project, it is required to:

- Consider seismic factors (if applicable)
- Check platform mounting joints
- Perform calculations according to SP 16.13330.2017
- Account for snow load on the roof.

Unlike existing foreign constructions, the presented system is capable of movement in both vertical and horizontal directions. This feature enables the construction of parking facilities that adapt to the mountainous landscape that is prevalent in Georgia.

Figure 6 shows a balcony parking system, a mechanized garage with an elevator and movable hangers in the vertical and horizontal planes. P 2021 7228 B.

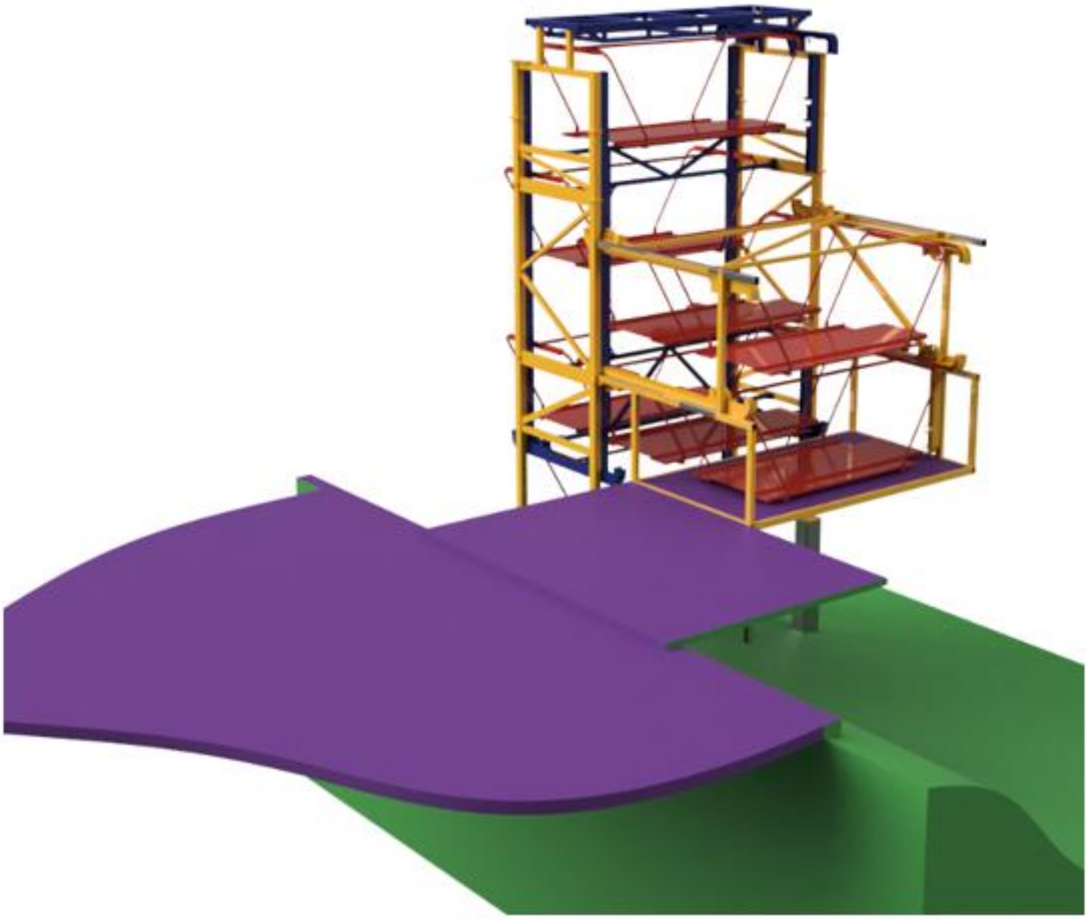

Figure 6 The balcony parking system Mechanized garage with elevator and movable cradles in vertical and horizontal planes

4 Results and discussion

The balcony parking system is a hybrid solution that offers a key advantage: the ability to utilize complex and space-constrained landscapes for organizing parking. Vehicles enter the system through a specially designed balcony platform, allowing the installation of parking facilities on virtually any slope.

The vertical-horizontal (hybrid) parking system combines the features of both vertical and horizontal systems, enabling efficient use of complex terrains for organizing parking spaces. Its main advantage is the simultaneous utilization of vertical and horizontal space, which allows for the accommodation of more vehicles in areas with difficult terrain. Figure 7.

The horizontal parking system is essentially a 90-degree rotated adaptation of the vertical system, designed for efficient vehicle parking on both flat surfaces and inclined terrains. Figure 8.

A car parking lift comprising metal load-bearing vertical support columns formed in the form of a Π-shaped guide, a lifting platform for raising the automobile, a hydraulic drive implemented as a hydraulic compressor and hydraulic cylinder, which is connected to flexible lifting elements mounted on pulleys. In addition, to maintain the balance of the platform, a slide bar is inserted with the ability to slide in each column of the lift, where each slide bar contains at least one spring-loaded eccentric cam mounted with the ability to rotate on an axle, and a conical wedge connected to it and equipped with an emergency displacement spring, which is mounted on the flexible lifting element, while the automobile lifting platform is mounted on the slide bar. Also, the flexible lifting elements mounted on pulleys are connected to a pulley mechanism of a polyspast, which is horizontally positioned at the base of the lift structure and is connected to a drive, which in turn comprises emergency automatic brakes and an electronic control system.

The technical result is an increase in the reliability and stability of the device, improvement of operational efficiency, simplification of the construction, and reduction of economic costs. The reliability and stability of the device is achieved by the fact that the columns have a special Π-shaped form, in which the carriage moves with the ability to slide, and the latter is equipped with a spring-loaded eccentric cam, which in the case of rotation relative to the axle comes into engagement with a conical pawl mounted on the lifting flexible element, which simplifies the construction and reduces economic costs.

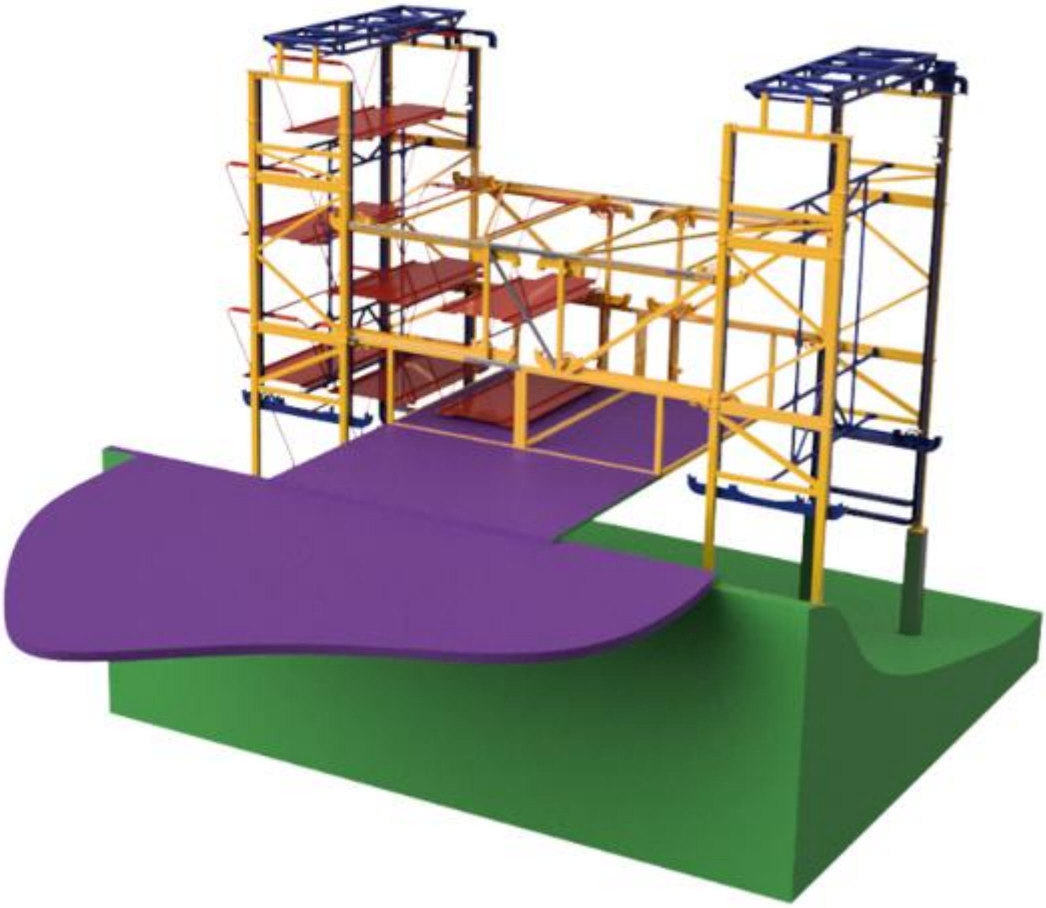

Figure 7 The vertical-horizontal parking system

However, the economic component is of particular importance. The cost of parking in densely populated metropolises, for example, in the city of Tbilisi, can reach approximately USD 5,000 or more; while using an area of 21 m² (6 m × 3.5 m), a four-space vertical parking system can accommodate nearly three vehicles per equivalent ground-level parking area.

If a parking lot occupies an area of 5m × 6m = 30m² and can accommodate 4 cars, then on an area of 21m² it is possible to accommodate 2.8 cars. With a 5-space system, 3.5 cars can be accommodated; with 6 spaces - 4.2 cars; with 7 spaces - 4.9 cars; with 8 spaces - 5.6 cars; with 9 spaces - 6.3 cars; with 10 spaces - 7 cars. If we consider that the cost of a parking space in densely populated urban areas will exceed $5,000, and in underground garages the price will be significantly higher - in some places it is practically equivalent to the cost of apartments - then the benefit here is obvious. On a site where only 2-3 cars would fit, a system for 10-20 cars can be installed. This is especially beneficial in the centers of large cities. Compared to the construction of underground or multi-level reinforced concrete parking structures, automated systems made of metal structures can be more economical. They require lower foundation costs (up to 30% savings) due to the lighter weight of the structures and can be erected faster. Automated systems require minimal staff involvement. Costs for lighting and ventilation are also reduced compared to large underground garages. In closed automated systems, the risk of theft, vandalism, or accidental damage to vehicles is virtually eliminated, since only the owner has access to the cars. This reduces potential expenses for insurance and legal costs. Parking spaces in areas with a parking deficit are liquid assets. They can be profitably leased, providing passive income, or resold. The payback period for a vertical parking installation project can be around 3 years, although this indicator strongly depends on specific conditions. The presence of parking in a residential or office complex directly affects the value and attractiveness of the property. Apartments and offices in buildings with modern parking solutions are sold and rented faster and at higher prices.

Figure 8 Vertical parking with horizontal vehicle arrangement

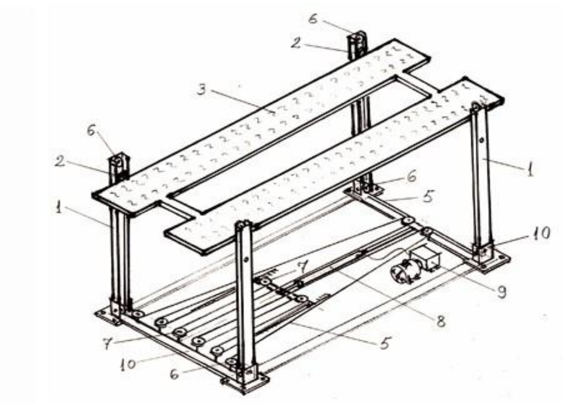

Figure 9 Schematic representation of a parking lift with corresponding kinematics

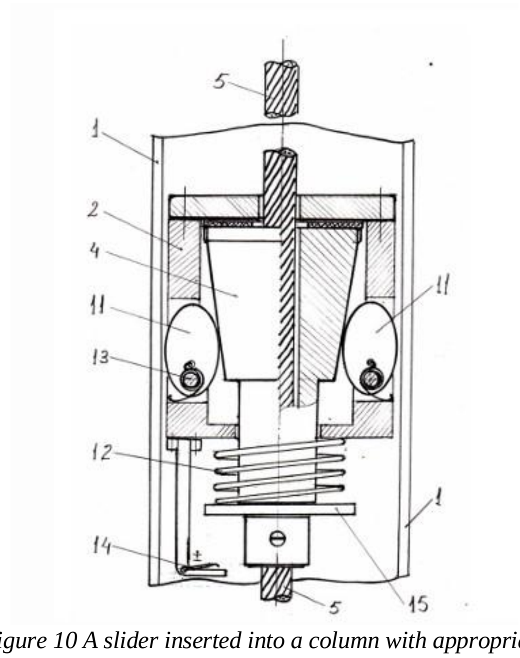

Figure 10 A slider inserted into a column with appropriate structural elements to allow sliding

Figure 9 illustrates a schematic representation of the car parking lift with corresponding kinematics.
Figure 10 shows a slider inserted with the possibility of sliding in the column with corresponding structural elements.

5 Conclusion

Vertical parking is more than just a technological innovation; it is a practical and increasingly essential solution for cities struggling with traffic congestion and limited space. Despite the high cost and technical nuances, its key benefits, such as substantial land savings, enhanced vehicle security, and improved user convenience, make it an attractive option for urban planners and developers alike [12]. This is a forward-looking step in urban infrastructure, where efficiency and convenience converge [13]. As technology evolves and implementation costs decline, vertical parking systems will become as a familiar element of the urban landscape as multi-story garages once were.

This article presents the results of the design, calculation, and manufacturing of a vertical parking structure. Vehicle movement, along with the platforms, is achieved in both vertical and horizontal directions using a chain-driven transmission system. The structure comprises a frame, chain drive, guide rails, and a control unit, which manages platform positioning and enables vehicle entry and exit from the parking system.

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Multi-class fault classification in conveyor systems using machine learning: enhancing reliability in production logistics

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Keywords: industrial conveyor systems, multi-fault detection, predictive maintenance, production automation.
Abstract: Industrial conveyor systems are vital to modern manufacturing and logistics operations, where unexpected failures can cause substantial operational disruptions in material flows and economic losses. Traditional maintenance strategies often fall short in addressing the complex and interrelated failure patterns present in contemporary conveyor systems. This study presents a machine learning-based framework for developing multi-class classification models, designed to enable reliable deployment for real-time fault diagnosis in logistics environments. Using real-world operational data with sensor-derived features, multiple machine learning models are trained and evaluated to classify key types of conveyor faults. Experimental results demonstrate that ensemble methods achieved the highest performance, attaining an accuracy of 92.56% and significantly outperforming linear and instance-based approaches. This research aims to advance predictive maintenance by introducing a unified framework for the development of a multi-class classification model, enabling the identification of the most effective model for deployment in logistics settings. The main contribution of this work lies in the integration of machine learning techniques into logistics systems for predictive maintenance, offering an advanced, scalable solution that can be deployed to improve system reliability, reduce downtime, and enhance operational efficiency.

1 Introduction

Industrial conveyor systems represent a cornerstone of modern manufacturing, logistics, and material transport across diverse sectors, including mining, agriculture, food processing, automotive, and distribution centers. Conveyors are commonly used to move materials efficiently, helping ensure smooth operations and consistent productivity across various environments. The widespread application of industrial conveyors across various sectors underscores their critical role in logistics and material flow management in modern industrial operations. They not only improve the efficiency of material transport but also help reduce labor costs, enhance worker safety, and increase overall productivity. As industries continue to evolve and expand, the role of conveyors is becoming even more vital, with innovations such as automation, artificial intelligence, and robotics driving further improvements in performance, capabilities, and logistics optimization. Figure 1 illustrates the extensive range of applications for industrial conveyors across these sectors, highlighting their integral role in streamlining processes and boosting productivity in modern industrial operations.

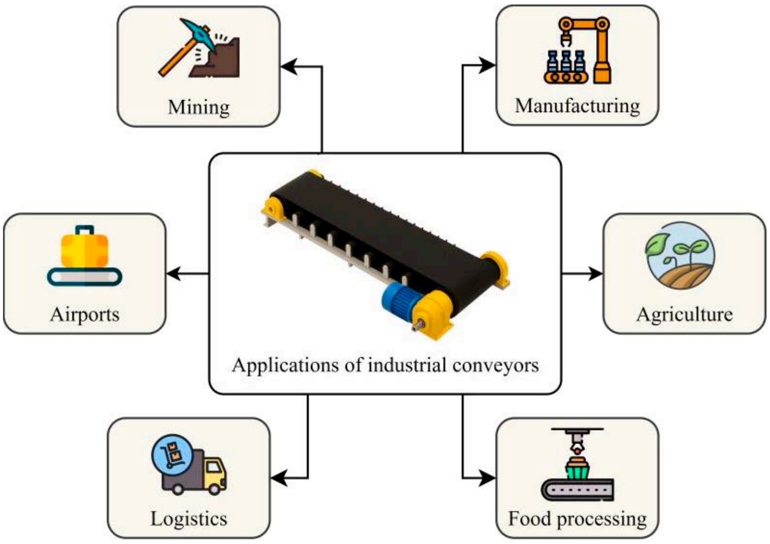

Figure 1 Common applications of industrial conveyors

Conveyor system failures can lead to significant financial losses in industrial operations by disrupting material flows, increasing downtime, and driving up maintenance costs. These unplanned downtimes resulting from component failures can halt entire production lines, leading to immediate revenue losses and cascading effects throughout the logistics chain. Beyond direct operational costs, unexpected failures often necessitate emergency repairs, premium pricing for expedited parts procurement, and extended maintenance personnel overtime. Safety concerns further compound these issues, as sudden mechanical failures can pose risks to personnel working in proximity to the equipment. The fundamental design of a belt conveyor system, as depicted in Figure 2, consists of several interconnected mechanical components, including drive motors, gearboxes, conveyor belts, rollers, pulleys, and bearings. Each component plays a vital role in the system's overall functionality, and the failure of any element can result in a complete system shutdown, leading to significant operational disruptions and economic losses.

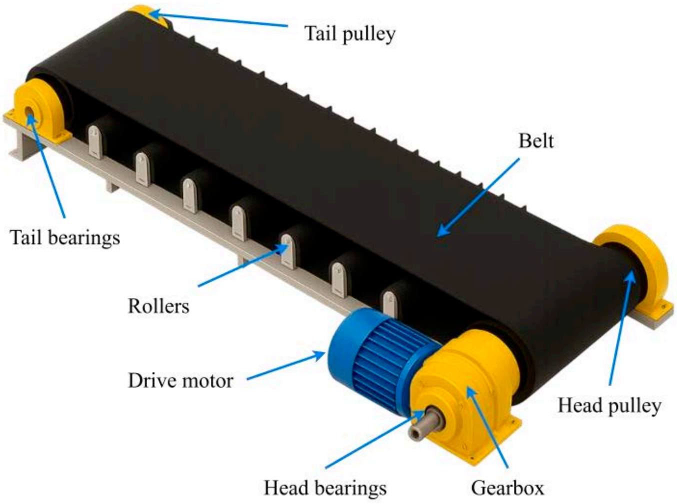

Figure 2 Key components of a belt conveyor: drive motor, gearbox, conveyor belt, rollers, pulleys, and bearings

Traditional maintenance approaches, predominantly based on periodic maintenance or reactive strategies following equipment failure, have proven inadequate for addressing the complex failure patterns exhibited by modern conveyor systems [1,2]. Periodic maintenance often results in unnecessary component replacements and increased operational costs, while reactive maintenance leads to unexpected downtime and potential safety hazards, disrupting material flows and logistics operations. The limitations of these conventional approaches have driven the industrial sector toward predictive maintenance strategies that leverage advanced monitoring technologies and data analytics to anticipate failures before they occur. The evolution of conveyor fault detection has progressed through several distinct phases, each characterized by technological advancements and improved diagnostic capabilities. Early detection methods relied primarily on manual inspections and basic vibration monitoring, providing limited insight into component health and often failing to detect incipient failures [1]. The introduction of vibration and acoustic signal analysis marked a significant advancement, enabling the detection of bearing and rotating component defects through frequency domain analysis [3,4].

Recent technological advancements have enhanced diagnostic capabilities, incorporating tools like acoustic monitoring, thermal imaging, and computer vision techniques. Acoustic signal analysis has emerged as a particularly effective approach for identifying bearing and idler roller defects, with researchers demonstrating the successful application of signal processing techniques such as Fast Fourier Transform (FFT) and Mel Frequency Cepstral Coefficient (MFCC) extraction for fault classification [5-7]. The integration of autonomous inspection systems has further enhanced diagnostic capabilities, with mobile robots equipped with acoustic sensors proving effective for continuous monitoring in challenging industrial environments [5,6]. The integration of machine learning and artificial intelligence has transformed conveyor fault detection from reactive monitoring to proactive predictive maintenance systems. Modern approaches utilize advanced techniques such as deep learning, anomaly detection, and reinforcement learning to analyze complex sensor data, uncover meaningful patterns, and predict component failures with high accuracy. Deep learning techniques have shown particular promise for visual inspection tasks, with Convolutional Neural Networks (CNNs) achieving remarkable performance in detecting belt damage and component defects from video feeds and thermal images [8-10]. Edge computing implementations have further enhanced the practical applicability of machine learning approaches, enabling real-time fault detection with reduced computational overhead and improved response times [11].

While these technological advancements have significantly enhanced diagnostic capabilities and demonstrated impressive performance in controlled research environments, their translation into comprehensive industrial solutions remains challenging. The promising results achieved through acoustic monitoring, thermal imaging, and machine learning approaches have primarily been validated under specific operational conditions and targeted fault scenarios. However, the complexity of real-world industrial conveyor operations characterized by simultaneous multi-component interactions, varying operational loads, and diverse environmental conditions presents significant challenges for logistics operations that extend beyond the scope of current research focuses. The convergence of these technological limitations with evolving industrial requirements creates a compelling need for more sophisticated diagnostic solutions. Modern industrial facilities increasingly demand predictive maintenance systems that can provide actionable intelligence about specific fault conditions rather than generic anomaly alerts. The economic implications of unplanned downtime, which often exceed thousands of dollars per hour in manufacturing environments, necessitate diagnostic systems capable of distinguishing between fault types to enable targeted maintenance interventions. Moreover, the integration of Industry 4.0 principles requires condition monitoring systems that can seamlessly interface with existing industrial Internet of Things (IoT) infrastructures while providing granular diagnostic information that supports data-driven maintenance scheduling and resource allocation decisions.

This research addresses these critical needs through the development of a framework capable of training and selecting a multi-class fault classification model specifically designed for conveyor system diagnostics. The study establishes two primary research objectives: first, to develop and validate a machine learning-based diagnostic system capable of simultaneously identifying six distinct conveyor fault categories (ball bearing, central shaft, pulley, drive motor, idler roller, and belt slippage); and second, to conduct a comprehensive comparative evaluation of multiple classification algorithms under realistic operational conditions, including detailed feature importance analysis that identifies the most discriminative features for each fault type. The best model identified by the proposed framework is suitable for deployment in logistics environments, where it can provide real-time fault classification and support predictive maintenance decision-making processes. The modular design approach adopted ensures that the proposed model development framework can be adapted for deployment across diverse industrial conveyor installations through appropriate sensor integration and system calibration procedures.

The rest of this paper is organized as follows: Section 2 provides a comprehensive review of related work in conveyor fault detection, examining existing approaches and identifying research gaps that motivate this study. Section 3 details the methodology, describes the dataset used for model development and evaluation, including fault categorization and statistical characteristics, encompassing data preprocessing techniques, feature extraction methods, model training procedures, and hyperparameter tuning strategies. Section 4 discusses experimental results, including comparative performance, feature importance analysis, and practical implications for deployment in logistics. Finally, Section 5 concludes the paper with a summary of key findings, contributions to the field, and recommendations for future research directions.

2 Literature review

Conveyor fault detection has become an increasingly active area of research, with notable progress in both theoretical development and industrial applications. Initially, fault detection relied on manual inspections; however, recent advancements in technology have introduced machine learning, computer vision, distributed sensing, and hybrid approaches. These innovations are aimed at improving system reliability, enabling predictive maintenance, and enhancing cost efficiency in conveyor operations. Conveyor systems are prone to various faults, which can significantly impact their performance and safety. Common faults include belt misalignment or deviation, belt slippage, belt tearing, as well as failures in idlers, bearings, pulleys, and gears. These issues typically arise due to factors such as uneven loading, adverse environmental conditions, inadequate maintenance, or mechanical wear. These faults can result in costly downtime and pose safety risks, making their detection crucial. This section systematically examines the literature on conveyor fault detection and the limitations of the existing approaches.

Traditional approaches, such as periodic manual inspection and monitoring of sensor outputs, offer limited fault coverage and may not catch early-stage defects [1]. Vibration and acoustic signal-based detection have emerged as a standard, particularly for idler and bearing issues. Techniques such as FFT and MFCC extraction form the basis for signal analysis, with machine learning playing a growing role in classification and anomaly detection [3]. Skoczylas et al. developed an autonomous legged robot that uses acoustic signals to detect faulty idler rollers in underground conveyor systems. Their approach combines cyclostationary signal analysis with Principal Components Analysis (PCA) to enable robust fault detection [5]. Wodecki et al. refined the acoustic diagnostic pipeline by incorporating cyclic spectral coherence, local mode decomposition, and envelope analysis. The proposed method improved the robot's ability to distinguish real bearing faults from environmental or structural noise artifacts [6]. Wijaya et al. proposed an automated conveyor fault detection system using distributed acoustic sensing via optical fibers, enabling long-range, real-time vibration monitoring. Their method identifies abnormal roller behavior by analyzing acoustic signal patterns and applies automated decision rules to reduce inspection delays in mining environments [2]. Liu et al. propose a fault detection system for belt conveyor idlers using acoustic signals processed through 13 MFCCs. A Gradient Boosted Decision Tree (GBDT) model is trained on these features to classify the idler condition, achieving 94.53% accuracy and up to 99.7% recall on test data [7]. Milovancevic explored diagnoses of belt conveyor idler faults using vibration signals. The study employs Short-Time Fourier Transform (STFT) and CNN for effective fault classification under various operational conditions, enhancing maintenance reliability [4].

Thermal and acoustic imaging combined with computer vision and machine learning techniques have been widely applied for early, non-invasive conveyor fault detection. Bortnowski et al. explored the use of an acoustic camera combining a video feed with a microphone array for spatial mapping of noise sources on a belt conveyor in a controlled laboratory setup. The authors recorded and visualized sound pressure level maps to locate and characterize noise from three principal elements: the electric motor, idler roller bearings, and tail pulley misalignment [12]. Fedorko et al. proposed a methodology for identifying noise sources in continuous transport systems using an acoustic camera. The proposed approach combines beamforming and spectral analysis to localize and classify mechanical noise from components like idlers and motors, supporting condition monitoring and preventive maintenance [13]. Thermal imaging combined with computer vision and machine learning techniques has been widely applied for early, non-invasive conveyor fault detection by analyzing temperature anomalies. Yang et al. introduced a motor-driven inspection robot that uses infrared thermography to monitor critical mechanical components of belt conveyors. By processing thermal images of parts like motors, pulleys, and rollers, the robot automatically detects abnormalities and issues failure warnings, overcoming the limitations of traditional inspection methods [14]. Siami et al. proposed a binary classification method using CNN for identifying overheated belt conveyor idlers using thermal images. The proposed method achieved a precision of 0.9740 and an F1 score of 0.9782, significantly improving previous results [15]. Zhan et al. proposed a deeply lightweight target detection network based on the Yolov4 for foreign object detection on conveyor belts. The proposed system offers superior speed and accuracy, enabling real-time alerts that support timely interventions and minimize system downtime [16]. Xiuyu et al. proposed a method for diagnosing faults in conveyor rollers using thermal infrared imaging. The approach utilizes the YOLOv4 vision method to accurately locate rollers. This method effectively distinguishes between normal and faulty rollers based on temperature changes observed during operation, achieving a recognition accuracy of 93.8% [17]. Siami et al. proposed an image processing pipeline using U-Net-based CNNs enhanced with thermal image augmentation for automatic semantic segmentation of thermal defects in belt conveyor idlers. The proposed approach improved detection accuracy for thermal anomalies, achieving a mean pixel accuracy of 99.9%, supporting more reliable, automated fault monitoring in challenging industrial environments [18].

In recent years, machine learning and deep learning techniques have gained significant attention for conveyor fault detection, offering advanced capabilities for real-time and accurate monitoring. Various studies have demonstrated the effectiveness of machine learning and deep learning in detecting conveyor faults, enabling timely fault identification and predictive maintenance. Li et al. developed a hybrid fault diagnosis model for belt conveyors, integrating support vector machine (SVM), principal component analysis, and grey wolf optimization. The methodology addresses the limitations of standard optimization methods, achieving a fault classification accuracy of 97.22% using monitoring data from underground mine conveyors [19]. Zhang et al. proposed a lightweight deep learning method for detecting damage in mining conveyor belts by integrating MobileNet with YOLOv4. It achieves 93.22% accuracy and 70.26 FPS speed, outperforming the original Yolov4 and demonstrating strong generalization for visual monitoring [8]. Liu et al. developed a deep learning-based method for detecting damage in mining conveyor belts using on-site monitoring video. It combines temporal and spatial features, employing an improved attention mechanism and Temporal Convolutional Networks, achieving over 20% higher accuracy than traditional methods [9]. Dwivedi et al. developed a deep learning framework for real-time damage detection in long conveyor belts, utilizing edge devices for immediate results. It effectively identifies damage sizes from 1 cm to 100 cm, achieving an 85% mean average precision in tunnel construction sites [10]. Soares et al. highlighted the use of predictive techniques like vibration analysis and machine learning to address reliability issues in bulk transportation systems, specifically belt conveyors. By combining Wavelet Packet Decomposition for feature extraction and GBDT for fault classification, the system achieved high accuracy (100% for bearing faults and 97.5% for surface wear), proving effective for diagnosing issues in conveyor idlers [20]. Gunckel et al. proposed a flexible machine learning workflow for developing failure forecasting systems for mining conveyor belts in Chile. The approach involved integration between various components, including the distributed control system, a digital twin, and an operational logbook. The proposed approach achieved precision and recall above 0.83, reducing dependence on maintenance data [11]. Liu et al. proposed an intelligent fault diagnosis method for belt conveyor rollers using a polar KNN algorithm with audio features. By extracting and analyzing audio signals, their method enhances fault classification accuracy, outperforming traditional KNN and similar classifiers for detecting roller defects [21].

Although significant advancements have been made in conveyor fault detection through the application of acoustic sensing, thermal imaging, computer vision, and machine learning techniques, the majority of existing studies concentrate on the detection of a single fault type or component. Commonly investigated faults include idler roller failure, bearing defects, or belt surface damage, each typically addressed in isolation. While these focused approaches have demonstrated high accuracy within controlled settings, they often lack scalability and practical relevance in logistics, where multiple faults can occur simultaneously, disrupting material flows. Despite the growing interest in predictive maintenance, relatively few studies have proposed diagnostic frameworks capable of identifying and distinguishing multiple fault types within a unified model. There remains a clear gap in the literature for multi-class classification techniques that can generalize across fault categories and support multi-fault diagnosis. To address this shortcoming, the present study introduces a machine learning-based classifier designed to detect and differentiate six critical types of conveyor faults: ball bearing, central shaft, pulley, drive motor, idler roller, and belt slippage. By targeting multiple components within a single diagnostic model, this research aims to enhance fault coverage, improve practical applicability, and contribute to the development of more robust condition monitoring systems for logistic conveyor operations.

3 Methodology

The development of an accurate and reliable machine learning model for industrial conveyor fault detection requires a structured, transparent, and replicable pipeline. This research follows a methodical approach comprising three main stages: data preprocessing, model training and hyperparameter tuning, and finally model evaluation and Selection. The preprocessing stage ensures that the data is preprocessed and is suitable for model input. Model training with hyperparameter tuning ensures that each model is finetuned for the fault classification task, and performance evaluation helps identify the best model for the classification task. The following text describes each step in detail.

3.1 Dataset description

This study employs an open-source operational conveyor fault dataset, publicly available on Kaggle, a well-known and reputable source of machine learning datasets. The dataset comprises 1,209 operational records collected from a conveyor system operating under industrial conditions. A distinguishing characteristic of this dataset lies in its multi-fault coverage, which includes six real-world conveyor faults: Ball Bearing Fault, Central Shaft Fault, Pulley Fault, Drive Motor Fault, Idler Roller Fault, and Belt Slippage. This contrasts with many publicly available industrial datasets, which often focus on detecting a single fault type. The multi-fault nature of the dataset significantly enhances its applicability to real-world industrial diagnostics, where simultaneous or interacting faults are common. Each record in the dataset encapsulates a detailed snapshot of system performance, capturing five key sensor-derived features: rotational speed, load, temperature, vibration, and electric current. A summary of feature types and their respective measurement units is provided in Table 1.

Table 1 Dataset features with measurement units

Features	Data types	Unit
Speed	Integer	rpm (rotations per minute)
Load	Integer	Kg (kilogram)
Temperature	Integer	°C (degree Celsius)
Vibration	Float	m/s^2 (meters per second squared)
Current (A)	Float	A (ampere)

Some random samples from the dataset for each fault class are presented in Table 2, showing how different operational parameters correspond to various faults. Since the dataset is based on variable load conditions, this operational variability makes it highly suitable for machine learning tasks such as predictive maintenance, fault classification, anomaly detection, and multi-class modelling. Also, its open-source availability on Kaggle promotes transparency, reproducibility, and benchmarking, making it a valuable resource for academia and industry alike in the pursuit of reliable, efficient conveyor diagnostics. The next section presents the methodology used to develop a multiclass fault classifier using this dataset.

Table 2 Random data samples with associated faults

Speed	Load	Temperature	Vibration	Current	Fault
116	490	43	0.82	3.17	Ball bearing
123	503	43	0.88	3.54	Central shaft
123	507	39	0.86	3.57	Pulley
122	535	44	1.06	3.56	Drive motor
118	509	40	0.8	3.48	Idler roller
116	473	40	0.77	3.23	Belt slippage

3.2 Data preprocessing

Data preprocessing is the crucial step of preparing raw input data before feeding it into machine learning algorithms. This step encompasses essential tasks such as handling missing values, normalizing feature scales, and partitioning the dataset into appropriate subsets, among other transformations. This process ensures data quality, consistency, and compatibility with machine learning models, directly impacting model performance and reliability. Effective preprocessing can significantly improve model accuracy, while poor preprocessing often leads to suboptimal results regardless of the algorithm used. For this study, since the dataset contained no missing values, the preprocessing steps were focused on feature scaling to normalize the input variables and partitioning the data into training, validation, and test sets. Feature scaling is an important step, especially when dealing with heterogeneous sensor data, like the one used in this study. To ensure optimal model performance and convergence, all numerical features were normalized using Min-Max scaling. This transformation maps each feature to a fixed range between 0 and 1, preventing features with larger numerical ranges from dominating the learning process. The formula for the Min-Max scaling transformation is presented in the following Equation (1).

$$X_{scaled} = \frac{X - X_{min}}{X_{max} - X_{min}} \tag{1}$$

where $\boldsymbol{X}$ represents the original feature values, $\boldsymbol{X_{min}}$ and $\boldsymbol{X_{max}}$ are the minimum and maximum values of each feature, respectively. This scaling method was chosen over standardization (z-score normalization) as it preserves the original distribution shape while ensuring all features contribute equally to distance-based calculations commonly used in machine learning algorithms.

Another important preprocessing step was partitioning the dataset into subsets. Initially, the dataset was divided into training and test sets using an 80:20 ratio, with stratified sampling applied to maintain the original class distribution in both subsets. The test set was reserved exclusively for final model evaluation and remained untouched throughout the model development process. The training portion (80% of the original data) served as the foundation for model training and hyperparameter optimization. This training set was further subdivided during the model training phase using 5-fold cross-validation, as detailed in the subsequent model training section. This approach ensures that model performance estimates are derived from multiple independent validation sets while maintaining a held-out test set for unbiased final evaluation. The next steps in the developed pipeline are model training and evaluation.

3.3 Model training and hyperparameter tuning

To identify and select the best algorithm for conveyor fault detection, six distinct machine learning algorithms were selected to provide a comprehensive comparison of classification approaches, ranging from linear models to ensemble methods. The selected algorithms encompass different learning paradigms: Logistic Regression as a linear probabilistic classifier, Decision Tree as a rule-based approach, Random Forest as a bagging ensemble method, k-Nearest Neighbors as an instance-based learner, Support Vector Machine as a margin-based classifier, and XGBoost as a gradient boosting ensemble technique. This diverse selection ensures robust evaluation across various algorithmic approaches and provides insights into the most suitable modelling strategy for the given classification problem. To ensure each model achieves the best performance, hyperparameter optimization was conducted using an exhaustive grid search approach combined with 5-fold cross-validation to ensure robust parameter selection and prevent overfitting to specific data splits. The grid search methodology systematically evaluates all possible combinations of hyperparameters within predefined search spaces, providing comprehensive exploration of the provided parameter combinations for each algorithm. The 5-fold cross-validation procedure partitioned the training dataset into five equal stratified folds, maintaining the original class distribution within each fold.

Table 3 Hyperparameters and search space of grid search

Classifier	**Parameters and Search Space**
Logistic Regression	C: [0.1, 1, 10] solver: liblinear
Decision Tree	criterion: [gini, entropy] min samples leaf: [1, 2, 4] max depth: [None, 5, 10, 15, 20] min samples split: [2, 5, 10]
Random Forest	max depth: [None, 10, 20] n estimators: [50, 100, 200]
k-Nearest Neighbors	n neighbors: [3, 5, 7] weights: [uniform, distance]
Support Vector Machine	Kernel: [linear, rbf] C: [0.1, 1, 10]
XGBoost	learning rate: [0.01, 0.1, 0.2] max depth: [3, 6, 9] n estimators: [50, 100, 150]

For each hyperparameter combination, the model was trained on four folds and validated on the remaining fold, with this process repeated five times to ensure each fold served as the validation set exactly once. The final performance metric for each hyperparameter configuration was computed as the mean validation score across all five folds, providing a robust estimate of model performance while minimizing variance due to specific train-validation splits. Table 3 presents the defined search space of hyperparameters for various models.

Model selection was based on cross-validation accuracy, with the hyperparameter configuration yielding the highest mean validation score selected as optimal for each algorithm. The computational complexity of this approach resulted in training multiple model instances: for each algorithm, the total number of models trained equaled the Cartesian product of hyperparameter options multiplied by the number of cross-validation folds. This exhaustive evaluation ensures optimal hyperparameter selection while providing statistically robust performance estimates through repeated validation on different data subsets. Following hyperparameter optimization, final models were retrained using the complete training dataset with optimal parameters, preparing them for evaluation on the held-out test set. The following subsection describes the model evaluation process and metrics used to assess and select the best model.

3.4 Model evaluation

Following hyperparameter optimization through grid search and cross-validation, the best-performing configuration for each algorithm was selected based on cross-validation accuracy. These optimized models were subsequently evaluated on the previously unseen (held out) test set to assess their generalization capability and provide unbiased performance estimates. The test set, comprising 20% of the original dataset, remained completely isolated during the model development phase to ensure evaluation of model performance on new, unseen data. The best model was selected based on various evaluation metrics, including accuracy, Matthew's Correlation Coefficient (MCC), precision, recall, and F1 score. These metrics collectively capture various aspects of classification performance, including overall correctness, class-specific performance, and balanced evaluation measures. The following text briefly describes each evaluation metric:

- **Accuracy:** Accuracy represents the proportion of correctly classified instances across all classes and serves as the most intuitive measure of overall model performance. Equation (2) shows the formula for calculating accuracy.

$$Accuracy = \frac{TP + TN}{TP + FP + TN + FN} \tag{2}$$

where TPs (True Positives), TNs (True Negatives), FPs (False Positives), and FNs (False Negatives) represent the counts of four possible prediction outcomes in the confusion matrix. The confusion matrix organizes these counts in a total classes × total classes table (6 x 6 in our case), with rows representing actual classes and columns representing predicted classes, providing a comprehensive view of classification performance. For any specific class i, the metrics are calculated using a one-vs-all approach: TPs_i are instances of class i correctly predicted as class i, FPs_i are instances of other classes incorrectly predicted as class i, FNs_i are instances of class i incorrectly predicted as other classes, and TNs_i are instances of other classes correctly predicted as not being class i. This decomposition allows computation of class-specific performance metrics, which are then aggregated using macro-averaging to provide overall model performance measures that treat all classes equally, regardless of their frequency in the dataset. While accuracy provides a straightforward interpretation of model performance, it can be misleading in cases of class imbalance where high accuracy might be achieved by simply predicting the majority class.

- **Matthew's Correlation Coefficient (MCC):** Although accuracy is commonly used to measure classification performance, it is asymmetrical and can be affected by class imbalance problems. In contrast, the MCC score is a more reliable metric for evaluating classification performance. Equation (3) shows the formula to calculate the MCC score.

$$MCC = \frac{(TP \times TN) - (FP \times FN)}{\sqrt{(TP + FP)(TP + FN)(TN + FP)(TN + FN)}} \tag{3}$$

MCC ranges from -1 to +1, where +1 indicates perfect prediction, 0 represents random prediction, and -1 indicates completely incorrect prediction. Unlike accuracy, MCC provides a balanced measure that accounts for all four confusion matrix categories and remains informative even with unbalanced datasets.

- **Precision:** Precision (4) is defined as the ratio between the true positives and the total predicted number of samples that are indicated as positive.

$$Precision = \frac{TP}{TP + FP} \tag{4}$$

Precision is particularly important in scenarios where false positive predictions carry significant consequences. High precision indicates that when the model predicts a positive class, it is likely to be correct, though it may miss some true positive instances.

- **Recall:** Recall (5) is the ratio of true positives to the total actual number of samples reported as positive. Recall captures the model's ability to identify positive instances and avoid false negative errors. High recall indicates comprehensive detection of positive cases, though it may come at the cost of increased false positives.

$$Recall = \frac{TP}{TP + FN} \tag{5}$$

- **F1-score:** The F1-score (6) provides a harmonic mean of precision and recall, offering a balanced measure that considers both false positives and false negatives. The harmonic mean ensures that the F1-score is low when either precision or recall is poor, making it particularly valuable for evaluating model performance when both false positives and false negatives are equally important. The F1-score ranges from 0 to 1, with 1 representing perfect precision and recall. It is computed as:

$$F1\ score = \frac{2\ \times Precision\ \times Recall}{Precision + Recall} \tag{6}$$

The precision, recall, and F1-score were computed using macro-averaging, which calculates metrics independently for each class and then takes the unweighted mean of these values. This approach ensures equal treatment of all classes regardless of their frequency in the dataset. The macro-averaging approach provides insights into model performance across all classes and prevents bias toward majority classes that might occur with micro-averaging. All metrics were computed using the confusion matrix generated from test set predictions, ensuring consistent and standardized evaluation across all algorithms. Comprehensive evaluation using multiple metrics allows for a nuanced interpretation of model performance, as different metrics may favor different aspects of classification behavior. This multi-metric approach enables the identification of models that excel in specific performance dimensions and supports informed decision-making based on the relative importance of different types of classification errors in the given application context.

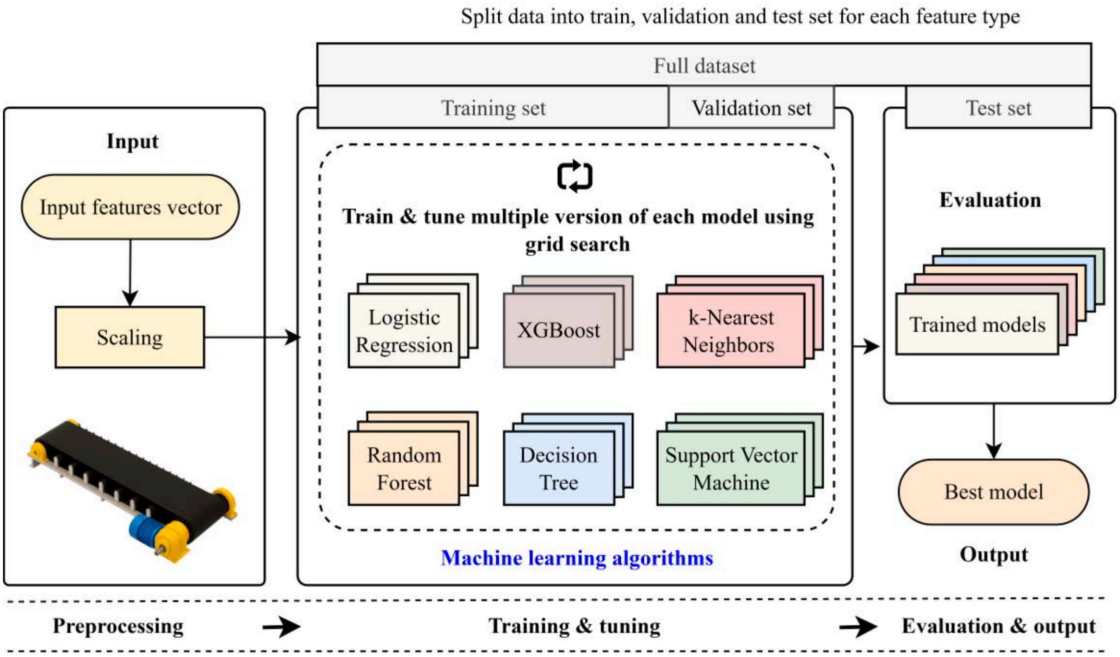

Figure 3 Model development framework for conveyor fault classification

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Figure 3 presents a comprehensive overview of the model development framework implemented in this study for conveyor fault classification. The pipeline begins with the input features, followed by preprocessing steps that include feature scaling and partitioning the data into training, validation, and test sets. Six different machine learning classifiers were then trained. Each trained model was evaluated on an unseen test set to determine the most effective solution for fault classification. The best-performing model demonstrates strong generalization capability and is well-suited for deployment in a production environment to enable accurate and reliable fault detection on future data. This structured pipeline in the model development framework ensures a rigorous and reproducible approach to model development, tuning, and evaluation.

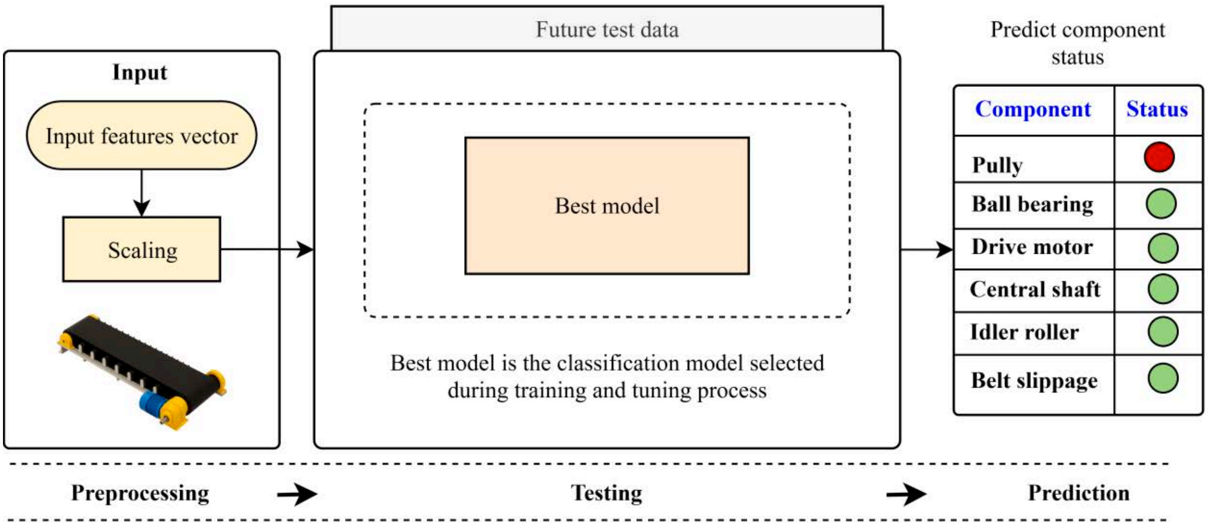

Figure 4 Best model deployment in a production environment for prediction on future data

Figure 4 illustrates how the best classification model can be deployed within a production environment following the training and tuning phases. The first phase (preprocessing) is the same as the training tuning process; the resulting feature vector is then used as an input to the classification model. The model then evaluates the input to predict the status of various components, including the ball bearing, drive motor, central shaft, and belt slippage. The model outputs a status for each component, with a red indicator representing a fault or failure (e.g., faulty ball bearing) and green indicators signifying normal operation. This deployment process enables real-time predictive maintenance and monitoring within an industrial or production setting. The results of the model evaluation, including detailed performance comparisons across all algorithms and metrics, are presented in the following section.

4 Results and discussion

This section presents the outcomes of the machine learning-based conveyor fault classification system developed in this study. The objective was to accurately classify six distinct types of mechanical faults commonly encountered in conveyor systems: ball bearing failure, central shaft issues, pulley malfunction, drive motor faults, idler roller defects, and belt slippage. Various supervised machine learning algorithms were trained and evaluated, and their performance was compared using several standard metrics, including precision, recall, F1-score, MCC, and overall accuracy. These metrics collectively offer a comprehensive understanding of how well each model performs in both detecting and correctly identifying the different fault categories. Table 4 summarizes the classification performance of six different algorithms: Logistic Regression, k-Nearest Neighbors, Random Forest, Decision Tree, Support Vector Machines, and XGBoost. The best performance scores are present in bold font, and the second-best scores are underlined in Table 4. Among these, the Random Forest classifier exhibited the highest overall performance, achieving an accuracy of 92.56%, the highest among all models tested. In addition to accuracy, it also achieved the highest scores across other evaluation metrics, with a precision and recall of 0.93, an F1-score of 0.92, and an MCC of 0.91. These results indicate not only the model's ability to correctly classify the majority of fault instances but also its robustness across all classes, exhibiting a high MCC score. On the other hand, the Logistic Regression model achieved the lowest performance among all classifiers, with an accuracy of 73.55%, a precision and recall of 0.73, and an F1-score of 0.73. These results highlight the limitations of linear models in capturing the complex, nonlinear relationships inherent in conveyor fault patterns. In comparison, XGBoost and Decision Tree classifiers both attained the second-highest accuracy scores of 91.32% and exhibited balanced performance across evaluation metrics. Each achieved a precision, recall, F1-score of 0.91, and MCC of 0.90. Other classifiers, such as k-Nearest Neighbors and Support Vector Machines (SVM), performed reasonably well but were comparatively less effective. KNN achieved an accuracy of 85.12%, with a precision and recall of 0.85 and an MCC of 0.82, while SVM recorded a slightly higher accuracy of 85.54%, with corresponding precision and recall of 0.86 and 0.85, respectively, and an MCC of 0.83. The random forest classifier outperformed all other models across every metric. These results affirm the random forest's capability to effectively model the complex fault patterns across multiple conveyor components and justify its selection as the optimal model for deployment and fault-specific analysis.

Table 4 Various performance scores of different models

Classifier	Precision	Recall	F1	MCC	Accuracy (%)
Logistic Regression	0.73	0.73	0.73	0.68	73.55
k-Nearest Neighbors	0.85	0.85	0.85	0.82	85.12
Random Forest	**0.93**	**0.93**	**0.92**	**0.91**	**92.56**
Decision Tree	0.91	0.91	0.91	0.90	91.32
Support Vector Machines	0.86	0.85	0.85	0.83	85.54
XGBoost	0.91	0.91	0.91	0.90	91.32

To gain a deeper understanding of how the Random Forest model performs across individual fault categories, the confusion matrix is shown in Figure 4. This confusion matrix presents the classification performance of the Random Forest model across six fault classes. The matrix demonstrates generally strong predictive accuracy, with several notable patterns worthy of detailed examination. The overall diagonal dominance of the confusion matrix indicates that the random forest model successfully learned distinguishing characteristics for each component type. The model exhibits strong performance for certain component types, achieving perfect or near-perfect classification accuracy. Drive motor components show perfect classification with all 41 instances correctly identified (100% accuracy), while idler roller components demonstrate similarly robust performance with 40 out of 40 instances correctly classified. Belt slippage classification also proves highly effective, with all 41 cases accurately predicted, indicating the model's strong capacity to distinguish these particular failure modes.

Ball bearing classification presents a more complex pattern, correctly identifying 33 out of 40 instances (82.5% accuracy). The misclassifications are distributed across pulley (5 instances) and belt slippage (2 instances), suggesting some similarities between these component failure signatures that challenge the model's discriminative capability. Central shaft classification demonstrates strong overall performance with 39 out of 40 instances correctly identified (97.5% accuracy), with only a single misclassification as the idler roller category. This high accuracy indicates well-defined characteristic features for central shaft failures that the random forest algorithm can effectively capture. Pulley classification reveals the most challenging classification task for the model, achieving 30 correct classifications out of 40 total instances (75% accuracy). The error distribution shows misclassifications spread across ball bearing (2 instances), central shaft (2 instances), and, notably, idler roller (6 instances). This pattern suggests potential overlap in the feature space between pulley failures and other mechanical components, particularly idler rollers, which may share similar feature signatures. These results demonstrate the best random forest's robust performance in conveyor fault diagnosis while highlighting specific areas where feature engineering or additional data collection might improve classification accuracy for the more challenging component pairs.

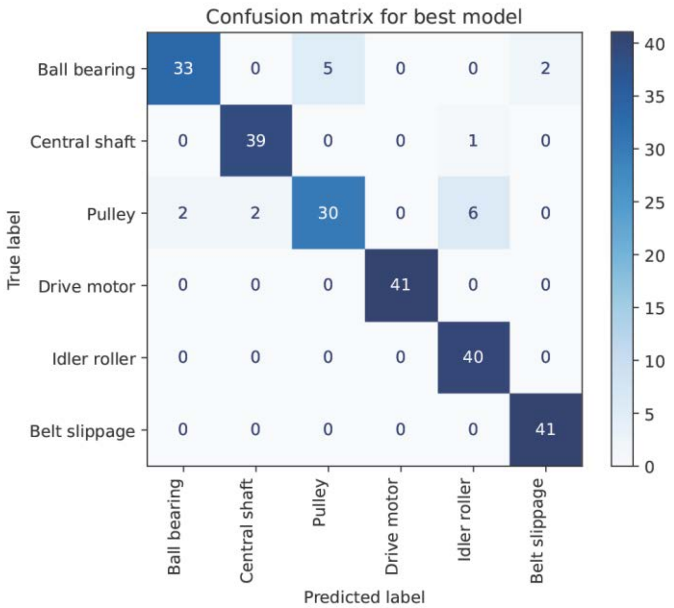

Figure 4 Confusion matrix best model (Random Forest)

Further class-level performance analysis is shown in Figure 5, which compares the precision, recall, and F1-score for each of the fault categories. This performance analysis provides a comprehensive evaluation of the random forest model's classification capabilities across fault classes, revealing distinct performance patterns that align with the confusion matrix findings. The model demonstrates exceptional performance for drive motor and belt slippage classifications, both achieving perfect scores of 1.00 across precision, recall, and F1-score metrics. This indicates complete success in identifying these failure modes without any false positives or missed detections, suggesting these components possess highly distinctive failure signatures that the Random Forest algorithm can readily distinguish. Central shaft classification exhibits robust performance with a precision of 0.95, a recall of 0.98, and an F1-score of 0.96. The slightly higher recall compared to precision indicates the model successfully captures most central shaft failures while maintaining strong specificity, consistent with the minimal misclassifications observed in the confusion matrix. Ball bearing and idler roller classifications present contrasting performance profiles. Ball bearing achieves high precision (0.94) but lower recall (0.83), resulting in an F1-score of 0.88, indicating the model rarely misclassifies other components as ball bearings but occasionally fails to identify actual ball bearing failures. Conversely, the idler roller demonstrates perfect recall (1.00) with lower precision (0.87) and an F1-score of 0.93, suggesting the model captures all idler roller failures but sometimes misclassifies other components as idler rollers. Pulley classification reveals the most challenging discrimination task with a precision of 0.88, a recall of 0.75, and an F1-score of 0.81. The lower recall indicates difficulty in identifying all pulley failures, with some being confused with other components, particularly idler rollers, as shown in the confusion matrix. This suggests potential overlap in failure characteristics between these rotational components.

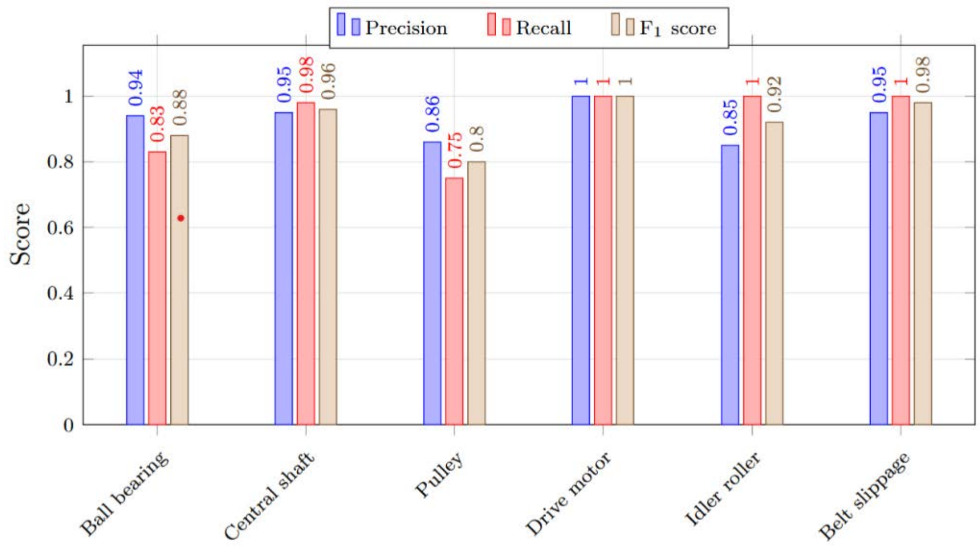

Figure 5 Comparison of class-wise precision, recall, and F1 score of the best model

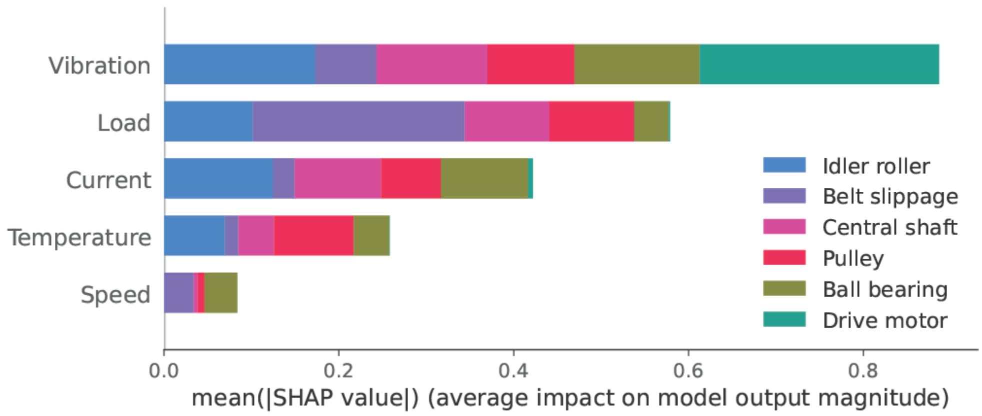

Figure 6 SHAP plot of mean absolute SHAP values across five features for the best model (Random Forest)

Figure 6 shows an SHAP plot explaining the feature contribution towards each fault class. SHAP (SHapley Additive exPlanations) is a model-agnostic interpretability method based on cooperative game theory, where each feature is assigned a Shapley value representing its contribution to a specific prediction. In essence, SHAP quantifies how much each feature increases or decreases the model's output by considering all possible combinations of features. By visualizing these contributions, SHAP helps diagnose model behavior, uncover hidden data relationships, and build trust in machine learning systems by making complex models more transparent. More specifically, the plot shown in Figure 6 presents a detailed visualization of the mean absolute SHAP values across five features for six fault classes in the conveyor system, illustrating the average impact of each feature on the model's predictions for each class. Each horizontal bar corresponds to one of the five features—Vibration, Load, Current, Temperature, and Speed, while the colors within each bar represent the relative contribution of that feature to the prediction of each class. The length of each colored segment within a bar indicates the average contribution (mean absolute SHAP value) of that feature to a specific fault class. The SHAP analysis shows that Vibration and Load are the most influential features, with vibration being especially critical for detecting Drive Motor, Pulley, and Ball Bearing faults, and load being most relevant for Belt Slippage and Central Shaft issues. The current has moderate importance, mainly for Central Shaft, Ball Bearing, and Pulley faults, while temperature is lower in impact but indicative of heat-related problems, particularly in Pulley, Ball Bearing, and Central Shaft. Speed has the least influence, offering only slight contributions to Belt Slippage, Ball Bearing, and Pulley. Overall, the results highlight vibration and load as key diagnostic signals, with current and temperature playing supportive roles and speed having limited predictive value. Overall, the model achieves strong performance, successfully addressing the identified literature gap by demonstrating effective conveyor fault classification capabilities across six distinct fault categories using a unified model. These results validate the feasibility of comprehensive multi-fault classification systems and contribute to the development of more robust condition monitoring solutions for industrial conveyors that can generalize across multiple fault types simultaneously.

5 Conclusion and future work

This study introduces a comprehensive framework for multi-class fault classification in conveyor systems, addressing the limitations of traditional binary approaches by enabling precise fault identification. The framework was validated using real-world operational data collected under variable loading conditions, ensuring practical relevance for logistics operations. Among the evaluated algorithms, Random Forest demonstrated superior performance, achieving an accuracy of 92.56%, a precision of 0.93, a recall of 0.93, an F1-score of 0.92, and an MCC of 0.91. Beyond predictive accuracy, the model's interpretability was enhanced through SHAP-based feature analysis, which provided insights into the most influential diagnostic signals for each fault class. These capabilities support informed maintenance decisions, operator training, and seamless integration with Industry 4.0 initiatives, contributing to proactive and cost-effective asset management for logistic applications.

Despite these strengths, certain fault types, such as pulley faults, remain challenging due to overlapping feature spaces with mechanically similar components. This limitation underscores the need for further refinement and motivates future research. Promising directions can be grouped under three broader themes: (i) Integrating complementary modalities such as acoustic signals, vibration patterns, and thermal imaging to enrich the feature space and improve classification accuracy for complex fault scenarios; (ii) Investigating deep learning architectures, including CNNs for spatial feature extraction and LSTMs for temporal dependency modeling, to capture nuanced fault progression patterns directly from raw sensor data; (iii) Developing edge-computing solutions for on-site inference, coupled with extensions for fault severity assessment and remaining useful life prediction, to deliver actionable insights and enable predictive maintenance strategies. By addressing these directions, the proposed framework can evolve into a robust, scalable solution for intelligent condition monitoring and decision support in modern logistics environments.

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Global research trends in logistics performance and trade facilitation: a bibliometric analysis of logistics flows and trade

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Keywords: logistics performance, logistics flows, trade facilitation, supply chain management, bibliometric analysis.
Abstract: Logistics performance plays a critical role in enabling efficient material, information, and financial flows across international trade networks. Despite extensive empirical research examining the relationship between logistics performance and trade outcomes, the literature remains fragmented, with no comprehensive bibliometric synthesis mapping its intellectual structure and thematic evolution. This study addresses this gap by conducting a bibliometric analysis of 265 peer-reviewed journal articles indexed in the Scopus database between 2008 and 2025. Using Biblioshiny and VOSviewer, the study analyzes annual scientific production, influential authors and journals, institutional and country-level collaboration patterns, citation structures, and thematic clusters. The findings reveal a steady growth in logistics–trade research following the introduction of the World Bank's Logistics Performance Index, with dominant themes centered on logistics efficiency, trade facilitation, transport infrastructure, and supply chain management. Emerging research directions emphasize sustainability, green logistics, digitalization, and supply chain resilience. By systematically mapping logistics-related knowledge flows, this study provides a consolidated overview of the field and identifies research gaps that are relevant for logistics scholars, policymakers, and practitioners. The study contributes to logistics science by clarifying how logistics performance is conceptualized within international trade research and by offering future research directions aligned with contemporary logistics challenges.

1 Introduction

Logistics are critical to international trade, as they encompass planning, storage, transportation, and distribution of goods between production centres and end consumers. Even small logistical disruptions can raise costs, reduce product quality, and undermine competitiveness. In recent years, as geopolitical tensions have increased, resources have become more constrained, and global shocks such as the coronavirus pandemic (Covid-19) have exposed the vulnerabilities of global supply chains, the need for resilient supply chains has become apparent in our logistics systems [1,2]. Reliable and interconnected logistics networks reduce transaction costs and make trade more competitive. Positive investments in logistics infrastructure have significantly improved the trade performance of many countries as measured by the Logistics Performance Index (LPI).

The World Bank has developed the Logistics Performance Index (LPI) to measure logistics effectiveness of a nation in six areas, focusing on customs, infrastructure, international shipments, logistics competence, tracking and tracing, and timeliness [3], and has used it as a benchmark to assess logistics capacity and trade facilitation in the world. For example, evidence shows that logistics performance is one of the main determinants of international trade, and advances in infrastructure, customs, and supply chain management have a greater effect on export competitiveness in an economy than tariff reductions, especially in emerging markets [4]. Studies on logistics show that the lack of cold chain infrastructure can jeopardize competitiveness in trade, especially for agricultural goods [5,6].

Accordingly, this study analyses 265 peer-reviewed journal articles published between 2008 and 2025 using the Scopus database and bibliometric tools (Biblioshiny and VOSviewer). It addresses five guiding questions: How has annual scientific production and citation evolved in logistics performance and trade research? Who are the most influential authors, journals, and institutions in this field? What are the dominant and emerging themes revealed through keyword and thematic analysis? How do citation networks, co-citation, and bibliographic coupling shape the intellectual structure of the field? What insights can be drawn to advance theory, policy, and practice? The study contributes to the field by offering a bibliometric mapping of research in logistics performance and international trade as well as providing directions for future researchers to develop scholarly publications in logistics and international trade.

Although numerous empirical studies confirm that logistics performance significantly influences international trade, existing research is largely dispersed across econometric, sectoral, and regional analyses, limiting cumulative theoretical development in logistics science. The central problem addressed in this study is the absence of a structured overview that explains how logistics performance research has evolved, which themes dominate the field, and how logistics-related knowledge flows across authors, institutions, and countries. The primary objective of this study is to systematically map global research trends in logistics performance and international trade using bibliometric techniques. The novelty of this work lies in its comprehensive visualization of the intellectual structure, collaboration networks, and thematic evolution of logistics-focused trade research. By positioning logistics performance as a core analytical construct rather than a peripheral explanatory variable, this study advances logistics research and provides evidence-based directions for future logistics policy and supply chain strategy development.

2 Literature review

2.1 Theoretical background

Logistics is a key factor of trade that minimizes transaction costs, increases reliability and competitiveness [7]. Poor logistics performance, characterized by delays, high costs, and inefficiencies act as a trade barrier [8]. The gravity model of trade, which explains trade flows based on economic size and distance, has been extended to include logistics performance, which demonstrates that logistics reduces the negative impact of distance and reinforces the influence of trade [9]. On this theoretical foundation, empirical studies and research are carried out on logistics as a tool for reducing trade costs and improving international competitiveness.

2.2 Empirical evidence on logistics performance and trade

The evidence from the experimental literature consistently shows that logistics improves trade. Strengthening logistics reduces trade costs and enhances competitiveness, which was found in middle-income economies [10,11]. The sectoral studies have highlighted some of the weaknesses. For example, in agriculture, infrastructure of both exporters and importers, competence and quality, and tracking and tracing of the importers positively and significantly affect trade [12]. Research based on surveys of container terminals, seaports, and multimodal transport has found that logistics infrastructure is a critical enabler for timely exports [13,14]. At the regional level (e.g., Africa, South America, Asia), stronger logistics, measured by an increase in LPI, would benefit exporting countries more than importing countries [15,16].

2.3 Trade facilitation and institutional dimensions

There is a common belief that the provision of trade facilitation measures, such as customs modernisation, the use of ICT, and infrastructure development, contributes to higher export performance [17,18] . Institutional quality is also seen as an enabler, as a higher LPI score is also connected to better governance and integration into global value chains. Logistics, thus, is both a technical and an institutional challenge that calls for coordinated sectoral reforms.

2.4 Disruptions and emerging themes

The vulnerability of global supply chains has been a new concern because of COVID-19 and geopolitical tensions, and recent studies have suggested that green logistics, blockchain supplying chain, and resilient trade systems capable of withstanding shocks are necessary [19], that is, a conceptual change from models focusing on the efficiency aspects of logistics to multidimensional models that incorporate technology, sustainability, and resilience. For example, a study on Ukraine's grain exports using resilient supply chain of rail and road network amid periodic port blockades, emphasizing the need to adapt effective logistics management under geopolitical tensions [20].

2.5 Research gaps

Despite rich empirical evidence, three major gaps remain:

1. Lack of bibliometric synthesis: Most existing research consists of econometric analyses or sector-specific case studies, but no study systematically maps the intellectual structure, thematic evolution, and collaboration patterns in logistics–trade research.
2. Underrepresentation of cross-cutting themes: While digitalisation, sustainability, and resilience are increasingly studied, they remain fragmented across different strands of literature.
3. Limited integration of theory and practice: Although logistics is shown to influence trade outcomes, it is rarely conceptualised as a central theoretical construct within trade models.

This study addresses these gaps through a bibliometric analysis of 265 peer-reviewed articles (2008-2025), providing a comprehensive view of research trends and advancing trade theory through conceptual additions.

3 Methodology

3.1 Data source and database selection

The study is based on the Scopus database because it was chosen to cover as much of the peer-reviewed publications in the field of logistics, international trade, and economics as possible [21]. Publications are analyzed from 2008 to January 2025 to match the timeframe of the first publication of the Logistics Performance Index (LPI) by the World Bank in 2007-2008 it established new focus in the field.

3.2 Bibliometric tools and analytical techniques

We created a Boolean search string to identify studies at the intersection of logistics performance and international trade: (Logistics performance index OR LPI) AND (international trade OR global trade OR trade flows OR export performance OR agricultural trade). This resulted in 673 documents, and the following filters were applied to ensure relevancy and quality:

- Document type: Journal articles (excluding conference papers, reviews, book chapters).
- Language: English only.
- Subject area: Economics, econometrics, finance, social sciences, and related fields.
- Publication stage: Final published.

3.3 Screening procedure and reporting standards

Screening followed a two-step process:

1. Automated filtering using Scopus' subject and document-type restrictions.
2. Manual review of abstracts to ensure direct relevance to logistics performance and trade.

After filtering, 350 articles remained. Following manual review, 85 were excluded as irrelevant (e.g., studies focused solely on domestic logistics or unrelated supply chain topics). The final dataset comprised 265 peer-reviewed journal articles, as shown in Figure 1.

3.4 Analytical tools

Two bibliometric software packages were employed:

- Biblioshiny (R package bibliometrix) – for descriptive statistics, annual scientific production, citation analysis, and visualisation of collaboration networks.
- VOSviewer (v1.6.20) – for mapping co-authorship, co-citation, bibliographic coupling, and thematic keyword clusters.

These tools were chosen for their reproducibility, open access, and widespread adoption in bibliometric research.

3.5 Bibliometric indicators

The following indicators were used to capture scientific production and intellectual structure:

- Scientific output: Number of publications per year, growth rate.
- Citation analysis: Average citations per article, highly cited works.
- Authorship analysis: Most productive and influential authors.
- Source analysis: Most relevant journals and their citation impact.
- Institutional and geographic output: Contributions by universities and countries.
- Collaboration patterns: Threefold plots linking authors, sources, and institutions.
- Thematic evolution: Keyword co-occurrence, cluster analysis, and longitudinal theme mapping.
- Intellectual structure: Co-citation and bibliographic coupling analyses.

3.6 Limitations

There are a few limitations of this methodology: It may be based on Scopus and thus biased toward regional journals or non-indexed materials; the language restriction to English may exclude relevant research in other languages; and the settings of the algorithms in VOSviewer may result in thematic clustering (cluster formation).

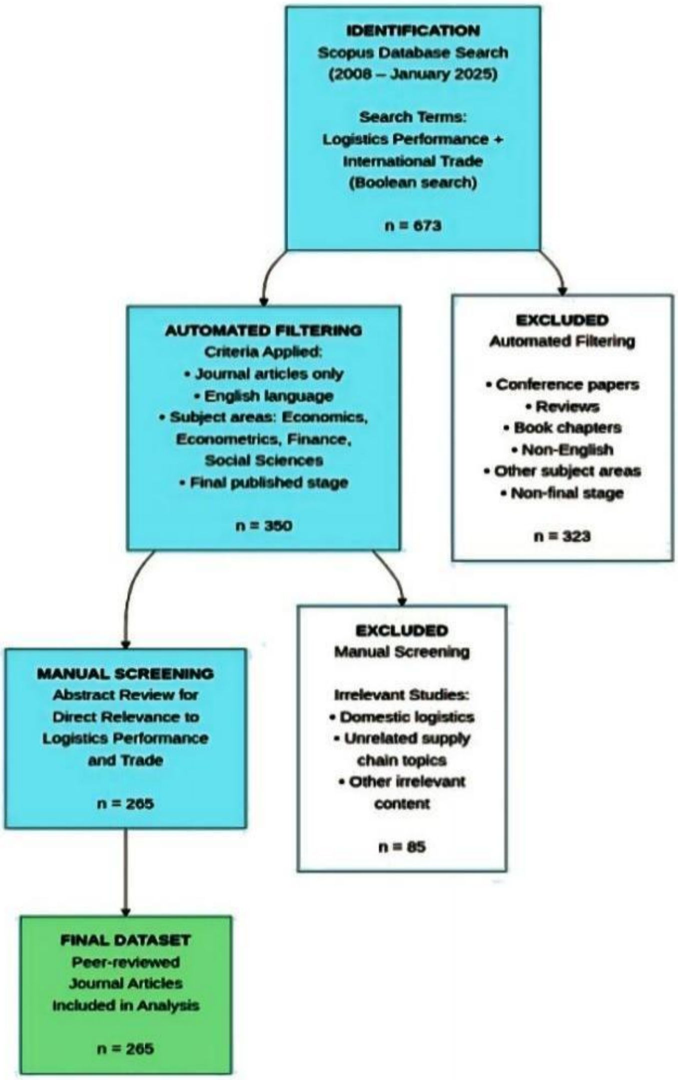

Figure 1 PRISMA flow diagram for article selection [22]

4 Results

4.1 Annual scientific production and citation trends

The 265 selected documents were published in 136 sources with an average of 14.81 citations per document, written by 682 authors with 48 single-authored papers and 28.2% of the authors are international authors collaborating at a rate of 2.92 co-authors per document, showing increasing collaborative efforts. The literature on logistics performance and international trade has expanded since 2008 (the year after the introduction of LPI) at an annual growth rate of 4.16% and peaked at 48 documents in 2024 (Figure 2).

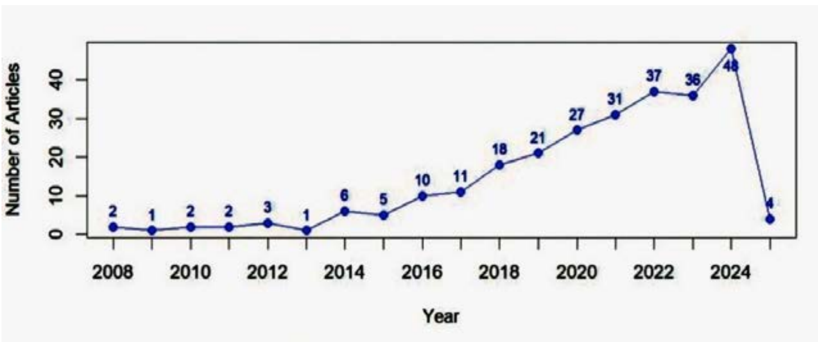

Figure 2 Number of articles published per year

Mean Citations/Article is the average number of citations per article, and Mean Citations/Year is the average number of citations per year (i.e., the average annual citation rate). The two articles published in 2008 had a mean of 28.5 citations per article and a mean of 1.58 citations per year (Table 1).

Table 1 Average Citations Per Year

Year	Documents Published	Mean Citations /Article	Mean Citations / Year
2008	2	28.5	1.58
2014	6	61.3	5.11
2017	11	31.27	3.47
2019	21	30.38	4.34
2025	4	0	0

In 2014, the higher citation rates make the means inflate, then 2017 to 2019 has an average of 30 per article, 2022 to 2024 is lower because they are newer and have not had time to be cited, and 2025 will have no citations.

4.2 Authors' productivity and impact

The most relevant authors are those who have published the most articles in a specific discipline, or area of study as shown in Table 2. The core and significant authors in the field are: Bugarcic F., Grainger A., Puertas R., Raimbekov Z., Zaninovic PA., with four articles each, which indicates that the authors have published consistently in the same field, and Dong Q.L., Garcia L., Havenga J.H., Marti L., Syzdykbayeva B., and Turkcan K., with three publications each.

Table 2 Most relevant authors'

Authors	Articles
Bugarcic F.	4
Grainger A	4
Puertas R	4
Raimbekov Z	4
Zaninovic P.A	4
Dong Q.L	3
García L	3
Havenga J.H.	3
Martí L	3
Syzdykbayeva B	3

In Figure 3, shows the author's productivity over time. Dots represent how many papers an author has published (small: one paper; medium: two; large: three plus). Authors with the highest number of citations include Puertas R, Garcia L, Marti L., Grainger A., has been active from 2011 to 2019 and has published four articles. Puertas R., published three articles in 2014 and one in 2017. Raimbekov Z., has been active from 2016 to 2023 and has published four articles. Zaninovic P.A., published multiple articles from 2019 to 2023. Syzdykbayeva B., published three articles from 2016 to 2023. Havenga J. H., published two papers in 2018 and one in 2022. Marti L, published two papers in 2014, which got high citations and published one in 2017.

4.3 Analysis of sources, affiliations, and their collaboration

The most relevant sources are the journals that published the most articles; as noted in Table 3, the top journals include Sustainability (Switzerland) (14 articles), Transport Policy (12 articles), and the Asian Journal of Shipping and Policy (11 articles).

Table 3 Top journals by number of publications

Journal	Publications
Sustainability (Switzerland)	14
Transport Policy	12
Asian Journal of Shipping & Policy	11
Journal of Infrastructure Policy & Development	7
World Customs Journals	7

Relevant affiliation refers to all the universities that have published the most articles, and Chang'an University leads with 14 publications, indicating its active and operating institution that contributes the most articles, followed by IPB

University with 13 publications, and Beijing Normal University with 11 publications, showing that Indonesian and Chinese universities continue to produce scholarly works. The Dolishniy Institute of Regional Research of the National Academy of Ukraine has nine publications, showing a good number from Eastern Europe. L.N. Gumilyov Eurasian National University from Central Asia, RMIT University from Australia, and Universiti Sains Malaysia each have eight publications, and Leshan Normal University and the University of East Sarajevo each have seven publications, indicating their evolving contributions. Incheon National University has six publications, indicating South Korea's involvement (Table 4).

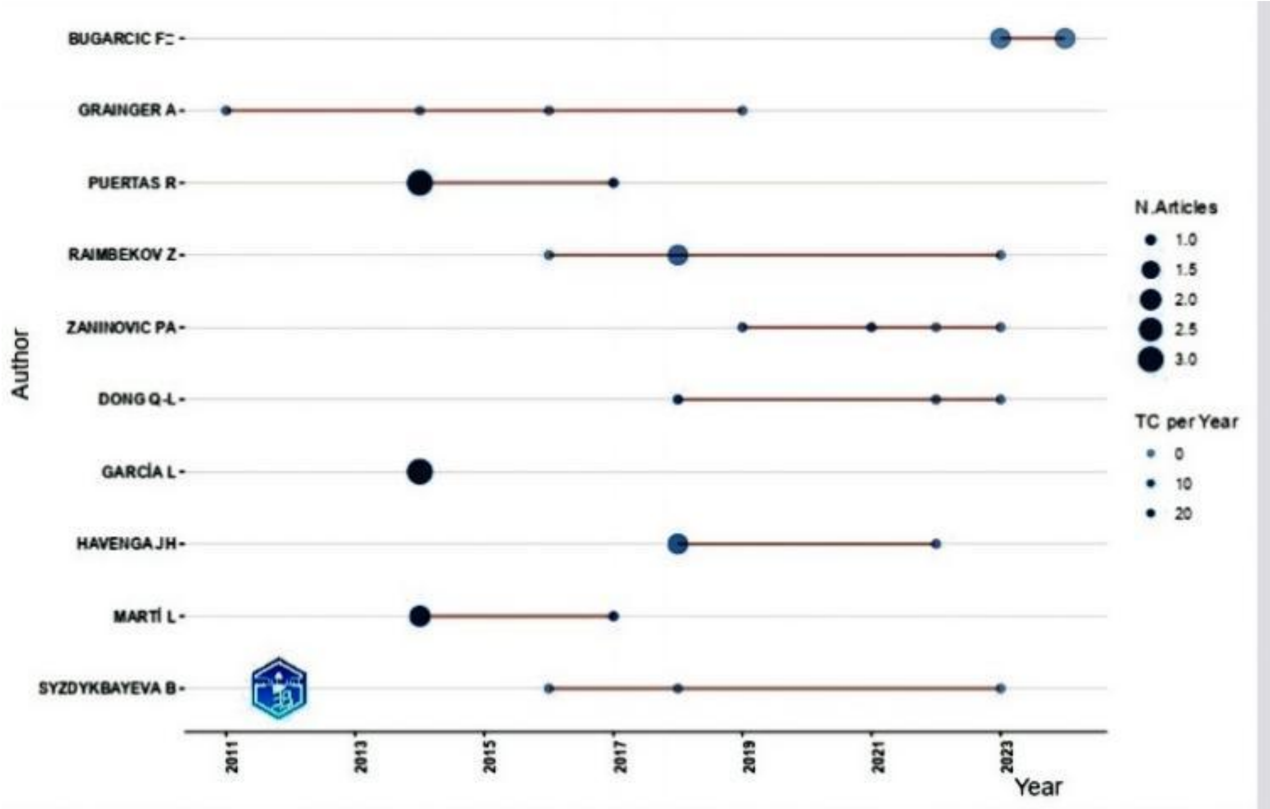

Figure 3 Authors' productivity over time

Table 4 Most productive institutions

Institution	Publications
Chang'an University	14
IPB University	13
Beijing Normal University	11
Dolishniy Institute, Ukraine	9
L.N. Gumilyov Eurasian National University	8

4.4 Collaboration patterns

The threefold plot visualization shows strong connections among high-impact journals (such as Sustainability), key authors (Dong Q.L., Puertas R., and Garcia L.), and top-ranked institutions (Chang'an University and Universidad Politécnica de Valencia). The institutional collaboration clusters revealed that the institutional collaboration core was observed in the regional research centres and universities (Figure 4).

4.5 Thematic and keyword analysis

There are 1128 Keywords associated with bibliometric research, and 128 items were visualised based on a co-occurrence threshold of 3. It is the overall thematic structure in logistics and international trade. Figure 5 explains that the larger the circle, the more frequency the keywords have, and the closer the keywords are to each other, the more closely they are placed in the distance. These keywords include, for example, economic growth, logistics performance index (LPI), the gravity model, trade performance, and trade flows, all of which are closely related and frequently observed in this context. Seven clusters are presented as follows: Cluster 1 (red): Competitiveness, economic development, transportation, freight transport, empirical analysis, the World Bank, and trade policy. Cluster 2 (Green): Logistics performance, economic growth, LPI, competition and regression analysis. Cluster 3 (Blue): Export, global trade, commerce, supply chain management, bilateral trade and comparative advantage.

This study involves export-based trade and supply chain management, and how a country engages in trade to enable trade and internalize comparative advantage. Cluster 4 (yellow): Logistics, shipping, port, maritime and cluster analysis: This cluster is about sea logistics and shipping infrastructure in trade facilitation. Cluster 5 (purple): International trade, Trade Facilitation, Gravity model, LPI, trade flow: This cluster is about promoting trade through trade gravity models based on trade facilitation and LPI. Cluster 6 (light blue): performance evaluation, connectivity, trade and decision making: This cluster is about appraising trade by making informed decisions. Cluster 7 (orange): Sustainability, environmental economics, innovation, green logistics and FDI: It is expected that more research will align trade logistics with environmental sustainability.

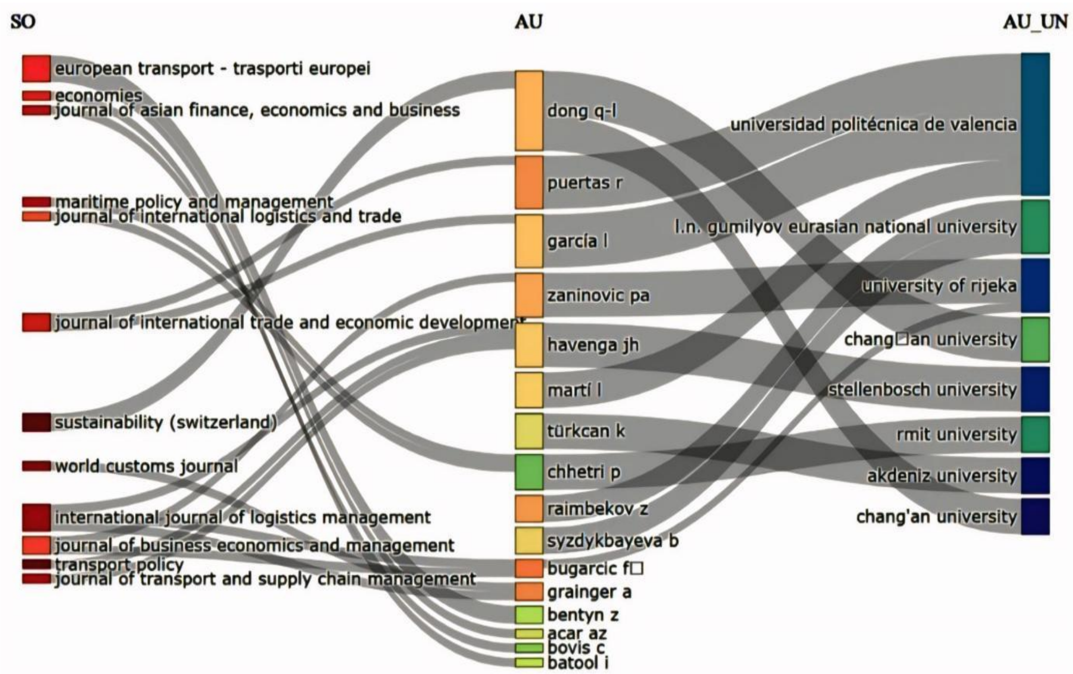

Figure 4 Threefold plot: journal, author and affiliation

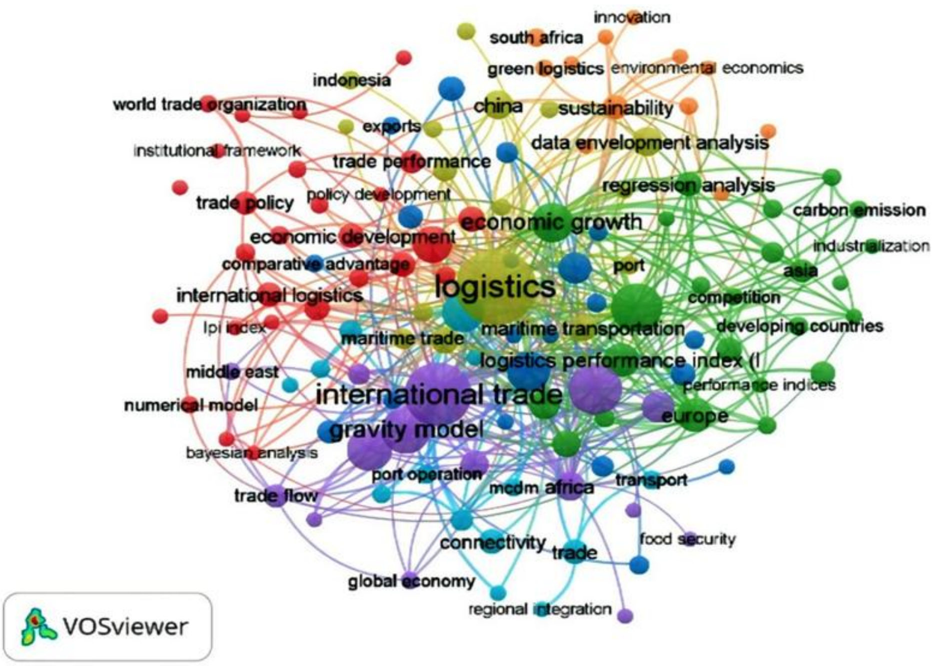

Figure 5 Co-occurrence by all keywords

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4.6 Citation networks, co-citation, and bibliographic coupling

Highly cited journals include Sustainability (Switzerland), Transport Policy, and Asian Journal of Shipping and Logistics, while high-impact institutions comprise Chang'an University (School of Economics and Management) and Nottingham University Business School. The leading contributing countries are China, Turkey, the United Kingdom, the United States, and South Korea. Co-citation analysis reveals four major clusters of co-cited authors, with Shepard, Puertas, Wilson, and Ojala acting as anchors for the clusters (Figure 6).

Bibliographic Coupling indicates the most strongly coupled papers are related to topics. It shows how two authors are linked based on the references they shared in the research paper. When two authors cite the same references, they are considered bibliometrically coupled. In Figure 7, Node represents an author, and its size represents the link strength or the degree of centrality. The degree of centrality measures the intensity of bibliographic coupling. The colour represents the cluster of authors based on the related shared references. The link between the authors shows shared references; the more links, the more references they share in their research paper. The papers with the highest degree of centrality are as follows:

- Logistics performance and export variety: Evidence from Turkey. Central Bank Review (DC=480) [23]
- Does the WTO trade facilitation agreement actually promote international trade? A Structural Gravity Model. International trade journal (DC=433) [24].
- The role of logistics performance index on trade openness in Europe. International Journal of Economics and Business Research (DC=377) [25].

The review shows that the field is very dynamic and participatory, logistics performance (as measured by the LPI) contributes to the development of international trade, and certain journals, institutions, countries, and authors have become the intellectual and collaboration network centers of the field. The themes have changed to reflect issues of sustainability, digitalization, and resilience in supply chain, which may be considered both scholarly and real-world issues in the logistics field.

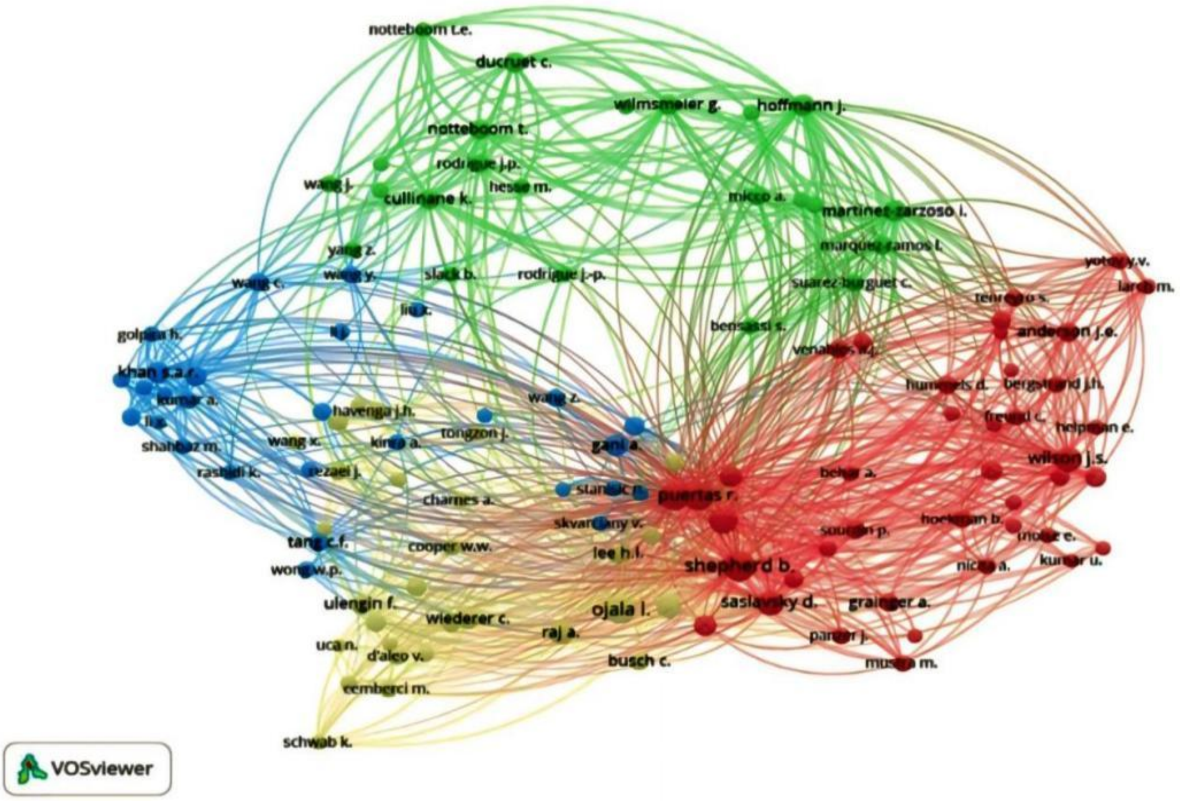

Figure 6 Co-citation network

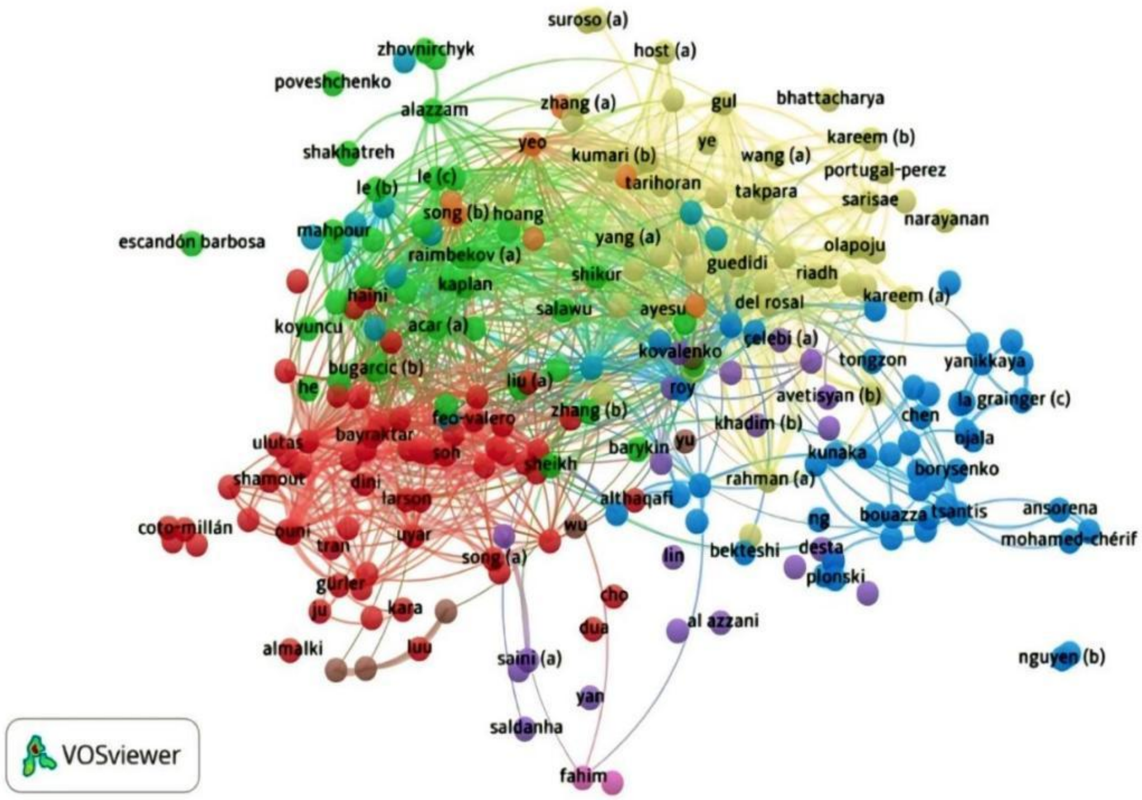

Figure 7 Bibliographic coupling

5 Discussion

The bibliometric results demonstrate that logistics performance has evolved into a central explanatory construct in international trade research, reflecting a growing recognition of logistics systems as enablers of efficient trade flows. The dominance of themes related to logistics efficiency, transport infrastructure, and trade facilitation indicates a shift from traditional tariff-based explanations toward logistics-centered competitiveness models. Furthermore, the emergence of sustainability, green logistics, and digital transformation clusters suggests that logistics research is increasingly responding to contemporary challenges such as environmental regulation, technological disruption, and supply chain vulnerability. These findings confirm that logistics performance research is no longer confined to operational efficiency but has expanded into strategic, policy-oriented, and resilience-driven domains.

This study is a systematic mapping of the research trends, thematic structures, and influential contributors in this field that has not been synthesized to date. The field is mature, with increasing publications and citations, especially after the World Bank introduced the LPI, and with the increasing recognition of the role of logistics as a driver of international trade competitiveness. The top journals (Sustainability [Switzerland], Transport Policy, and Asian Journal of Shipping and Policy) are multidisciplinary journals, showing the convergence of logistics, sustainability, and policy as new priorities, with resilience, environmental impact, and digital transformation in the supply chain. The geographic distribution and institutionalization of the data show the increasingly global nature of logistics studies, with China, Turkey, the United Kingdom, the United States, and South Korea increasing in terms of the number of citations and productive academic affiliation, and institutions such as the Chang'an University and the IPB University becoming a new research center, which is essential to bringing the contextually strong innovation in logistics management and trade facilitation. The knowledge network analysis (co-authorship, bibliographic coupling) demonstrates that academic collaboration is close (often geographically clustered) and the proportion of international co-authorship is very high (around 28%), suggesting the development of a globalizing research community. These findings highlight the growing importance of managing material flows, information flows, and transport flows within international logistics systems.

5.1 Future research directions

The future research directions in logistics performance and international trade as demonstrated in Figure 8 include the following: a multi-database and broader literature coverage, integrating additional databases such as Web of Science and Google Scholar, regional databases, grey literature such as reports, policy briefs, and non-peer-reviewed works, which can provide critical policy and practitioner insights that are currently underrepresented in indexed journals, and expanding the language scope to include non-English literature to capture perspectives from emerging economies and reduce language bias. Linking logistics research to policy and practice, with future studies focusing on policy-relevant mapping to identify research clusters that are most influential in shaping trade facilitation and logistics policy, guiding evidence-based interventions. Conducting in-depth sectoral, regional analyses on sector-specific logistics challenges (e.g., agriculture, which has specific logistics challenges in handling perishable and sensitive goods) to gain insights on trade facilitation in specific commodities.

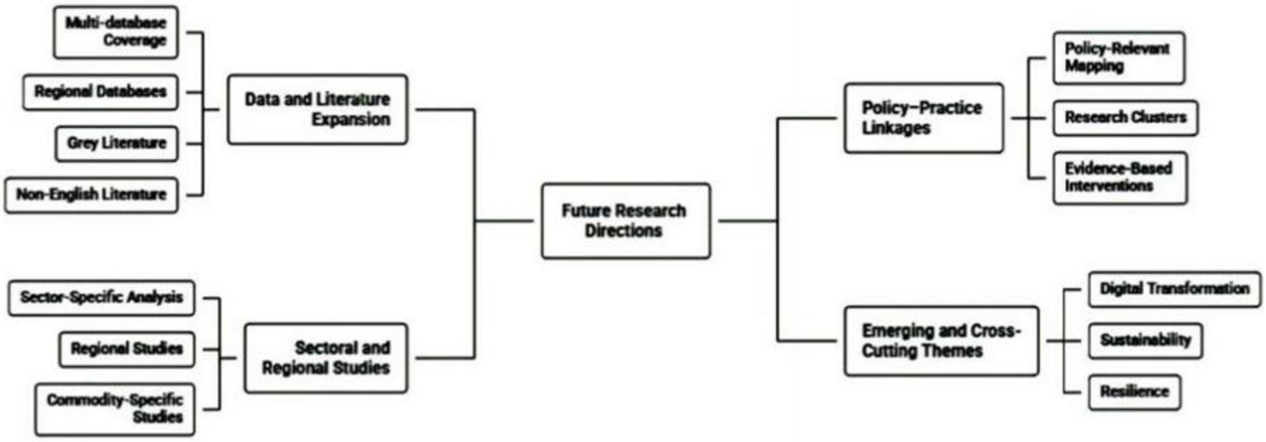

Figure 8 Future research directions in logistics and trade

Finally, emerging and cross-cutting themes provide significant scope for growth, including research on the impact of digital transformation, artificial intelligence, and disruptive technologies on logistics efficiency and trade facilitation. The progress and knowledge gaps in research connecting logistics to sustainability goals, climate action, and environmental policy; and studies of resilience and risk management, including how recent shocks (such as pandemics and geopolitical conflicts) have spurred research on supply chain resilience and proposed integrative frameworks for future disruptions.

5.2 Policy and practical recommendations

Effective policy interventions must focus on optimizing material flows, information flows, and financial flows across national and cross-border logistics systems. This study offers a range of policy and practical recommendations for governments, industry, academia, and international organizations on how they can improve the efficiency of their logistics chains in order to make trade more competitive (Figure 9). Policymakers should invest with data-driven evidence in upgrading hard infrastructure (transportation, ports, warehousing) and soft infrastructure (customs, digital systems, regulatory frameworks, and logistics), removing bottlenecks; sector-specific logistics such as cold chain logistics for agriculture; streamlining regulation reform and simplifying trade processes (regulatory reforms that address customs and border procedures); the digitisation of documentation related to trade (harmonization of standards, transparency, and predictability through digital systems) while strengthening regional and international cooperation (government fostering cross-border collaboration on infrastructure projects, technology adoption and capacity building within regional blocs or along trade corridors such as Belt and Road Initiative, ASEAN, APEC); sustainability and resilience: policies that advance green logistics reducing carbon emissions; energy efficiency; innovation to develop contingency plans and strategies for minimising disruptions caused by pandemics, conflicts, climate-related events.

Digital transformation should be used to invest in technology solutions for the logistics industry and the private sector to improve supply chain efficiency, traceability, and responsiveness; to pilot and scale innovative logistics solutions via public–private partnerships; to continuously upgrade skills by providing workforce training in digital and green logistics, supply chain risk management, and emerging trade facilitation standards; to align research agendas with policy and market needs; to focus more on areas underrepresented in the literature, such as agricultural logistics, sustainability in trade, and regional comparative studies; to disseminate research findings in accessible formats for non-academic stakeholders to support evidence-based decision-making; to foster multidisciplinary and cross-sector collaboration, including interdisciplinary teams that integrate logistics, economics, environmental science, and technology; and to engage in international collaboration to widen perspectives and promote global research equity.

Finally, international and multilateral organisations can help by directing funding and technical support to countries wishing to modernize logistics infrastructure and regulatory environments, with a special focus on the least developed and landlocked countries. If implemented, these recommendations can help stakeholders develop more efficient, resilient, and sustainable logistics systems, which would support international trade and broader economic development.

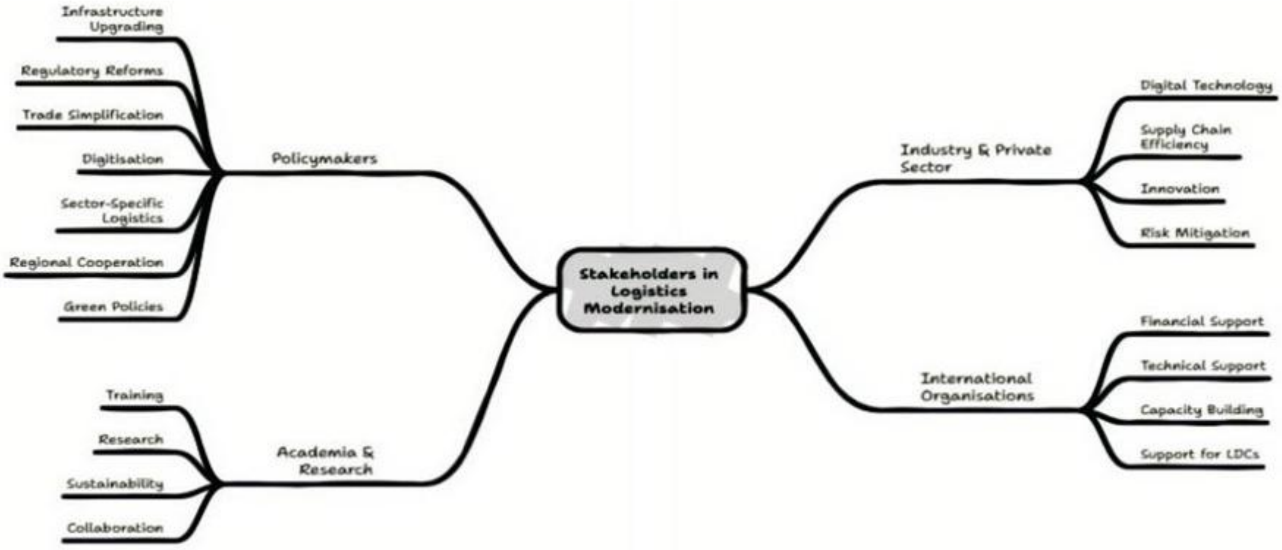

Figure 9 Policy and practical recommendations for logistics and trade

6 Conclusion

This study provides a comprehensive bibliometric mapping of global research on logistics performance and international trade based on 265 peer-reviewed Scopus-indexed articles published between 2008 and 2025. The findings reveal a sustained growth in scholarly attention following the introduction of the Logistics Performance Index and highlight logistics efficiency, trade facilitation, transport infrastructure, and supply chain management as core research themes. The study identifies emerging directions related to sustainability, green logistics, digitalization, and supply chain resilience, reflecting the increasing complexity of global logistics systems. From a scientific perspective, the study contributes to logistics research by consolidating fragmented knowledge and clarifying the intellectual structure of logistics-focused trade studies. From a practical and policy standpoint, the findings emphasize the importance of investing in both hard and soft logistics infrastructures to enhance trade competitiveness, increase the ease of doing of business by simplifying regulations, digitisation, and directing international funding to logistically not strong countries of the world. Despite limitations related to database coverage and language restrictions, the study offers a robust foundation for future logistics research that integrates policy relevance, technological change, and sustainability considerations.

The bibliometric evidence generated in this study offers practical value for policymakers and logistics practitioners by identifying dominant research streams and emerging priorities in logistics performance and trade facilitation. These insights can support evidence-based infrastructure investment, regulatory reform digitisation, and supply chain strategy development in both developed and developing economies.

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Digital transformation and economic growth: managing material and information flows in Central Asia's evolving digital economy

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Keywords: public administration, e-commerce, investment, financial services, global market.
Abstract: The study addresses uneven digital integration in Kazakhstan, Uzbekistan, Kyrgyzstan, and Tajikistan, with particular attention to how digital technologies affect economic development, logistics performance, e-commerce, and fintech. The aim is to examine the relationship between digital readiness and economic growth by analyzing the management of information, material, and financial flows across key sectors. The methodology was based on statistical, correlation, and comparative analyses, which made it possible to assess differences in digital infrastructure, investment levels, and sectoral implementation of digital tools. The results show that digitalization has improved business productivity, expanded e-commerce and financial technologies, optimized public administration, and strengthened logistics processes through route optimization, faster information exchange, and reduced operational costs. Kazakhstan and Uzbekistan demonstrated more advanced digital integration, while Kyrgyzstan and Tajikistan remained constrained by weaker infrastructure, limited investment, and insufficient ICT skills. Correlation analysis confirmed a strong link between digital readiness, investment in the digital economy, and economic growth, indicating the strategic importance of digital transformation for regional competitiveness. The findings emphasize the need for stronger governmental support, expanded digital logistics platforms, improved regulatory conditions, and targeted investment in infrastructure and human capital. The practical significance of the study lies in developing recommendations for reducing barriers to digitalization and improving the efficiency of economic and logistics systems in Central Asia.

1 Introduction

The need to study the digital transformation processes in the economies of Kazakhstan, Tajikistan, Uzbekistan, and Kyrgyzstan arises from the increasing impact of digital technologies on macroeconomic parameters, business development dynamics, and the efficiency of public administration. The asymmetry in digitalization levels among the countries of the region has led to significant differences in the pace of digital solution implementation, affecting the competitiveness of national economies. The development of the digital economy has facilitated the emergence of new business models, the transformation of labor market structures, the improvement of logistics processes, and the optimization of financial operations. However, the uneven distribution of digital infrastructure and the insufficient integration of big data, artificial intelligence (AI), and cloud computing into production and administrative processes have limited the region's ability to ensure sustainable economic growth.

The primary issue of this study was to identify key factors influencing digital transformation and its correlation with socio-economic development. Variations in internet accessibility, investment in the information and communication technology (ICT) sector, and governmental support for digital initiatives have complicated the process of coordinated digital development across the region. A low level of digital literacy and limited funding for small and medium-sized enterprises (SMEs) to implement e-commerce and financial technologies (fintech) solutions have created barriers to economic modernization [1,2].

An analysis of academic sources on digital economic transformation confirms a significant interest among researchers in various aspects of this process. The study by Agayev [3] examined the link between digital trade and investment to foster inclusive growth in Central Asian countries, with a focus on regional cooperation in the digital sphere. However, it did not sufficiently explore the impact of digital technologies on internal economic processes or the level of digital readiness in individual countries.

The study by Maltabarov & Sarybayev [4] analyzed the prospects of digital transformation for regional integration in Central Asia, emphasizing intergovernmental cooperation in the digital sector. However, it overlooked the impact of digital solutions on the business environment and the logistics industry. A follow-up study by Maltabarov et al. [5] examined the European Union's interest in Central Asia's digital transformation, but it lacked a detailed analysis of the regulatory environment and internal constraints limiting digitalization in the region's economies.

Gomboin et al. [6] explored the implementation of digital public services for SMEs in Kazakhstan, Kyrgyzstan, and Uzbekistan, focusing on government initiatives that promote business digitalization. However, the study did not analyze the impact of digital technologies on business productivity and financial performance. The research by Rudyk et al. [7] addressed digitalization as a factor of economic growth but did not sufficiently examine the correlation between digital readiness and macroeconomic indicators in Kazakhstan, Tajikistan, Uzbekistan, and Kyrgyzstan.

Olczyk and Kuc-Czarnecka [8] provided an analysis of digital transformation and economic growth in the European context. Although valuable for understanding general digitalization trends, its findings cannot be directly applied to Kazakhstan, Tajikistan, Uzbekistan, and Kyrgyzstan due to differences in digital readiness, regulatory environments, and economic structures.

The study by Irtyshcheva et al. [9] investigated the impact of digital technology development on economic growth but did not consider the specifics of digital technology implementation in Kazakhstan, Tajikistan, Uzbekistan, and Kyrgyzstan, limiting its applicability to regional digital transformation analysis. Similarly, Tudose et al. [10] explored the effects of digital transformation on macroeconomic indicators globally but did not address the specific challenges faced by these countries in the digitalization process.

Thus, the reviewed sources have examined specific aspects of digital transformation in the studied countries, particularly its influence on international cooperation, public administration, and economic growth. However, gaps remain in research on regulatory frameworks for digital processes, logistics digitalization, and the impact of digital solutions on business efficiency and SME productivity.

The problem addressed in this study is the uneven pace of digital transformation across Kazakhstan, Uzbekistan, Kyrgyzstan, and Tajikistan. Despite the increasing global importance of digitalization in driving economic growth, the Central Asian region has experienced significant disparities in digital infrastructure, internet access, investment in ICT, and the adoption of digital solutions in key sectors. This study integrates multiple indicators of digital readiness and economic performance, showing the correlation between digitalization levels and macroeconomic growth, unlike previous research that focused on isolated sectors or regions. The comparative framework shows how digital transformation, combined with strong government support and investments, can boost business productivity, streamline public administration, and boost Central Asian economic competitiveness. This research also sheds light on digital adoption barriers in Kyrgyzstan and Tajikistan, which are less digitally ready. This study recommends ways to accelerate digital transformation and promote inclusive economic growth in these nations by identifying their specific challenges, such as limited infrastructure and financial constraints. Pedagogically, the study emphasizes digital literacy as a foundational skill for Central Asian workers. This suggests a gap in current educational frameworks and the need for stronger programs that support digital skills development at all levels to bridge the gap between digitalization and economic development in the region.

The primary objective of this study was to investigate the relationship between the implementation of digital technologies and the economic development of Kazakhstan, Uzbekistan, Tajikistan, and Kyrgyzstan. Specifically, the research aimed to assess the level of digital readiness and the volume of investments in the ICT sector across these countries. Additionally, it sought to evaluate the impact of digital transformation on key sectors, such as public administration, business productivity, e-commerce, and fintech development. The study also aimed to identify the barriers and challenges to digitalization, including institutional constraints, financial limitations, and insufficient digital literacy. Furthermore, the research aimed to establish a correlation between the level of digital integration and overall macroeconomic performance, including GDP growth and business efficiency. These objectives guided the comprehensive assessment of digitalization's effects on the economic progress of the selected countries, considering their varying levels of technological adoption.

To achieve this objective, the following tasks were completed: an analysis of key digital transformation indicators in Kazakhstan, Tajikistan, Uzbekistan, and Kyrgyzstan, including internet penetration rates, ICT sector investment volumes, and the share of the digital economy in GDP; an assessment of the relationship between digital readiness and macroeconomic indicators, as well as the impact of digitalization on business productivity, e-commerce growth, and fintech development; and an evaluation of major barriers to digital transformation, including a shortage of skilled professionals, insufficient digital integration in SMEs, and regulatory constraints in the e-government and fintech sectors.

2 Materials and methods

At the macroeconomic level, the framework conceptualizes digital transformation as a structural factor influencing national productivity and competitiveness. Digital readiness (infrastructure, ICT investment, regulatory environment, digital literacy) is treated as an independent systemic variable that shapes the efficiency of national information flows and reduces transaction costs. At the sectoral level, the framework focuses on the transformation of logistics, financial services, and e-commerce ecosystems. The efficiency of logistics operations, speed of information exchange, supply chain transparency, and financial inclusion are analyzed as operational performance indicators. At the microeconomic level, the framework examines enterprise behavior and organizational adaptation. Digital platform adoption, automation of management processes, and integration of analytics into decision-making are analyzed as drivers of firm-level productivity and revenue growth. The framework also incorporates a barrier-analysis dimension, identifying institutional constraints, regulatory gaps, financial limitations, and skills shortages as structural moderators that influence the strength of relationships between digital readiness and economic outcomes.

The methodology of this study combined both quantitative and qualitative analysis to assess the impact of digital technologies on the economic development of Kazakhstan, Tajikistan, Uzbekistan, and Kyrgyzstan. The data spanned the period from 2020 to 2024, enabling an analysis of the dynamics of digital transformation over four years. Data collection was conducted using official statistics provided by international organizations such as the World Bank Group [11], the United Nations Development Program (UNDP) [12], the Organization for Economic Co-operation and Development (OECD) [13], as well as national statistical agencies of Kazakhstan [14], Uzbekistan [15], Kyrgyzstan [16], and Tajikistan [17]. Secondary data included indicators of digitalization levels, investment volumes in the ICT sector, the share of the digital economy in GDP, the development of e-commerce, fintech, and e-government.

The selection criteria for data were based on the availability of consistent and up-to-date indicators relevant to the digital economy's development. Key indicators included internet penetration rates, share of ICT sector in GDP, digital readiness index, investment in the digital economy, and the number of mobile banking users. These indicators were chosen to provide a clear picture of the digital economy's structure and its relationship to macroeconomic performance across the region.

The analysis employed several statistical methods. Correlation and regression analyses were used to examine the relationships between digital readiness and macroeconomic indicators such as GDP growth, business efficiency, and e-commerce development. Correlation analysis identified interdependencies among digital infrastructure, ICT sector investments, and digital transformation, while regression analysis quantified the impact of these factors on economic growth. Comparative analysis allowed for a cross-country examination of digitalization levels, revealing structural differences and factors influencing the pace of digital transformation in each country.

Dynamic analysis using time-series data traced changes in digital transformation over the study period. This method provided insight into the development trajectories of the digital economy, factoring in the influence of government policies, investment flows, and infrastructural development. A structural-functional approach was applied to systematize the main factors of digital transformation and identify barriers, while examining how digital solutions in business processes, public administration, and logistics can improve productivity. The analysis of structural interconnections between digital technologies, economic efficiency, and institutional conditions contributed to assessing the long-term consequences of digital integration.

Verification of the reliability of the obtained results was conducted by assessing multicollinearity in regression models to eliminate excessive correlation between variables. Data normalization was performed to ensure comparability between countries. The use of time series allowed for consideration of the dynamics of digital transformation over different periods of the study. The reanalysis of data based on various sources contributed to verifying the robustness of the results.

3 Results

Digitalization shaped the direction of economic policy formation and economic modernization, fostering labor productivity growth, increasing investments, and expanding access to financial and government services [18-21]. In the global context, the adoption of digital technologies led to structural changes in production processes, public administration mechanisms, and consumer market functioning. These processes contributed to reduced transaction costs, increased operational efficiency of businesses, and created additional jobs.

The assessment of key digitalization indicators in the analyzed countries (Table 1) highlighted differences in the pace of adoption of digital technology and the readiness of economies for digital transformation.

The development of digital infrastructure on a global scale largely depends on government support and investment in the technological sector [22,23]. According to the World Bank Group, countries that actively funded digitalization experienced increased labor productivity, reduced business costs, and improved interaction between businesses and the state. Investments in high-speed Internet, the creation of digital platforms, and the expansion of access to cloud computing contributed to enhancing economic competitiveness by ensuring rapid data processing and access to global markets [24-27]. In the countries analyzed, digital transformation progressed unevenly due to differences in institutional readiness, financing, and technological development.

Table 1 Key indicators of digitalization in Kazakhstan, Tajikistan, Uzbekistan, and Kyrgyzstan (2024)

Indicator	Kazakhstan	Uzbekistan	Kyrgyzstan	Tajikistan
Internet penetration rate (%)	88	72	60	48
Share of IT sector in GDP (%)	4.2	2.8	1.5	0.9
Digital readiness index (scale 0-100)	75	65	55	50
Investment in the digital economy (million USD)	1200	800	400	250
Number of mobile banking users (million people)	9.5	5.7	3.2	1.8

Source: compiled by the authors based on World Bank Group [11], UNDP [12], OECD [13], national statistical agencies of Kazakhstan [14], Uzbekistan [15], Kyrgyzstan [16], and Tajikistan [17].

Kazakhstan has the most developed digital economy among the analyzed countries, a result of implementing a national digitalization strategy and attracting foreign investments in the information technology sector. Internet penetration in the country exceeded 88%, and digital transformation encompassed the financial sector, public administration, and logistics. In Uzbekistan, despite a lower level of digital development, reforms in e-government and e-commerce were implemented, fostering the growth of businesses using digital platforms in their operations. In Tajikistan, digitalization progressed more slowly due to an underdeveloped digital infrastructure and limited broadband Internet access, restricting opportunities for process automation in public administration and the business sector.

Kyrgyzstan was at an intermediate stage of digital transformation compared to the other analyzed countries. The implementation of digital technologies occurred within the framework of government initiatives aimed at developing e-government, fintech, and administrative process automation. However, the dynamics of digital transformation were unstable, influenced by institutional factors, insufficient adoption of digital technologies in SMEs, and limited infrastructure resources. Analyzing the country's digital development level relative to neighboring states helped identify its potential for increasing economic efficiency through the expansion of digital services.

Table 2 Correlation matrix of digital transformation and economic growth

Indicator	Internet penetration rate (%)	Share of IT sector in GDP (%)	Digital readiness index (0-100)	Investment in the digital economy (million USD)	Number of mobile banking users (million people)
Internet penetration rate (%)	1.000	0.992	0.994	0.989	0.990
Share of IT sector in GDP (%)	0.992	1.000	0.999	0.999	0.997
Digital readiness index (0-100)	0.994	0.999	1.000	0.999	0.995
Investment in the digital economy (million USD)	0.989	0.999	0.999	1.000	0.996
Number of mobile banking users (million people)	0.990	0.997	0.995	0.996	1.000

Note: Table 2 presents a correlation matrix reflecting the relationship between key digital transformation indicators in the analyzed countries. The correlation coefficient values range from 0 to 1, where 1.000 indicates a complete dependency between variables. The high correlation values between Internet penetration, the share of the IT sector in GDP, the Digital readiness index, and investment in the digital economy suggest a strong interconnection among these indicators. These results indicate that improving digital infrastructure and increasing investment volumes are crucial factors in advancing digitalization. The high correlation between the number of mobile banking users and other digital transformation indicators confirms the growing importance of digital financial services in the region.
Source: compiled by the authors based on World Bank Group [11], UNDP [12], OECD [13], national statistical agencies of Kazakhstan [14], Uzbekistan [15], Kyrgyzstan [16], and Tajikistan [17].

Government digitalization policies remained a key factor in the region's digital transformation. In Kazakhstan, the automation of public services reduced bureaucratic burdens and increased the transparency of administrative procedures, creating favorable conditions for business growth. In Uzbekistan, the expansion of state digital platforms improved access to online services for citizens and businesses. In Tajikistan and Kyrgyzstan, lower levels of government support for digitalization limited opportunities for ICT sector development and slowed the implementation of digital solutions in key economic sectors. The correlation matrix of digital transformation and economic growth, presented in Table 2, illustrates the relationship between key digital economy indicators.

The obtained results confirmed the necessity of a comprehensive approach to the digital transformation of the economy, as the development of individual components of digital infrastructure was interconnected with overall economic growth rates. High correlation coefficients between the key indicators of digital transformation and their impact on GDP indicated that regional differences in digitalization levels could determine the dynamics of economic development. This underscored the need for further analysis of the mechanisms through which digital technologies influence business processes, which could contribute to a deeper understanding of their role in the structural changes of the analyzed countries' economies.

The digital transformation of business in the analyzed countries occurred unevenly, which was explained by differences in the level of digital infrastructure, investment volumes, and government policies in the digital economy sector. Kazakhstan demonstrated a high level of digital integration in the financial sector, facilitating the modernization of the business environment. As part of the activities of the Astana International Finance Centre, a strategy for the digitalization of financial services and fintech development was implemented, creating favorable conditions for innovative entrepreneurship and attracting foreign investment. As noted in the study by Zhanibek et al. [28], Kazakhstan's digital transformation was based on the active development of digital platforms, the expansion of e-government services, and the stimulation of digital business, which enhanced the competitiveness of the economy.

In Uzbekistan, business digitalization was carried out through the implementation of electronic document management, the automation of tax processes, and the development of e-commerce. Government initiatives were aimed at reducing administrative barriers for businesses by introducing digital services in enterprise registration and financial accounting. As noted in the work of Kuldosheva [29], Uzbekistan's digital transformation was characterized by the active use of big data and automated systems for public finance management, which contributed to an improved business environment and increased enterprise productivity.

In Kyrgyzstan, business digitalization progressed more slowly due to limited investment opportunities and an insufficient level of digital infrastructure. As indicated in the study by Momunalieva et al. [30], the development of digital technologies in the country faced several barriers, including a shortage of specialized ICT sector personnel and low integration of digital solutions into SMEs. Limited access to fintech services and an insufficient level of e-government slowed the pace of digital transformation and hindered the efficiency of business processes.

In Tajikistan, the digital transformation of business remained in its early stages due to the underdeveloped digital infrastructure and low integration of digital technologies into entrepreneurial activities. As noted in the study by Akhrorova & Boboev [31], the country's economic digitalization process was characterized by the fragmented implementation of digital solutions in the banking sector, particularly the expansion of online banking and the introduction of electronic payments. At the same time, the overall level of digital literacy among entrepreneurs remained low, limiting the effective use of fintech solutions and e-commerce. The insufficient volume of investment in the digital economy and the slow implementation of digital platforms in the business environment constrained the development of competitive business models, reducing the efficiency of Tajik enterprises at the regional level.

Table 3 contained data on the level of digital platform usage by large, medium, and small enterprises in the analyzed countries, as well as indicators of revenue growth following digitalization, the level of big data application, and the prevalence of e-commerce among companies in the region.

Table 3 Level of digital technology implementation in business

Indicator	Kazakhstan	Uzbekistan	Kyrgyzstan	Tajikistan
Share of large enterprises using digital platforms (%)	75	70	60	50
Share of medium enterprises using digital platforms (%)	65	60	45	40
Share of small enterprises using digital platforms (%)	50	45	30	25
Company revenue growth following digitalization (%)	25	20	15	10
Share of enterprises using big data (%)	40	35	25	20
Share of enterprises engaged in e-commerce (%)	55	50	35	30

Source: compiled by the authors based on World Bank Group [11], UNDP [12], OECD [13], national statistical agencies of Kazakhstan [14], Uzbekistan [15], Kyrgyzstan [16], and Tajikistan [17].

The main barriers to business digitalization in the analyzed countries remained financial constraints, a shortage of qualified personnel, and legal aspects of the digital economy. In Kyrgyzstan and Tajikistan, SMEs faced difficulties in financing digital transformations due to the high costs of implementing information systems, limited access to credit resources, and insufficient state support. In Kazakhstan and Uzbekistan, the conditions for digital development were more favorable due to the implementation of government programs; however, financial constraints remained relevant, especially for enterprises expanding digital infrastructure. Additionally, a shortage of qualified specialists in the ICT sector was observed across all countries in the region, complicating the adoption of new technologies. The level of digital literacy among entrepreneurs remained relatively low, limiting the effective use of digital technologies.

As noted in the study by Kalyuzhnova & Holzhacker [32], business and infrastructure digital transformation in the region was inextricably linked to the development of trade corridors and the strengthening of regional cooperation. The study emphasized that reducing trade costs and increasing Central Asia's integration into global value chains required the adoption of digital solutions in the transport and logistics sector. Uzbekistan and Kazakhstan, as key centers of regional trade activity, needed to intensify initiatives aimed at technological modernization and increasing business digitalization levels, which would contribute to attracting additional investments and enhancing the region's competitiveness in the context of global economic transformation.

Regulatory aspects of the digital economy also posted significant obstacles to business digitalization. The absence of an adapted legislative framework complicated the activities of enterprises operating in fintech, e-commerce, and big data. Inadequate legal regulation in the areas of personal data protection, electronic document management, and digital payments hindered the development of the digital economy, particularly in Kyrgyzstan and Tajikistan [33,34]. Meanwhile, in Kazakhstan and Uzbekistan, government initiatives were implemented to support business digital transformation. Kazakhstan introduced the "Digital Kazakhstan" program [35], which included the development of a digital ecosystem for SMEs. Research into Uzbekistan's experience [36] focused on the adoption of a series of regulatory acts governing digital financial services and e-commerce, which contributed to reducing administrative barriers and simplifying business registration procedures. The implementation of similar approaches could be beneficial for Kyrgyzstan, facilitating the acceleration of digital transformation in entrepreneurial activities.

The digitalization of the logistics sector in the analyzed countries also progressed unevenly, explained by varying levels of technological development, state support, and financial capabilities. Kazakhstan and Uzbekistan demonstrated significant progress in adopting digital solutions in logistics, whereas in Kyrgyzstan and Tajikistan, the development of digital technologies in this sector was slower due to infrastructure constraints and an insufficient level of logistics process automation. To assess the impact of digital solutions on transport sector efficiency, an empirical analysis was conducted, enabling a comparison of digital transformation results in the region's logistics sector.

Table 4 contained data on the reduction of delivery times, decreases in operational costs, improvements in route planning efficiency, reductions in logistics process delays, and enhancements in customer service levels resulting from the adoption of digital technologies in the logistics sectors of Kazakhstan, Uzbekistan, Kyrgyzstan, and Tajikistan.

Table 4 Analysis of logistics digitalization

Indicator	Kazakhstan	Uzbekistan	Kyrgyzstan	Tajikistan
Reduction in delivery time (%)	15	13	8	6
Decrease in operational costs (%)	10	8	5	4
Improvement in route planning efficiency (%)	12	10	6	5
Reduction in logistics process delays (%)	10	9	6	5
Increase in customer service level (%)	14	12	7	6

Source: compiled by the authors based on World Bank Group [11], UNDP [12], OECD [13], national statistical agencies of Kazakhstan [14], Uzbekistan [15], Kyrgyzstan [16], and Tajikistan [17].

The digital transformation processes in Kazakhstan, Uzbekistan, Kyrgyzstan, and Tajikistan have significantly influenced the management of information, material, and financial flows, as well as the efficiency of logistics systems across these countries. The integration of digital technologies has streamlined business processes, improved the flow of information between businesses and government entities, and optimized the management of material resources in the logistics sector [37-39]. In Kazakhstan, the adoption of advanced logistics technologies, such as automated route planning and IoT-based cargo monitoring, has reduced operational costs and delivery times, resulting in a 15% decrease in delivery time and a 10% reduction in operational costs. Similarly, Uzbekistan has seen improvements in logistics efficiency through digital platforms that enhance supply chain management and route optimization. However, in Kyrgyzstan and Tajikistan, the flow of information and materials remains constrained by limited digital infrastructure and insufficient digital literacy, slowing down the adoption of automated systems in logistics. Moreover, the financial flow management in both e-commerce and fintech sectors has improved, particularly in Kazakhstan and Uzbekistan, where digital platforms have enabled smoother financial transactions and greater access to financial services, facilitating business operations and increasing economic efficiency.

The digital development of the analyzed countries was uneven, influenced by differences in levels of digital infrastructure, Internet accessibility, digital literacy, human capital, and state support for digital initiatives. Kazakhstan and Uzbekistan demonstrated higher levels of digitalization due to the implementation of digital economy strategies and the attraction of significant investments. Kyrgyzstan and Tajikistan faced more challenging conditions, slowing down the integration of digital technologies into key economic sectors. In this context, a key task was to determine priority measures aimed at accelerating digital transformation, considering the economic development specifics of each country.

Table 5 presented summarized recommendations for the digital development of Kazakhstan, Uzbekistan, Kyrgyzstan, and Tajikistan, formulated based on the analysis of structural challenges.

Table 5 Recommendations for digital development

Development direction	Kazakstan	Uzbekistan	Kyrgyzstan	Tajikistan
Expansion of digital infrastructure	Expansion of 5G networks, Internet coverage in remote regions	Expansion of fibre-optic networks, state investments in digital infrastructure	Development of broadband Internet in rural areas	Increased access to mobile Internet, expansion of network coverage
Enhancement of digital literacy	Development of digital education programs, mandatory IT studies in schools	State initiatives to improve digital literacy	Creation of national digital education programs, adaptation of international practices	Integration of digital literacy courses into the education system
Strengthening human capital in IT	Support for tech parks, grant programs for startups	Training of IT specialists through international education programs	Implementation of mechanisms to support IT startups	Development of educational programs with a focus on IT specialization
Effective public policy for digitalization	Integration of digital technologies in the public sector, automation of services	Expansion of e-government, development of e-commerce	Adoption of a comprehensive digitalization strategy	Automation of public services, creation of unified digital platforms
Forecasting and strategic planning	Use of big data for digital development forecasting	Forecasting digital trends to optimise the business environment	Use of analytics to assess the effectiveness of digital initiatives	Development of digital economy strategies considering local specifics
Attraction of international investments	Attracting investors in fintech, stimulation of tech companies	Investment incentives for tech companies, partnerships with international IT corporations	Expansion of cooperation with international organizations to attract digital investments	Attraction of technology investors through international initiatives

Source: compiled by the authors.

The proposed recommendations considered the current level of digital development in each country and its main structural challenges. Kazakhstan had the most advanced digital infrastructure and was actively implementing 5G technologies, which contributed to the improvement of digital services. In Uzbekistan, the primary focus was on expanding fiber-optic networks and stimulating state investments in the digital economy. In Kyrgyzstan and Tajikistan, the level of digital infrastructure remained lower, making the improvement of Internet access, particularly in remote regions, a priority.

The level of digital literacy also varied significantly among the countries. Kazakhstan and Uzbekistan actively expanded educational programs that included the development of ICT competencies, whereas in Kyrgyzstan and Tajikistan, a deeper integration of digital literacy courses into the education system was required. A key challenge remained the human capital in the ICT sector. Kazakhstan supported the development of startups and technology hubs, while Uzbekistan actively fostered international cooperation in IT specialist training. In Kyrgyzstan and Tajikistan, the creation of grant programs and mechanisms to stimulate professional development in digital technologies was necessary.

Public policy played a crucial role in the region's digital transformation [40,41]. Kazakhstan and Uzbekistan implemented large-scale state digitalization programs, promoting the automation of public services and the development of e-government. In Kyrgyzstan and Tajikistan, the structuring of digital initiatives was less developed, limiting their effectiveness. A crucial aspect of digital development remained strategic planning, which encompassed forecasting digital trends and applying big data to enhance the effectiveness of managerial decisions in digital transformation.

Attracting international investments was of particular importance. Kazakhstan and Uzbekistan already used preferential conditions to support technological companies, contributing to the expansion of the ICT sector. In Kyrgyzstan and Tajikistan, there was significant potential for strengthening cooperation with international financial institutions, which could facilitate further digital integration and the development of key economic sectors.

4 Discussion

The process of digital transformation played a key role in shaping economic development, encompassing all leading sectors of the economy. The integration of digital technologies contributed to the renewal of business models, the enhancement of management processes, and the optimization of resource use. Significant changes took place in public administration, industry, the financial sector, and logistics, necessitating a comprehensive analysis of the impact of digitalization at both the macro- and microeconomic levels. At the same time, the process of digital integration was accompanied by several challenges, including institutional constraints, financial barriers, and regulatory issues. Given the rapid pace of digital economy development, identifying key trends, risks, and opportunities arising from digitalization in various economic systems became a relevant task.

The analysis of the obtained results demonstrated that digital transformation significantly influenced economic productivity and the development of leading industries, particularly energy, entrepreneurship, and logistics. The study conducted by Mihai et al. [42] focused on the digitalization of the energy sector and highlighted the main challenges in ensuring its resilience. The authors identified the interrelation between the level of digital technology implementation and the efficiency of energy enterprises. The findings were consistent with the results of this study, confirming the significance of digital modernization as a tool for enhancing economic efficiency and reducing costs in various economic sectors.

The digitalization of the business environment was considered a key factor in strengthening the competitiveness of regional economies. In the study by Vîrjan et al. [43], the relationship between the level of digital integration and economic competitiveness was analyzed. The authors established that the active implementation of digital technologies contributed to increased labor productivity, investment attraction, and the development of innovation potential. An analysis of the economies of the studied countries confirmed these patterns, as it was found that Kazakhstan and Uzbekistan had higher levels of digital integration, which positively affected their macroeconomic indicators.

The study of digital transformation in SMEs in the analyzed countries showed that the level of digital technology implementation significantly influenced business productivity and competitiveness. In the study by Martínez-Peláez et al. [44], the relationship between the use of digital solutions, organizational culture, and business resilience was examined. The authors found that the application of big data and active stakeholder engagement enhanced the effectiveness of digital transformation in enterprises. The obtained results confirmed that state support and strategic planning for digitalization in SMEs in the analyzed countries could contribute to their economic resilience and innovation potential.

The research results demonstrated that the digitalization of business processes contributed to improving customer interaction and optimizing marketing strategies. Similar conclusions were drawn in the study by Fernández-Rovira et al. [45], which analyzed the role of big data in customer data management and consumer behavior forecasting. The authors emphasized that the widespread use of digital technologies in business created both new opportunities and certain threats, particularly of an ethical nature. These findings aligned with the need to implement regulatory mechanisms to ensure data security in the digital environment of the analyzed countries.

Organizational changes driven by digitalization processes required a systematic approach and a high level of adaptability. In the study by Hanelt et al. [46], a systematic analysis of scientific literature on digital transformation was conducted, allowing for the identification of four key approaches to managing this process. The authors concluded that digital transformation involves not only technological upgrades but also a revision of organizational models and business ecosystems. Similar results were obtained during the study of digital reforms in the public sector of the analyzed countries, where the implementation of digital solutions contributed to improving the efficiency of management processes.

The study of digital transformation processes demonstrated that its successful implementation depended not only on technological innovations but also on workforce adaptability, the effectiveness of management strategies, and an established organizational culture. In the work by Trenerry et al. [47], a multilevel analysis of digital transformation factors was conducted, covering individual, team, and organizational aspects. The authors identified key determinants of employees' successful adaptation to digital changes, including technological literacy, staff training levels, organizational culture, and leadership effectiveness. The obtained results aligned with the conclusions on business digital transformation in the analyzed countries, confirming that enterprises' readiness to implement new technologies largely depended on personnel competence, internal communication quality, and strategic leadership vision. This underscores the need to develop comprehensive digitalization strategies that combine technological investments with measures aimed at human capital development.

Recent literature emphasizes the centrality of digital transformation in shaping information, financial, and material flows within logistics and broader economic systems. Ptashchenko et al. [48] reveals that digital technologies significantly enhance logistics efficiency and transparency, reducing operational costs and delivery times while strengthening the integration between digital logistics and international trade development, findings that resonate with the observed improvements in material and information flows in our regional analysis. Additionally, Şahan [49] demonstrates through panel regression analysis across multiple European contexts that components of digital transformation (including internet connectivity and digitized public services) have a positive effect on logistics performance, highlighting the importance of digital integration for competitive logistics and supply chain management. Complementing these empirical insights, Al Ababneh et al. [50] argue that digital transformation of supply chain management is a multifaceted process that enhances efficiency, transparency, and sustainability, underscoring how information technologies optimize logistics, inventory, and transportation flows.

Digital transformation was a key factor in economic modernization, contributing to enterprise productivity growth, business process optimization, and improved public administration efficiency. It was established that the level of digital integration directly influenced economic competitiveness, investment attraction, and innovation sector development. The findings show that digital integration improved delivery coordination, route planning, supply chain transparency, and customer service quality, especially in Kazakhstan and Uzbekistan, where digital logistics tools were associated with reduced delivery times and lower operational costs. These results indicate that logistics is not merely a secondary area of digitalization but one of the main channels through which digital technologies influence business productivity, trade efficiency, and regional economic competitiveness. The comparison of obtained results with other researchers' conclusions confirmed common patterns of digital changes, particularly the impact of big data, automated platforms, and companies' digital maturity levels on their economic efficiency. It was proven that the success of digital transformation largely depended on adapting strategic approaches to the development level of the institutional environment and technological infrastructure. At the same time, a number of challenges have been identified related to ensuring effective risk management, data protection, and regulatory aspects of digitalization. Given these factors, the further implementation of digital solutions required a comprehensive approach that encompassed the expansion of digital infrastructure, the improvement of regulatory frameworks, and the enhancement of digital literacy among economic actors.

5 Conclusions

The study provides a comprehensive assessment of how digital transformation affects economic development, the business environment, and logistics in Kazakhstan, Uzbekistan, Kyrgyzstan, and Tajikistan, which constitutes its scientific novelty. The analysis of key digitalization indicators revealed substantial differences in the pace and depth of technology adoption across countries. A strong relationship was identified between digital readiness, the ICT sector's share in GDP, and investment in the digital economy, confirming the role of digital integration in supporting economic growth.

Kazakhstan and Uzbekistan demonstrated more advanced implementation of digital technologies in finance, e-government, business, and logistics. In contrast, Kyrgyzstan and Tajikistan showed slower progress due to institutional, financial, infrastructural, and human-capital constraints. Business digitalization positively affected enterprise productivity and revenues, especially among large companies. Kazakhstan recorded the highest level of enterprise digital integration, with 75% of large firms using digital platforms. However, the effect on SMEs remained uneven, particularly where access to e-commerce tools, big data, and qualified ICT specialists was limited.

Digitalization also improved logistics performance by reducing operational costs, optimizing routes, and enhancing service quality. In Kazakhstan and Uzbekistan, digital logistics tools reduced delivery time by up to 15% and increased transport efficiency. The findings confirm the need for expanded investment in digital infrastructure and sector-specific technologies. Recommended measures include further 5G deployment, technology hubs, and fintech support in Kazakhstan; digital literacy and ICT training in Uzbekistan; and improved Internet access, digital education, and regulatory support in Kyrgyzstan and Tajikistan.

The limitations of the study were determined by the specifics of the data used, the methodological approach, and the time frame. The analysis was based on official statistical indicators, ensuring their representativeness, but not reflecting short-term changes. The applied methods of correlation and regression analysis allowed for the identification of relationships between digitalization and economic development but did not detail sectoral specificities. The time frame (2020-2024) ensured the relevance of the conclusions, although the long-term effects of digital transformation required further monitoring.

Promising areas for further research could include analyzing the impact of digital transformation on specific economic sectors, particularly financial services, education, and industry. Special attention should be given to studying the mechanisms of state incentives for digitalization in SMEs, as well as developing adaptive models for implementing digital technologies in countries with different levels of economic development.

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Risk assessment of ESG-based logistics systems using a TOPSIS-based approach

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Abstract: The operation of ESG-based systems is a complex task, as a multitude of environmental, social, and governance factors must be simultaneously addressed within logistics and recycling processes. ESG, as a legal and risk management framework, permeates all economic activities, making it indispensable in logistics, the largest globally interpretable service (supply) activity. The research aims to optimize the application of ESG obligations and opportunities in the field of recycling logistics. The research examined possible solutions through a systematic literature review and the creation of a holistic model. For the model, it was necessary to define the main logistics processes, their components, the scope and types of data required for data-based operation, and the relationships between the elements of the system. Achieving sustainability objectives necessitates the identification, evaluation, and management of risks through approaches capable of integrating diverse considerations. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) provides a suitable tool for ranking decision alternatives by quantifying and comparing various criteria. Integrating the ESG perspective with multi-criteria decision support enables more sustainable and efficient management of logistics operations. An additional advantage of this methodological framework lies in its adaptability to different industry environments and organizational structures. The study's findings lay the groundwork for the development of further model applications and practical implementation strategies.

1 Introduction

Over the past decade, the issue of sustainability has become a defining element of academic and economic discourse, especially in light of global environmental and social challenges such as climate change, the overexploitation of resources, and the necessity to transform supply chains from a sustainability perspective [1].

The emergence of the ESG (Environmental, Social, and Governance) framework offers an integrated approach that enables the coordinated management of environmental, social, and corporate governance dimensions, thereby contributing to companies' long-term sustainability and competitiveness [2].

Recycling logistics plays a pivotal role in today's sustainability efforts. It encompasses not only waste management but also the efficient use of resources, the reduction of environmental burdens, and the construction of a more sustainable future. Recycling logistics includes the collection, transportation, sorting, and processing of waste, as well as the reintegration of recycled materials into production processes [3]. However, it faces numerous complex challenges that must be overcome to achieve a circular economy [3].

The recycling process is inherently complex and costly, encountering several barriers:

- The heterogeneous nature of waste makes the collection and separation of mixed refuse a significant technological and logistical challenge.
- Contaminants reduce the quality and value of recycled materials.
- Deficiencies in logistical infrastructure—such as inadequate collection points or high transportation costs—further hinder efficient recycling.
- Consumer behaviour is also critical: lack of awareness and improper selective waste collection diminish overall system performance.

2 Literature review

The rise of the ESG framework has fundamentally reshaped corporate sustainability and supply chain management. Empirical evidence consistently shows that integrating environmental, social, and governance aspects enhances financial performance and competitiveness [1-2]. Institutional pressures further drive firms to adopt green supply chain practices that indirectly improve efficiency and legitimacy [3]. At the same time, social capital within networks mitigates the negative effects of dependence and supports innovation. On a global scale, multinational corporations use ESG-based, self-regulatory, and information-driven strategies to influence climate policy. Overall, ESG integration has become a strategic foundation for sustainable and responsible corporate governance [4-5]. Logistics plays a key role in this process, as the energy use, emissions footprint, resource consumption, and transparency of supply chains determine the practical achievement of ESG goals [4,6-9].

In the field of sustainable supply chain management, one starting point is the multi-period network redesign model, which aims at developing environmentally friendly systems [10]. The paradigm-shifting importance of the circular economy is confirmed by several authors [11], with special emphasis on logistics solutions that support resource recovery, waste reduction, and decentralized recycling [7,12]. Life Cycle Assessment (LCA) provides a methodological foundation for measuring the environmental impacts of products and processes over their entire life cycle, thereby contributing to sustainable logistics decision-making [12]. Research shows that aligning LCA with reverse logistics carries significant potential for emissions reduction and cost optimization [4,6,13]. In addition, decentralized recycling centers increase network flexibility and reduce transportation burdens [13].

Digitalization and data-driven technologies play an increasingly important role in ESG implementation. Blockchain-based models support transparency, traceability, and data integrity, while also enabling supply chain optimization [6]. The use of IoT and predictive analytics promotes energy efficiency, real-time monitoring, and the search for logistical optima [14]. These technologies also provide risk reduction and cost-efficiency benefits [6,15].

A key element of sustainable logistics is green procurement and supplier collaboration, which help reduce emissions and support ESG auditing processes [9,16]. Corporate reporting and supply chain transparency are evolving in parallel with digital transformation [7], further reinforced by international recommendations and policy frameworks. Sustainability reports also play an important role in the automotive industry and other relevant sectors [6].

Empirical research consistently confirms that ESG performance improves operational efficiency, investor confidence, and financial results [7]. Logistics systems contribute to this not only as an implementation platform but also as a driver of innovation [8,13,14]. Overall, the literature identifies the greatest potential for ESG application in logistics at the intersection of recycling, LCA, digitalization, and network sustainability. Based on the reviewed sources, it can be stated that ESG-based logistics systems simultaneously support environmental sustainability and economic competitiveness.

3 Fundamental tasks of ESG systems

Based on the foregoing, it is apparent that ESG systems hold a pivotal role across various societal sectors. For the optimal operation of any such system, the following fundamental tasks must be addressed:

- Clearly define and delimit the operational domain of the system under investigation.
- Within the delimited system, determine the types and quantities of entities to be examined.
- Identify the characteristic parameters of those entities and their operational strategies within the delimited system.
- Establish the structure of the evaluation framework for the delimited system, specifying which criteria will be used to assess performance and which operational strategies will be compared.
- Uncover the relationships between entity parameters and system performance metrics based on the parameters of the entities comprising the delimited system.
- Employ an appropriate optimization procedure to identify the system optimum under the given conditions.

Based on Figure 1, it is evident that the task at hand involves solving a highly complex problem. The intricacy of the task is further amplified by the following factors:

- A multitude of subsystems can be delineated, yet the ultimate objective remains the optimal operation of the entire ESG system.
- For each entity, the number and types of parameters to be managed must be specified.
- Multiple operational strategies may be assigned to each individual entity, resulting in a wide array of possible system-level behaviours.
- Diverse types of operational characteristics may apply to the various subsystems.
- The relational structure between different entities, their operational strategies and parameters, and the evaluation metrics characterizing the subsystems is inherently complex.
- Multiple optimization procedures and sets of conditions may be employed for system evaluation.

In light of these considerations, it can be concluded that the proper analysis of an ESG system requires a sophisticated data infrastructure, comprehensive operational strategy frameworks, and specialized optimization processes. Such complexity can only be addressed through the implementation of an advanced simulation system.

Figure 1 The evaluation process of ESG systems

3.1 The role of risk management in ESG systems

A further analytical perspective on ESG systems involves the systematic identification and management of risk factors and potential threats. Within each operational process—including the logistics processes embedded in ESG systems—various risk elements may arise that jeopardize the continuity and stability of system operations. These risks, stemming from environmental, social, or governance-related uncertainties, necessitate targeted mitigation strategies to preserve the integrity and resilience of the system throughout its lifecycle.

It is a critical consideration that risk factors may disrupt system operations with varying degrees of severity. Therefore, a key task is to rank these risk factors according to the magnitude of the associated risk. This prioritization enables the formulation of appropriate measures to ensure uninterrupted system functionality.

The principal domains of the risk management procedure are illustrated in Figure 2.

The objective of the risk management procedure is to establish and define a comprehensive list of potential risks based on events that may adversely affect the operation of the logistics process within the ESG system.

In the context of logistics processes and systems, a substantial number of risk factors can be identified. These risk factors are associated both with the material flow component and the information flow component of the logistics process. Moreover, they may be linked to the characteristics of material handling equipment as well as to the various operational strategies employed.

The first step in the risk management procedure is the identification of risks. This activity inherently involves subjective elements, which are influenced by the individual conducting the identification. In contemporary practice, artificial intelligence can be utilized effectively in this phase, significantly reducing the degree of subjectivity and enhancing the consistency and reliability of risk detection.

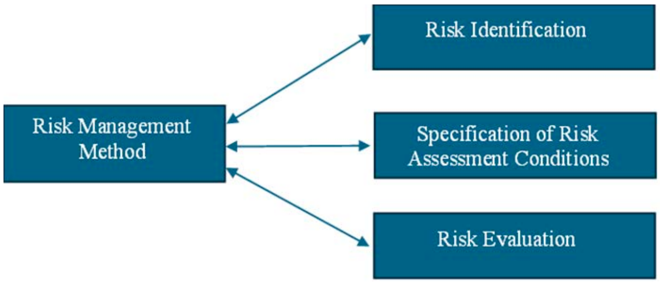

Fig. 2 Risk management method

In order to mitigate the risks inherent in logistics processes, it is essential to identify the full spectrum of risk factors, along with their underlying drivers, associated conditions, and triggering events. This comprehensive exploration serves as the foundation for the development of targeted risk management strategies aimed at ensuring operational continuity and resilience within ESG-oriented logistics systems.

In the context of logistics operations, the following categories of risks are typically considered:

- Material Flow Risk,
- Information Flow Risk,
- Technological Risk,
- Disaster Risk,
- War Risk,
- Globalization Risk,
- Financial Risk,
- Product and Service Risk,
- Social Impact Risk,
- Environmental Impact Risk,
- Product Structure Risk,
- Energy Supply Risk,
- etc.

A wide range of conditions may be specified in the context of risk assessment criteria. In the following, three key factors are highlighted:

- The probability of occurrence of the individual risk
- The potential impacts of the examined type of risk
- The quality of controls implemented to reduce risks across processes, systems, and system components

We evaluate risk factors and conditions using a method that seeks a compromise solution based on the best (positive) and worst (negative) possible values of each parameter. The approach applied for identifying such compromise solutions is the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method. In the context of ESG integration among logistics SMEs, this framework enables a systematic comparison of sustainability criteria and reveals key areas where implementation lags behind strategic priorities [17]. The application of TOPSIS thus opens up new possibilities for assessing ESG maturity and guiding more targeted, evidence-based sustainability actions within the sector [18].

3.2 Application of the TOPSIS method in ESG evaluation

In the following section, we outline the application of this method based on the solution-seeking methodology. The application of the TOPSIS method in ESG evaluation enables corporate decision-makers to rank alternatives based on multiple criteria [18,19]. During the integration of environmental, social, and governance dimensions, it is essential that the individual criteria are represented in the assessment with different weights. The advantage of the method is that it compares the performance of the alternatives to the best and worst solutions, thus ensuring an objective comparison. In the process, the evaluation criteria are first defined, followed by the assignment of the corresponding weights and data. This is followed by normalization, which ensures comparability despite different units of measurement. After identifying the positive and negative ideal solutions, the distance of each alternative from both reference points can be calculated.

The final ranking is based on relative closeness, which is well suited for identifying and managing risks in an ESG context. The figure visually presents the steps of the procedure, supporting the understanding and practical application of the process. The first step of the method is the construction of the decision matrix, where the performance of the alternatives is recorded in relation to ESG criteria. This is followed by normalization and weighting, which ensure comparability and the enforcement of priorities. After defining the positive and negative ideal solutions, the distance of the alternatives from each reference value can be calculated. The final evaluation is based on relative closeness, from which a clear ranking of sustainability performance can be established.

The method is particularly useful in cases where several corporate units, suppliers, or investment alternatives need to be evaluated from an ESG perspective. As a result of the decision-support process, not only can the most favorable option be identified, but the areas requiring improvement can also be revealed. This enables the definition of strategic directions and the allocation of resources in line with sustainability objectives.

4 Key components of the general application of the TOPSIS method

Outline of the necessary calculations based on the presented flowchart. Figure 3. illustrates the workflow of the decision-support method developed in this study. The procedure begins with the construction of the task matrix, followed by the normalization and weighting of its elements. Subsequently, the positive and negative ideal solutions are identified, and the deviations of each alternative from these reference points are determined. Finally, the relative closeness of the alternatives to the ideal solution is calculated, enabling their systematic ranking within the evaluation framework. These steps provide a transparent mathematical structure for comparing alternatives, while ensuring consistency in the assessment process. The outlined procedure thus supports robust and reproducible decision-making in ESG-oriented evaluations.

Figure 3 Risk management procedure

4.1 *Task matrix (F), normalized task matrix (G) and weighted normalized task matrix (H)*

The task matrix F (Figure 4) represents the evaluation framework in which each row corresponds to a possible solution alternative and each column corresponds to a specific risk factor. The element *f(i,j)* denotes the value of the *j-th* risk factor associated with the *i-th* alternative, where i = 1, 2, …, m and j = 1, 2, …, n. Based on this initial matrix, the normalized task matrix G is derived using the subsequent normalization formula. This transformation ensures that the differing scales of the risk factors do not distort the comparative assessment of the alternatives (1):

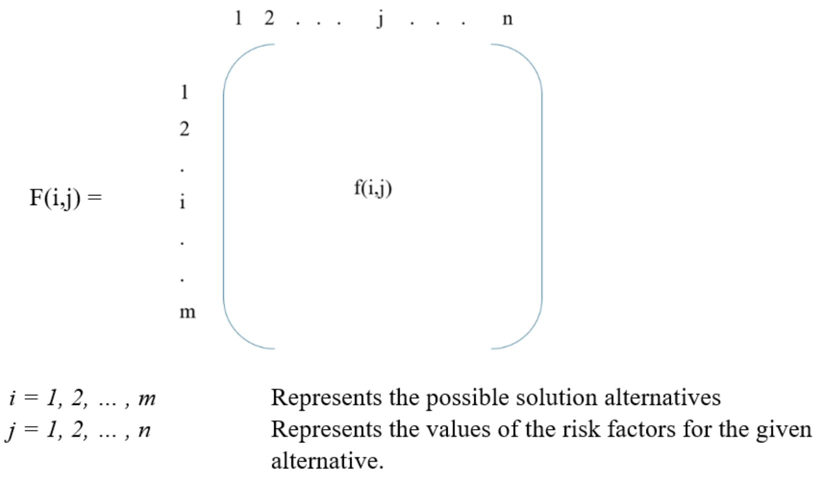

Figure 4 Representation of task matrix

$$g(i,j) = \frac{f(i,j)}{\sqrt{\sum_{i=1}^{j} f(i,j)^2}} \tag{1}$$

In determining the weighted normalized task matrix (H), the weighting factors must be taken into account. These weighting factors pertain to the risk factors and are represented by the vector (2) *h(j).*

$$\sum_{j=1}^{n} h(j) = 1, \text{ and } 0 < h(j) < 1 \tag{2}$$

Multiplying each column of the normalized task matrix by its corresponding weighting factor yields the weighted normalized task matrix (3).

$$H(i,j) = h_j \times G(i,j), \text{ where } i = 1, 2, ..., m \tag{3}$$

4.2 *Identification of positive ideal and negative ideal solutions*

The matrix H(i,j) used to identify the positive ideal solutions, which are contained in the vector (4) $M^{+}(j)$, where

$$M^{+}(j) = \max H(i,j), \text{ if } j \in J \tag{4}$$

and contains the negative ideal solutions (5), where

$$M^{-}(j) = \min H(i,j), \text{ if } j \in J' \tag{5}$$

where J and J' denote the sets of benefit and cost attributes, respectively.

4.3 *Determination of deviations from the positive and negative ideal solutions for each alternative*

In the calculations, we use the weighted normalized task matrix H(i,j), along with the vectors containing the positive ideal solutions (M^{+}), and the negative ideal solutions (M^{-}).

The positive deviations are determined by (7)

$$S(i)^{+} = \sqrt{\sum_{i=1}^{m} [H(i,j) - M^{+}(j)]^2}, \tag{7}$$

Negative deviations are calculated based on (8)

$$S(i)^{-} = \sqrt{\sum_{i=1}^{m}[H(i,j) - M^{-}(j)]^2}, \tag{8}$$

4.4 *Determination of the relative closeness of each alternative to the ideal solution*

C(i) value expresses the relative closeness of the *i-th* alternative to the positive ideal solution. Based on the resulting of C(i) values, the alternatives can be systematically ranked according to their performance. It is calculated by (9), (10):

$$C(i) = \frac{S^{-}(i)}{S^{+}(i) - S^{-}(i)}, \tag{9}$$

$$0 \leq c_i \leq 1 \tag{10}$$

During the optimization of ESG risks, the simultaneous consideration of ESG-related parameters affecting logistics processes results in substantial computational complexity. The international ESG standards currently in use define approximately 1,000-1,100 indicators across the environmental, social, and governance dimensions. For the calculation of distances to the positive and negative ideal solutions, and for the methodologically sound application of the TOPSIS method, it would be justified to incorporate at least 5-10% of this indicator set. However, computations of this scale require extensive data preparation, weighting, and normalization procedures, which exceed the length constraints of the present study. Accordingly, the primary objective of this research is the conceptual and methodological establishment of ESG-based logistics risk assessment using the TOPSIS method, while large-scale numerical optimization based on an extensive indicator set is deferred to a subsequent, simulation-based research phase.

5 Discussion

The key contribution of the research lies in the systematic integration of the ESG criteria, recycling logistics, and multi-criteria decision support. Going beyond theoretical approaches, a holistic model has been outlined that reorganizes basic logistics processes along the lines of data-driven operations and environmental and social determinants. Given that recycling is one of the most critical segments of modern supply chains, the research interprets the optimization of this process as a complex risk management task.

The methodological framework is based on an adaptation of the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) algorithm, which allows for an objective comparison of different logistics strategies. With the help of the model, the individual alternatives are not only evaluated on a scale, but their proximity to the positive ideal solution and their distance from the worst case can also be determined with mathematical precision. This approach is particularly relevant in an uncertain economic environment where risk assessment is essential.

The modernized risk management protocol developed as part of the research focuses on eliminating subjectivity beyond traditional material and financial processes, integrating responses to global challenges. The developed mathematical framework, including the use of normalized and weighted matrices, is not only a theoretical approach but also provides a direct basis for the development of subsequent digital simulation systems. This integrated approach allows companies to view ESG compliance not as a separate issue, but as an integral part of logistics efficiency and competitiveness. Its practical significance lies in its multidisciplinary nature, technology-focused risk assessment, and the development of a mathematical optimization process that can be translated into practice.

6 Conclusions

The study highlights that the evaluation of logistics systems based on ESG principles can only be effectively conducted through complex, multi-criteria methodologies. ESG frameworks simultaneously encompass environmental, social, and governance factors, which exhibit strong interrelations with the challenges of recycling logistics. Due to the multifaceted nature of risk factors, their structured identification, prioritization, and management are essential. The TOPSIS method serves as a suitable tool for comparing potential solution alternatives, as it quantifies the impact of risk variables and facilitates the selection of the optimal option.

The applied approach enables the mitigation of operational disruptions within logistics systems and supports the achievement of sustainability objectives. Furthermore, the method is adaptable to various organizational and industrial contexts, thereby enhancing its practical relevance. The integration of artificial intelligence into subjective risk identification further strengthens the reliability of the evaluation process.

The findings of the research provide a foundation for the development of simulation models and advanced decision-support systems. Future work should involve testing the methodology on specific industrial cases and comparing it with other multi-criteria techniques. The study contributes to both the theoretical advancement and practical implementation of ESG-oriented logistics systems.

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Optimizing fulfillment center flows to improve delivery speed and service level

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Abstract: This article aims to develop a methodology for choosing the optimal configuration within the logistics network through placing regional fulfillment centers, thereby facilitating swifter delivery of goods. The study examines the influence of both the quantity and geographical positioning of fulfillment centers on critical delivery efficiency indicators, as well as inventory planning to attain the desired service level. The methodological framework is built upon a synthesis of discrete optimization techniques, inventory management theory, and stochastic simulation. A model for the placement of fulfillment centers, grounded in the p-median problem and constrained by delivery time, alongside a model for managing the safety stock, are employed to realize the target objective of timely and complete delivery. The empirical foundation is established using data derived from the global postal and parcel service market, along with logistics indices from the United States, Germany, and China. Sensitivity analysis indicated that the system is particularly susceptible to fluctuations in the proportion of international orders. The practical implications of this study lie in the applicability of the proposed approach for decision-making in the strategic planning of logistics flow expansion, contingent upon the specific stage of the business life cycle. Future research prospects include the integration of alternative transportation modalities, the modeling of dynamic stock redistribution among fulfillment centers, as well as evaluating the economic viability of warehouse operations automation. The paper introduces a flow management approach for regional fulfillment centers that jointly optimizes material and information flows to accelerate delivery with controlled cost trade-offs.

1 Introduction

Within the realm of e-commerce, the speed of goods delivery represents a critical factor of business competitiveness amidst escalating consumer expectations. In 2022, the global market for postal and parcel services reached 161 billion shipments, with projections indicating an increase to 225 billion by 2028, reflecting a compound annual growth rate of 6% [1]. Bruni et al. [2] formalize the complexities surrounding drone placement and routing while accounting for stochastic delays, yet they do not consider the critical regulatory constraints of airspace, particularly in urban areas.

Contemporary research on the optimization of e-commerce logistics networks flow primarily emphasizes the timeliness of product delivery [3]. This task encompasses the spatial configuration of fulfillment centers, inventory management, carrier selection, and the assurance of sustainable operational practices. Further, Yang et al. [4] investigate a network planning methodology in the context of fast commerce through micro-fulfillment centers, underscoring the significance of geographical proximity to consumers in securing a competitive edge in delivery speed. In addition, Silva et al. [5] and Miniharianti et al. [6] undertake a systematic literature review on sustainable urban last-mile logistics, identifying three predominant pathways for decarbonization, namely fleet electrification, freight consolidation, as well as alternative transportation modalities. The contributions of this author are noteworthy and warrant further exploration regarding the developmental potential of fulfillment centers.

The novelty of this study resides in the application of an integrated methodology to compare alternative logistics flow configurations, employing metrics of speed, reliability, cost, and sensitivity to external shocks. The proposed hypothesis posits that a regional configuration comprising three fulfillment centers achieves an optimal balance between operational efficiency and service level for the majority of medium-scale e-commerce operators. Three centers represent the minimum requisite to adequately cover the principal macro-regions at economically justified costs, drawing from U.S. experiences.

The aim of this study is to develop a methodology for selecting the optimal logistics network flow configuration through the strategic placement of regional fulfillment centers, thereby expediting the delivery of goods in the e-commerce sector. To address this aim, the following tasks were delineated: 1) to develop a model for the optimal placement of fulfillment centers grounded in the p-median problem, incorporating constraints on delivery time and demand coverage; 2) to compute safety stocks for each fulfillment center to achieve a target metric of timely and complete delivery of 95%; 3) to conduct simulation modeling to compare the key performance metrics of centralized, regional, and distributed network configurations; 4) to conduct a sensitivity analysis of the optimal configuration in response to external shocks and formulate decision-making recommendations for determining the number of fulfillment centers based on specific business characteristics.

2 Literature review

The optimization of fulfillment centers placement amidst uncertain demand and the development of omnichannel networks represent key areas of inquiry in enhancing the logistics efficiency of e-commerce. Lee et al. [7] examine the optimization of an omnichannel distribution network employing micro-fulfillment centers under conditions of demand uncertainty. We concur with the authors regarding the indispensable role of stochastic modeling in accounting for order volatility. Lamb et al. [8] investigate the planning of micro-fulfillment centers tailored for drone delivery. The value of this study lies in the formulating a spatial placement model that considers the technical constraints of unmanned aerial vehicles, including flight radius and payload capacity.

Technological automation of fulfillment operations and the incorporation of robotics are regarded as fundamental determinants in enhancing productivity and reducing costs. Accordingly, Wei [9] proposes a methodology for the selection of micro-fulfillment center locations based on a multi-criteria evaluation that combines financial (Net Present Value, Return on Investment) and logistical (coverage, lead time) metrics. The disadvantage is the absence of sensitivity analysis regarding the parameters, which diminishes the practical applicability of the model. Interestingly, Khudoyberdiev et al. [10] analyze the interaction between humans and unmanned systems in the context of hybrid picking and Hoffmann et al. [11] investigate the use of autonomous delivery robots for last-mile deliveries.

Operational strategies for final delivery and the spatial dimensions of e-commerce logistics expansion are explored in studies focusing on zoning and routing algorithms. In this regard, Younus et al. [12] delve into clustering methodologies for delivery zones within fulfillment centers to enhance order processing efficiency. The authors advocate for grouping based on geographical proximity and demand density, thereby facilitating a reduction in the transit time of the intermediary link. Nonetheless, the lack of comparative analysis with alternative approaches, particularly p-median or max-cover models, constrains the capacity to evaluate the optimality of the proposed solution. Furthermore, Allgor et al. [13] devise an algorithm for automated product selection in Amazon fulfillment centers that harmonizes the interaction between humans and robots. What is more, Rudolph et al. [14] assess the societal repercussions of Amazon's logistical expansion, including the impacts of establishing new fulfillment centers on the escalation of insurance claims related to industrial injuries.

The economic implications of implementing e-commerce infrastructure for local markets and tax policy are explored through examining the spillover effects and regulatory transformations. For instance, Chung [15] investigates the spillover effect of e-commerce on local retail real estate markets, revealing a nuanced impact contingent upon the type of retail. Next, Houde et al. [16] delve into innovation within e-commerce by analyzing the Amazon fulfillment center network, illustrating that tax modifications incentivize the strategic placement of fulfillment centers under more advantageous conditions. Furthermore, DeValve et al. [17] assess the significance of fulfillment flexibility within the online retail environment.

Systematic reviews concerning sustainable urban logistics and the spatial proliferation of e-commerce flows reveal environmental and urban challenges engendered by heightened delivery intensity. Orozonova et al. [18] emphasize the role of smart logistics technologies in multimodal cargo delivery systems, which improve the delivery efficiency. Fried and Goodchild [19] scrutinize the spatial dynamics of e-commerce logistics networks, observing a trend wherein fulfillment centers are migrating to suburban areas. In this light, Gonzalez et al. [20] investigate the perspectives of key stakeholders regarding the enhancement of sustainability in urban logistics for e-commerce.

Specialized domains within e-commerce logistics, particularly the fresh product delivery and omnichannel models, are emerging as important areas of contemporary operational research. Prajapati et al. [21] propose a heuristic clustering-based routing methodology that accommodates time windows and product shelf life, achieving a reduction in spoilage by

15–22% relative to the conventional FIFO approach. Risberg [3] synthesizes the findings of 147 studies to construct a conceptual decision-making framework in omnichannel logistics systems.

An analysis of scholarly sources corroborates the substantial potential for further inquiry into optimizing e-commerce logistics networks through the efficient placement of fulfillment centers. Frequently, studies focus on niche segments, such as fresh produce delivery or express commerce, which complicates the generalizability of their conclusions to the broader e-commerce landscape. Approaches that combine the analysis of diverse configurations of logistics networks remain inadequately developed. Future research should prioritize the establishment of p-median analytical models, taking into account service level agreements (SLA) and inventory management for a specified OTIF indicator.

3 Methodology

3.1 Research procedure

The research methodology is predicated on a comprehensive approach to optimizing e-commerce delivery logistics networks through integrating discrete optimization techniques, inventory management principles, and simulation modeling. The research was conducted in five consecutive stages. The first stage, in which an empirical foundation was established, was conducted by systematically organizing data pertaining to the structure of the global postal and parcel market, logistics metrics of the USA, and operational parameters of leading international operators. The dynamics of parcel volumes from 2020 to 2024, delivery speed, reliability metrics, specifically OTIF (On-Time In-Full), and cost structures were analyzed. This analysis was grounded in data sourced from Pitney Bowes Inc. [1,22], the World Bank [23], the Universal Postal Union [24], the International Post Corporation [25], McKinsey & Company [26], and the DHL Group [27]. The second stage, in which a conceptual framework was constructed, entailed the identification of critical parameters of the logistics network. The third stage, which focused on operationalization of objectives, was realized through the development of delivery speed normalization and the optimal placement of fulfillment centers (p-median analysis). The fourth stage, which carried out empirical validation, was conducted utilizing Monte Carlo simulation for 10,000 orders across each flow configuration (centralized, regional, distributed).

The fifth stage, which was devoted to the formulation of recommendations and practical solutions, was achieved by synthesizing the modeling results into comparative tables. Based on the derived data, optimal configurations of the logistics flow were delineated for varying scales of business.

3.2 Research sample

The sample base of the study was constituted through integrating three distinct data clusters (Table 1). The criteria for selecting sources encompassed the representativeness of data pertaining to the largest markets in terms of parcel volume, as well as the reliability and credibility of the sources, achieved through the utilization of official statistics from international organizations and the financial disclosures of publicly traded companies. The sample size is sufficient for modeling purposes, as the Monte Carlo simulation, comprising 10,000 iterations, yields the necessary statistical precision for calculating efficiency metrics.

Table 1 The structure of the research sample base

Cluster	Data source	Types of indicators
Market dynamics	Pitney Bowes Inc. [1]	Parcel volumes by country (2016–2022), growth rates, market structure (B2C/B2B)
	Pitney Bowes Inc. [22]	US dynamics (2022–2023), operator shares (USPS, UPS, FedEx, Amazon Logistics)
	Universal Postal Union [24]	International/domestic parcel flows (1874–2024), 2IPD metrics (Reach, Reliability, Relevance, Resilience)
	International Post Corporation [25]	Aggregated data from 50 postal operators, revenue structure, e-commerce trends
Logistics efficiency	World Bank [23]	Logistics Performance Index (LPI) for 139 countries: Timeliness, Infrastructure, Customs, International Shipments
	European Commission [28]	EU delivery standards, comparative tariffs, cross-border logistics
	McKinsey & Company [26]	Survey of 1000+ US consumers: speed vs reliability priorities, willingness to pay for sustainability
Operational parameters	DHL Group [27]	Express Division cost structure, EBIT/EAC metrics, asset charge methodology, Time Definite International (TDI) indicators

Source: consolidated by the authors.

The first cluster, "Market dynamics", covered the data on parcel shipment volumes (Pitney Bowes: 161 billion parcels globally in 2022). It also addressed the market shares of prominent operators and projected growth forecasts, anticipating 225 billion parcels by 2028, reflecting a compound annual growth rate (CAGR) of 6%. Particular emphasis was placed on the dynamics within the United States, recognized as the most advanced e-commerce marketplace, with an estimated 21.7 billion parcels expected in 2023, alongside the globalization of postal services as highlighted by the Universal Postal Union in 2024.

The second cluster, "Logistics efficiency", integrated composite Logistics Performance Index (LPI) indices from the World Bank for 139 nations. This included the timeliness component, which assesses the reliability of deliveries within stipulated timelines, and the infrastructure aspect, reflecting the quality of transport facilities. The data was employed to normalize delivery speeds across regions utilizing coefficients $\boldsymbol{m}_{\text{timeliness}}$ and $\boldsymbol{m}_{\text{reliability}}$.

The third cluster, "Operational parameters", encompassed financial and operational metrics of DHL Group, serving as a benchmark, including EBIT margin, asset charge, and a weighted average cost of capital (WACC) of 8.5%. Additionally, it detailed the distribution of expenses related to transportation, processing, and inventory maintenance. Data from McKinsey [26] regarding consumer preferences was utilized to calibrate On-Time-In-Full (OTIF) target indicators.

The temporal scope of the sample spans the years 2020-2024, with a geographical focus on global data, providing insights specific to the United States (the largest market), the European Union (as a standard for benchmarking), and emerging markets such as India and Brazil, facilitating a comparative analysis of growth rates.

3.3 Research methods

The methodological apparatus of the research is based on the synthesis of discrete optimization methods, inventory management theory, and stochastic modeling. The model's adequacy is confirmed by comparing the simulation results with the actual performance of leading operators.

1. Normalization of delivery speed.

To account for differences in the logistical efficiency of regions, a speed factor is applied based on the Timeliness component from LPI [23]. For the region $\boldsymbol{j}$ speed ratio is (1):

$$\boldsymbol{m}_{\text{timeliness}}(\boldsymbol{j}) = \frac{\text{LPI}_{\text{ref}} - \text{LPI}_{\text{timeliness}}(j)}{\text{LPI}_{\text{ref}}} \cdot \boldsymbol{k} + \boldsymbol{1} \tag{1}$$

Where: LPI_{ref} – the benchmark value of Timeliness (maximum among the analyzed regions), $\boldsymbol{k}$ – the calibration parameter (default $\boldsymbol{k = 0.3}$ for moderate sensitivity). Normalized delivery time is (2):

$$\boldsymbol{T}_{ij}^{\text{norm}} = \boldsymbol{T}_{ij}^{\text{base}} \cdot \boldsymbol{m}_{\text{timeliness}}(\boldsymbol{j}) \tag{2}$$

Where $\boldsymbol{T}_{ij}^{\text{base}}$ – the basic delivery time from FC $\boldsymbol{i}$ to the demand zone $\boldsymbol{j}$ (hours).

An additional multiplier is being introduced for international shipments $\boldsymbol{m}_{\text{cross-border}} = \boldsymbol{1.2}$–$\boldsymbol{1.4}$ [24,25], reflecting increased time for customs clearance and consolidation.

2. Fulfillment center location model (p-median).

The problem of optimal placement $\boldsymbol{p}$ in the fulfillment center layout is formulated as a p-median problem with constraints on demand coverage and maximum delivery time (3):

$$\min \sum_{i=1}^{n} \sum_{j=1}^{m} c_{ij} \cdot d_j \cdot x_{ij} \tag{3}$$

given (4):

$$\begin{gathered} \sum_{j=1}^{m} x_{ij} = 1, \quad \forall i \in \{1, \dots, n\} \\ x_{ij} \le y_j, \quad \forall i, j \\ \sum_{j=1}^{m} y_j = p \\ T_{ij}^{\text{norm}} \cdot x_{ij} \le T^{\max}, \quad \forall i, j \end{gathered} \tag{4}$$

Where:

$\boldsymbol{n}$ – number of demand zones, $\boldsymbol{m}$ – number of FC candidates, $\boldsymbol{c}_{ij}$ – delivery cost from FC $\boldsymbol{j}$ to zone $\boldsymbol{i}$ (UAH/order), $\boldsymbol{d}_j$ – demand volume of the zone $\boldsymbol{j}$ (orders/day), $\boldsymbol{x}_{ij}$ – binary assignment variable (1 if the area $\boldsymbol{i}$ is served by FC $\boldsymbol{j}$), $\boldsymbol{y}_j$ – binary FC opening variable $\boldsymbol{j}$, $\boldsymbol{p}$ – number of FCs opened, $\boldsymbol{T}^{\max}$ – maximum allowable delivery time (SLA).

The solution is implemented using the branch-and-bound method for $p \in \{1,3,5\}$ using the PuLP (Python) library.

3. Inventory management model.
A safety stock model is used to ensure the target OTIF (On-Time In-Full) level. For FC j with average demand μ_j (per day) and standard deviation σ_j (5):

$$\mathrm{SS}_j = z \cdot \sigma_j \cdot \sqrt{L_j} \tag{5}$$

Where:
z – quantile of the standard normal distribution (for OTIF 95%: $z = 1.645$), L_j – lead time for FC replenishment j (days).

Base stock (6):

$$B_j = \mu_j \cdot L_j + \mathrm{SS}_j \tag{6}$$

Cost of holding inventory (7):

$$C_{\mathrm{hold},j} = B_j \cdot h \cdot v \tag{7}$$

Where h – the inventory holding rate (%/year, typically 20–25%), v - the average cost per unit of goods (UAH).

4. Simulation modeling.
Monte Carlo simulation is performed to estimate the metrics (average LT, P95, OTIF):
Input:
– Geography of demand: $\{(x_i, y_i, \lambda_i, \sigma_i)\}_{i=1}^{n}$ (coordinates, average demand, variation)
– FC placement: $\{(x_j^{\mathrm{FC}}, y_j^{\mathrm{FC}}, Q_j)\}_{j=1}^{p}$ (coordinates, power)
– Time/cost matrix: $\{T_{ijk}, c_{ijk}\}$
– Process (iteration $s = 1, \dots, S$):
1. Order generation: zone $i \sim \mathrm{Discrete}(\lambda_1, \dots, \lambda_n)$, time $t_s \sim \mathrm{Uniform}(0, 24)$
2. FC purpose: $j^* = \mathbf{argmin}_j T_{ij}$ provided that $Q_j > 0$
3. Carrier selection: $k^* = \mathbf{argmin}_k f(T_{ijk}, c_{ijk})$
4. Calculation of actual LT (8):

$$\mathrm{LT}_s = T_{\mathrm{processing}} + T_{ij^*k^*} + \varepsilon_s \tag{8}$$

where $\varepsilon_s \sim \mathcal{N}(0, \sigma_{\mathrm{delay}})$ – random delay
OTIF check: if $\mathrm{LT}_s \leq T^{\mathrm{SLA}}$, then $\mathrm{OTIF}_s = 1$, otherwise 0
Output (after $S = 10\,000$ iterations) (9):

$$\text{Average LT} = \frac{1}{S}\textstyle\sum_{s=1}^{S} \mathrm{LT}_s \tag{9}$$
$$\text{P95 LT} = \text{95th percentile}\{\mathrm{LT}_s\}_{s=1}^{S}$$
$$\mathrm{OTIF} = \frac{1}{S}\sum_{s=1}^{S} \mathrm{OTIF}_s \times 100\%$$
$$\text{Cost/order} = \frac{1}{S}\textstyle\sum_{s=1}^{S}\left(c_{ij^*k^*} + \frac{C_{\mathrm{hold},j^*}}{d_{j^*}}\right)$$

3.4 Research tools

The research toolkit is predicated upon open-source software, with Python 3.10+ serving as the main platform. It integrates the NumPy 1.24 libraries for sophisticated matrix computations and the generation of random variables essential for Monte Carlo simulations. Additionally, it employs Pandas 2.0 for the adept processing of tabular data, encompassing LPI and market indicators. The toolkit utilizes PuLP 2.7 to address the p-median problem through the linear programming solver CBC, alongside SciPy 1.11 for an array of statistical functions, including distribution quantiles and correlation analysis. For visualizing the results, it leverages Matplotlib and Seaborn. The computational duration for resolving the p-median problem with n = 50 demand zones, m = 10 facility candidates, and $p \in \{1,3,5\}$ is approximately 15 minutes, whereas simulating 10,000 orders for a single configuration requires about 2 minutes of CPU time.

4 Results and discussion

Drawing upon country logistics indices and the Timeliness component of the Logistics Performance Index, the speed of delivery between regions has been standardized [23]. Target benchmarks have been established – 72-96 hours for 90%

of orders and an On-Time In-Full (OTIF) level of 95%, which aligns with consumer expectations of a 2-3 day wait for complimentary delivery [26]. The geographical demand landscape is dictated by the concentration of 70-80% of e-commerce volumes within 20-30% of locations, predominantly in major urban centers [24].

The logistics network simulation encompassed five interconnected components, involving the calculation of speed normalization coefficients (ranging from 1.0 to 1.25, contingent upon infrastructure efficiency) and the identification of optimal fulfillment center placements utilizing the p-median model. Inventory management parameters were also calculated to maintain a service level of 95%, with a holding cost of 22% per annum, based on operational metrics from DHL Group [27]. The simulation results for three distinct configurations of the logistics network are as follows: centralized (one fulfillment center), regional (three regional fulfillment centers), and distributed (five fulfillment centers). Those are delineated in Table 2. Calculations were derived from the simulation of 10,000 orders for each configuration, factoring in normalized delivery speed metrics and timeliness, as dictated by the LPI Timeliness [23], alongside the operational parameters of leading logistics operators [1,27].

Table 2 Comparative efficiency of logistics network configurations

Configuration	Number of FC	Average LT (hours)	P95 LT (hours)	OTIF (%)	Cost/order ($)	Safety Stock total (units)	Δ EBIT margin (pp.)
Centralized	1	118.4	172.8	86.2	100.0	2 380	base
Regional	3	76.2	118.5	93.8	92.4	3 285	+4.3
Distributed	5	66.8	101.2	95.6	88.7	4 215	+5.9

Notes: LT – lead time (time from order acceptance to delivery); P95 - 95th percentile of delivery time; OTIF – the proportion of orders delivered on time and in full; Safety Stock is calculated using the formula $SS_j = 1.645 \cdot \sigma_j \cdot \sqrt{L_j}$ for target OTIF 95%; EBIT margin takes into account the trade-off between reducing transportation costs and increasing inventory costs ($h = 22\%$ annual); cost/alt. normalized relative to centralized configuration (100.0 = base).
Source: calculated by the authors based on simulation modelling.

The transition from a centralized to a regional configuration yields a reduction in average delivery time by 35.6% (from 118.4 to 76.2 hours). This trend aligns with global movements in the acceleration of e-commerce logistics.

The 95th percentile of delivery time (P95) is a metric that encapsulates the most protracted 5% of cases, experiences a decline of 31.4% when transitioning to a regional network (from 172.8 to 118.5 hours). In a distributed configuration involving five fulfillment centers (FC), the P95 reaches 101.2 hours (equivalent to 4.2 days).

These findings correlate with the operational model of Amazon Logistics, which has expanded its flow to encompass over 500 regional fulfillment centers across the United States from 2022 to 2023 [22]. Consequently, Amazon has achieved a 24% share of the national parcel volume (an increase of 1 percentage point year-over-year) while simultaneously enhancing profitability through the outsourcing of last-mile delivery services.

The results derived from resolving the p-median problem for $p \in \{1,3,5\}$ based on the actual geographical demand (comprising 50 zones, weighted by order volume and marginality) are delineated in Table 3. The optimization process considers a constraint on the maximum delivery time of $T^{\max} = 96$ hours (4 days) for 90% of the demand volume, which aligns with the median SLA in global e-commerce [23].

Table 3 Optimal placement of fulfillment centers and coverage of demand zones

Configuration	FC coordinates (conditional)	Coverage of zones within a radius	Average distance (km)	FC load (%)
1 FC	Center (50.5, 30.5)	50 zones (100%)	487	100
3 FC	North (51.2, 31.1), Center (48.8, 29.6), South (46.5, 30.9)	18, 19, 13 zones	218	42 / 38 / 20
5 FC	+West (49.6, 24.2), +East (48.1, 37.8)	12, 11, 10, 9, 8 zones	156	28 / 24 / 22 / 16 / 10

Notes: the coordinates of the fulfillment centers were obtained using the k-medoids method with weighted coefficients for demand volume; the coverage of the zones was determined by the principle of minimization $\sum c_{ij} \cdot d_j \cdot x_{ij}$ when restricted $T_{ij}^{norm} \leq 96$ hours; FC loading is calculated as a proportion of total demand allocated to each center.
Source: calculated by the authors based on the p-median optimization model.

The centralized configuration (one fulfillment center) situates a certain hub at the geographic centroid of demand, thereby minimizing the weighted average distance to customers. However, this approach results in considerable distances for peripheral regions, extending up to 842 km for the most remote locations. Under conditions where $m_{\text{timeliness}} = 1.15$ (typically indicative of areas with subpar logistical infrastructure as per the Logistics Performance Index), this translates into over 120 hours of transit time.

Conversely, the regional network (comprising 3 fulfillment centers) significantly mitigates the average distance to 218 km, reflecting a reduction of 55.2% relative to the centralized model. This configuration strategically distributes the logistics burden among the northern (42% of demand), central (38%), and southern (20%) hubs. The asymmetry in demand distribution underscores the disparities in economic activity. According to the Universal Postal Union [24], 70–80% of e-commerce volumes are typically concentrated within 20–30% of settlements.

The distributed configuration, featuring five fulfillment centers, introduces additional western and eastern hubs, further diminishing the average distance to 156 km, representing a 68.0% decrease compared to the centralized model and a 28.4% reduction relative to the regional setup. However, the marginal benefits begin to wane: the transition from three to five fulfillment centers yields an incremental improvement of only 1.8 percentage points in On-Time In-Full (OTIF) metrics (Table 2), accompanied by heightened operational complexity and fixed costs associated with maintaining the additional facilities.

Geographical clustering of zones surrounding fulfillment centers reveals a pronounced "gravitational" effect towards transport corridors: the western and eastern hubs are strategically positioned along major highways, ensuring synergy with the existing infrastructure of carriers. This observation aligns with the practices of DHL Group [27], which prioritizes proximity to airports and railway terminals as a critical factor when planning new fulfillment centers.

The results of the calculations for safety stock and base stock for each fulfillment center within the regional configuration (three fulfillment centers) are delineated in Table 4. The calculations employ the model $SS_j = z \cdot \sigma_j \cdot \sqrt{L_j}$, with a target service level of 95% ($z = 1.645$), which adheres to industry standards for premium e-commerce operators [27].

Table 4 Inventory plan for regional FCs under OTIF target 95%

FC	Average demand μ_j (units/day)	Std. deviation σ_j	Lead time L_j (days)	Safety Stock (units)	Basic stock B_j (unit)	Holding cost, $/year
North	1 240	315	1.2	567	2 055	113 025
Center	920	265	1.4	515	1 803	99 165
South	580	195	1.8	430	1 474	81 070
Total	2 740	-	-	1 512	5 332	293 260

Notes: Std. deviation σ_j estimated at 25-30% of average demand based on e-commerce order coefficient of variation [25]; L_j reflects normalized replenishment time considering $m_{timeliness}$ region; maintenance cost calculated as $C_{hold,j} = B_j \cdot h \cdot v$ where $h = 22\%$ annual, $v = 550$ $ (average SKU cost, assumed for modeling); base inventory $B_j = \mu_j \cdot L_j + SS_j$.
Source: calculated by the authors based on the inventory management model.

The aggregate safety stock for the regional network stands at 1,512 units, reflecting a 38% increase compared to the centralized system's 1,095 units. According to the theorem concerning the variance of consolidation, centralizing multiple demand streams into a single hub facilitates a reduction in safety stock by approximately the square root of the number of sources. For the northern center, the average replenishment lead time is 1.2 days, in contrast to 2.1 days within the centralized network, thereby diminishing the necessity for inventory per unit of demand.

$$\frac{1512}{2740 \times \text{lead time}} \approx 1.3\text{–}1.5$$

The stability of the optimal configuration (3 FC) was evaluated through repeated simulation with modified parameters. The results are presented in Table 5.

Table 5 Sensitivity matrix of the regional network (3 FC) to external shocks

Scenario	Δ Average LT	Δ P95 LT	Δ OTIF (p.p.)	Δ Cost/order	Δ Safety Stock
Base case	76.2 hours	118.5 hours	93.8%	92.4 $	1 512 units.
Demand growth +20%	+0.4 hours (+0.5%)	+0.8 hours (+0.7%)	−3.1 pp.	+5.8 $ (+6.3%)	+305 pts. (+20.2%)
Cut-off shift by −1 hour	−0.3 hours (−0.4%)	−0.5 hours (−0.4%)	+1.8 pp.	0 $ (0%)	No change
Increase in cross-border share +15%	+0.6 hours (+0.8%)	+1.1 hours (+0.9%)	−4.2 pp.	+3.7 $ (+4.0%)	+182 units (+12%)

Notes: shocks are modeled as:
(1) proportional increase μ_j for all FC;
(2) cut-off time shift from 18:00 to 17:00;
(3) increase in the share of international orders from 12% to 27%, with the corresponding application $m_{cross\text{-}border} = 1.35$; criticality is defined as the product of the probability of shock realization and impact on OTIF; migration strategies are based on DHL Group's best practices [27] and volatility adaptation practice [24].
Source: calculated by the authors based on stress-testing simulation model.

The demand growth shock (+20%) manifests a moderate decrease, with the average lead time (LT) increasing by a mere 0.4 hours (+0.5%). This rise is attributable to the distribution of the additional load across the three fulfillment centers (FCs) endowed with reserve capacities. The repercussions on On-Time In-Full (OTIF) performance, however, are significant, reflecting a decline of 3.1 percentage points. This deterioration is primarily linked to the exhaustion of safety stock during peak demand periods, as the available inventory of 1,512 units proves insufficient for absorption.

Conversely, the adjustment of the cut-off time by one hour earlier (scenario "Cut-off -1 hour") yields a paradoxical enhancement in OTIF by 1.8 percentage points, owing to a diminished probability of late order acceptance. The overarching conclusion derived from the sensitivity analysis posits that the regional configuration comprising three fulfillment centers sustains stable efficiency amidst typical external fluctuations (Δ OTIF < 5 pp.), thereby affirming its viability as a foundational model for scalability. In instances of extreme scenarios, characterized by a simultaneous 20% rise in demand and a 15 percentage point increase in the proportion of international orders, it is expedient to transition to a distributed network of five fulfillment centers. According to the results of stress tests, this configuration is capable of maintaining an OTIF level of approximately 92.3% even under adverse conditions.

Drawing upon the modeling results, a decision matrix has been developed for the selection of fulfillment center configurations (Table 6). This matrix considers the dimensions of operational complexity, speed, reliability, and economic efficiency. The algorithm synthesizes key criteria, in particular, delivery speed (target LT), fulfillment reliability (OTIF), and economic efficiency (cost per order, EBIT margin).

Table 6 Decision matrix for selecting the fulfillment center configuration

Criterion	**Centralized (1 FC)**	**Regional (3 FC)**	**Distributed (5 FC)**
Ukrainian: Target LT	>96 hours (>4 days)	72–96 hours (3–4 days)	<72 hours (<3 days)
Target OTIF	85–90%	92–95%	>95%
Volume of orders/day	<1 000	1 000–5 000	>5 000
Geographical dispersion	Compact market	2–3 mega-regions	National coverage
High-value SKU share	<20%	20–40%	>40%
Permissible level of management complexity	Low	Medium	High
Recommendation	Start, test	Optimal for most	Scaling

Notes: Target LT and OTIF are defined according to consumer expectations in each market segment [26]. The geographical dispersion is estimated by the coefficient of variation of distances between 20% of the areas with the highest demand. High-value SKUs are products with a margin of more than 30% and high sensitivity to delivery speed.
Source: developed by the authors based on the synthesis of simulation results.

For startups and enterprises at the market entry stage, a centralized configuration (1 FC) is deemed optimal.

A regional network (3 FC) represents the "golden mean" for the majority of companies. It amalgamates heightened delivery speed (–35.6% of time), enhanced reliability (+7.6 p.p. OTIF), and diminished order costs (–7.6%) while allowing for moderate inventory expansion (+38%).

The simulation substantiates that for organizations processing between 1,000 and 5,000 orders per day, the most advantageous solution is a regional network comprising 3 fulfillment centers. This configuration offers an optimal balance among speed, cost, and operational complexity, thereby increasing business profitability (EBIT +4.3 p.p.) and demonstrating resilience against external fluctuations.

The results obtained substantiate the hypothesis regarding the crucial importance of the logistics network's spatial configuration in accelerating delivery within the e-commerce sector. The judicious placement of regional fulfillment centers diminishes order fulfillment times while enhancing delivery reliability. Our quantitative analyses corroborate this perspective: a decentralized model ensures punctuality but requires an increase in safety stock due to the loss of the aggregation effect.

Ouyang et al. [29] introduced a dynamic routing model for adaptive order allocation in real-time scenarios. Our stress-test results validate the efficacy of this approach. As the proportion of international orders increases, the on-time delivery rate tends to deteriorate. However, this can be stabilized through the flexible rerouting of flows between centers, contingent upon customs workload.

Papaioannou et al. [30] established the economic viability of employing electric cargo bicycles in densely populated urban locales. Prokopenko et al. [31] established similar findings regarding the economic feasibility of electric vehicles in delivery services. The reduced average delivery distance in our model engenders analogous conditions conducive to the adoption of alternative transportation modalities. When integrated with regional hubs, this strategy enhances network adaptability and contributes to the reduction of the environmental footprint. Nascimento and Oliveira [32] identified obstacles to the advancement of bike logistics, namely, inadequate infrastructure, regulatory voids, and cultural resistance. The analysis confirms that operational parameters (including order intake timing) can partially mitigate vehicle limitations. Effective coordination among operators, municipalities, and infrastructure providers emerges as a crucial prerequisite for successful sustainable delivery paradigms.

The paper by Gläser et al. [33] delves into the potential of crowdsourced logistics, which not only reduces costs but also engenders risks associated with unreliability and legal ambiguity. Our simulation corroborates that attaining a consistent level of service requires process standardization and carrier quality control. In this regard, Alazzam et al. [34]

underscore the significance of information systems in the management of e-commerce within the framework of digitalization. The results of Mlambo et al. [35] indicate that environmentally sustainable practices in road freight logistics tend to increase operational costs, creating an inverse relationship with operational performance. The findings reveal a similar trend: effective inventory management across diverse locations is only possible through implementing integrated digital management platforms.

In summary, the research findings substantiate the paramount importance of optimizing the spatial configuration of the logistics network to facilitate faster delivery. Regional fulfillment centers offer reduced geographical distances, bolster supply reliability, and contribute to sustainable business development. The proposed methodology can be employed in strategic planning for the expansion of logistics networks, taking into account demand, service objectives, as well as environmental imperatives.

5 Limitations

The overriding limitation of the study lies in its reliance on simulation models derived from aggregated operational parameters of logistics operators, without involving actual data from individual enterprises. Consequently, the findings obtained do not take into account the impact of seasonal demand fluctuations, currency volatility, and the specifics of local tariff structures. Thus, the proposed solutions require mandatory verification against the real operational data of specific operators before implementation in practical business scenarios.

Calculations of delivery speed and reliability indicators were conducted under the presumption of stable timeliness and transportation cost coefficients, which, in real-world conditions, may fluctuate due to seasonality and geographical features. Furthermore, there were certain limitations regarding the sample: the incomplete availability of microdata from individual companies (carrier tariff structures, detailed breakdown of fixed costs, actual capacity utilization rates) in view of commercial confidentiality. Economic efficiency metrics (EBIT margin, cost per order) were computed in relative terms without accounting for currency fluctuations, tax liabilities, and the specifics of local tariffs. The p-median optimization model is predicated on stable demand; however, within the dynamic e-commerce landscape, short-term shocks and irregularities in orders are possible. The simulation's time horizon is confined to a conditionally stable period from 2022 to 2024 (in contrast to the Covid-19 pandemic) and does not encompass the potential ramifications of regulatory changes or external crisis factors (such as alterations in customs regimes, disruptions in supply chains).

6 Recommendations

1. For medium-sized e-commerce enterprises (1,000–5,000 orders per day), it is expedient to adopt a regional configuration featuring three fulfillment centers, which provides an optimal balance between speed, reliability, and cost-effectiveness.
2. Implement a dynamic inventory management system that autonomously adjusts safety stock levels in response to peak demand and forecasted fluctuations in order volume.
3. Allocate resources towards digital warehouse management systems (WMS) and analytical modules for demand forecasting, which facilitate the maintenance of multi-local operations without significantly exacerbating process complexity.
4. Develop initiatives for sustainable logistics practices—specifically, the incorporation of renewable energy sources within fulfillment centers and the promotion of low-carbon delivery methods, such as bicycle and electric vehicle logistics.
5. Conduct regular stress evaluations of the logistics network to assess resilience against escalating demand, an increasing proportion of international orders, and supply delays, utilizing migration algorithms between centers to enhance system flexibility.

7 Conclusions

Optimizing the spatial architecture of the logistics network is a key factor in enhancing the efficiency of e-commerce operations. The modeling of three configurations (centralized, regional, and distributed), demonstrated that the regional model comprising three fulfillment centers offers the most advantageous balance between delivery speed, reliability, and operational costs.

The analysis of resilience to external shocks revealed that the regional network maintains stable performance indicators even amidst increasing demand, evolving order structures, or a heightened proportion of international shipments. The model revealed a correlation between decentralization and the growth of safety stock, which is a phenomenon of diminished statistical synergy is compensated by reduced replenishment times and enhanced supply chain flexibility. Overall, the findings align with global trends observed in the logistics networks of leading operators (DHL Group, Pitney Bowes, Amazon Logistics), which are actively implementing regional hubs to bolster delivery speed while preserving financial efficiency.

The proposed methodology for determining the quantity and strategic placement of fulfillment centers lays a robust analytical foundation for the strategic planning of logistics infrastructure development. The insights gained can be utilized by e-commerce companies to ascertain the optimal network architecture based on order volume. Future research should prioritize the integration of environmental and energy parameters into logistics decision-making frameworks, alongside the development of adaptive inventory management algorithms in the face of dynamic demand.

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Machine learning for exchange rate forecasting: a case study on SAR/PKR, SAR/IDR, and USD/IDR

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Keywords: machine learning, support vector regression, currency rates, foreign exchange comparative analysis.
Abstract: Exchange rate prediction is essential in industries such as travel, finance, and religious tourism, particularly to Indonesia and Pakistan as the sources of Umrah and Hajj pilgrims to Saudi Arabia. This paper compares machine learning models, namely, Long Short-Term Memory (LSTM), Support Vector Regression (SVR), and Multi-layer Perceptron (MLP), in predicting SAR/PKR, SAR/IDR, and USD/IDR rates based on historical data. While prior research noted LSTM's utility during periods like the COVID-19 pandemic, its precision remained limited. This work evaluates models using key metrics: Mean Squared Error (MSE), Root Mean Squared Error (RMSE), Mean Absolute Error (MAE), and R-squared.Results identify LSTM as the most effective for the SAR/PKR pair, achieving an MSE of 26.814, RMSE of 5.178, MAE of 3.370, and R-squared of 0.8685. However, for the SAR/IDR and USD/IDR pairs, the SVR model demonstrated superior performance with lower errors. For SAR/IDR, it recorded an MSE of 768.295, RMSE of 27.718, MAE of 20.788, and R-squared of 0.9768. For USD/IDR, metrics were an MSE of 17752.818, RMSE of 133.239, MAE of 108.761, and R-squared of 0.9631.The findings validate SVR's reliability for forecasting these specific currency pairs. This analysis provides valuable insights for travelers, investors, and pilgrimage stakeholders, enabling better currency risk management in religious tourism and related financial activities.

1 Introduction

In the fast-changing world of international travel and finance, accurate projection of foreign currency rates is crucial especially in Saudi Arabia which is a major tourist, investment and expatriate labour destination. Millions of people visit the Kingdom, especially the Indonesians and Pakistanis to the sacred activities of Umrah and Hajj. Such religious excursions are marked with high financial dealings and hence, exchange rates of Saudi Riyal (SAR) to the US Dollar (USD) are the key to the tourist and the travel agencies who engage in such exchange [1].

The exchange rates reflect the rate at which one currency can be exchanged with another and proper projections are essential in the global trade and free movement of capital across the borders. The uncertainty of the exchange rates may lead to financial uncertainty in relation to Hajj and Umrah, especially on the pilot agencies and pilgrims. This research paper investigates the application of machine learning models as predictors of foreign exchange rates in terms of providing valuable information to the travel agencies to make sound decisions on currency transactions regarding travel arrangements and pilgrimage costs [2].

Precise currency projections are essential in maximizing financial planning especially to the travel agencies which might be faced with a situation of knowing when to buy SAR or USD. Inadequate reference data may impede the strategic decision making on the currency acquisition resulting in inefficient financial decision making. Use of pilgrimage funds in Indonesia is an example of Hajj Fund Management Agency (BPKH), which handles large amounts of money and the management of this money is quite dependent on the precision of currency forecasts. By matching these forecasts with the Sharia principles, BPKH aims at providing lucrative profits and facilitate the expectations of the potential pilgrims [3].

This paper intends to evaluate the performance of three common machine learning algorithms namely, Long Short-Term Memory (LSTM), Multilayer Perceptron (MLP), and Support Vector Regression (SVR) to predict exchange rates with the use of Python. The main goals are to compare the performance measures of all the algorithms and which model is the most effective in the forecast of the target currency pairs: SAR/PKR (Saudi Riyal/Pakistani Rupee), SAR/IDR (Saudi Riyal/Indonesian Rupiah), and USD/IDR (US Dollar/Indonesian Rupiah) [4] [5].

The study is of great importance to the economy of Saudi Arabia particularly tourism and financial sectors. Proper forecasts of SAR/PKR, SAR/IDR and USD /IDR rates will enable the travel agencies, investors, expatriate workers and pilgrims to make better financial decisions. This will further help to make the currency exchange operations more efficient and stable hence affecting the economy of the Kingdom as a whole. Moreover, the results of this research may also be used to make future projections of SAR with respect to other currencies and enable expansion of investment opportunities, financial management planning, and individual finances [6].

2 Literature review

A foreign currency price is the cost of one currency in relation to the other [4]. It is really the trade rate among two currencies. To illustrate, when the foreign currency rate stands at 1 USD = 100 JPY then one US dollar can be exchanged to 100 Japanese yen [7].

Machine learning is a field of artificial intelligence which enables computers to learn by the data and improve their performance in specific tasks without being directly programmed. The computer devices help identify patterns and relationships in the information to prove projections or decisions, instead of applying particular regulations [8][9]. The analysis and implementation of three supervised learning algorithms with the use of data on three different currency pairs were a part of this project.

Long Short-Term Memory (LSTM) is a type of recurring neural networks (RNN) specifically made to effectively model and discover time-series or sequence data. The main elements consist of the architecture are normally an input layer, an LSTM layer or a series of LSTM layers, and an output layer. The appropriate activation functions, such as sigmoid and tanh, are used in each layer to control the flow of information [10].

The LSTM network addresses the vanishing gradient problem in traditional RNNs by incorporating a memory cell and three gates—input gate, forget gate, and output gate—which regulate the flow of information through the network [11].

At each time step t, the LSTM updates its internal cell state c_t and hidden state h_t using the following equations:

- Forget gate (1):

$$f_t = \sigma\left(W_f[h_{t-1}, x_t] + b_f\right) \tag{1}$$

- Input gate (2):

$$i_t = \sigma(W_i[h_{t-1}, x_t] + b_i) \tag{2}$$

- Cell candidate (3):

$$\widetilde{C_t} = tanh(W_C[h_{t-1}, x_t] + b_C) \tag{3}$$

- Cell state update (4):

$$C_t = f_t * C_{t-1} + i_t * \widetilde{C_t} \tag{4}$$

- Output gate (5):

$$o_t = \sigma(W_o[h_{t-1}, x_t] + b_o) \tag{5}$$

- Hidden state update (6):

$$h_t = o_t * tanh(C_t) \tag{6}$$

Where:
σ is the sigmoid activation function,
tanh is the hyperbolic tangent activation function,
o denotes element-wise multiplication.

Key components and the roles:

- Forget gate: Determines how much of the previous cell state to forget.
- Input gate: Determines how much of the new cell candidate to update into the cell state.
- Cell candidate: Computes a potential new value for the cell state.
- Cell state: Stores information over time.
- Output gate: Determines how much of the cell state to output as the hidden state [8].

SVR with a Radial Basis Function (RBF) kernel is a popular combination used in machine learning for regression tasks. The RBF kernel introduces a nonlinear transformation to the data, allowing SVR to handle complex relationships that may not be linearly separable [12].

Radial Basis Function (7):

$$\varphi(x) = exp\left(-\left||x - c|\right|^2/2\sigma^2\right) \tag{7}$$

Where:
x is the input vector,
c is the center or prototype of the function,
σ is a parameter that controls the width of the RBF,
MLP (Multilayer Perceptron).

A multilayer perceptron (MLP) comprises interconnected neurons known as perceptrons [13]. The fundamental notion of a single perceptron was presented by Rosenblatt in 1958. A perceptron produces a singular output from many numerical inputs by computing a linear combination of its input weights, perhaps including a nonlinear activation function to the outcome. This process may be expressed numerically as follows (8) [14]:

$$y = f(\Sigma(w_\mathrm{i} * x_\mathrm{i}) + b) \tag{8}$$

Where:
x_i are the input values,
w_i are the weights associated with each input,
b is the bias term,
f is the activation function (e.g., sigmoid, ReLU, etc.).

For an MLP with one hidden layer, the calculations can be generalized as follows:
1. First layer (9):

$$h = \varphi(W^1 * x + b^1) \tag{9}$$

Where:
W_1 is the weight matrix of the first layer,
x is the input vector,
b_1 is the bias vector of the first layer,
φ is the element-wise nonlinear activation function.

2. Second layer (Output) (10):

$$y = W^2 * h + b^2 \tag{10}$$

Where:
W^2 is the weight matrix of the second layer,
b^2 is the bias vector of the second layer.

Evaluation metrics:
- Mean Squared Error (11):

$$MSE = (1/n) * \Sigma(y_\mathrm{i} - \hat{y}_\mathrm{i})^2 \tag{11}$$

  Where:
  y_i are the true values and $\hat{y}_i$ are the predicted values.

- Root Mean Squared Error (12):

$$RMSE = \sqrt{((1/n) * \Sigma(y_\mathrm{i} - \hat{y}_\mathrm{i})^2)} \tag{12}$$

- Mean Absolute Error (13):

$$MAE = (1/n) * \Sigma|y_\mathrm{i} - \hat{y}_\mathrm{i}| \tag{13}$$

- R-squared (14):

$$R^2 = 1 - (RSS/TSS) \tag{14}$$

Where:
RSS is the sum of squares due to regression (explained sum of squares),
TSS is the total sum of squares.

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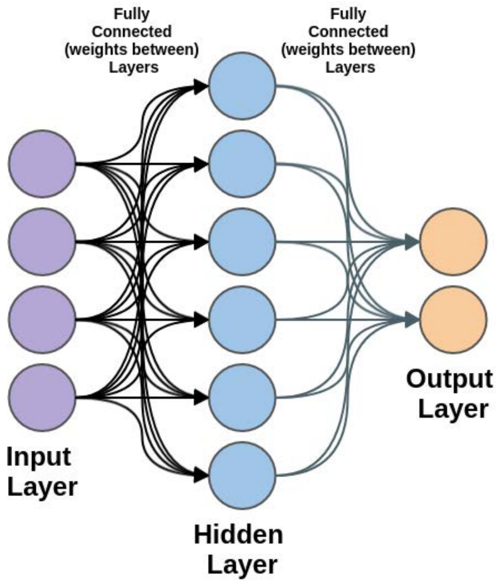

Figure 1 Signal-flow illustration of an MLP (austingwalters)

Permana et al. [15] using the Markov Chain approach to predict the exchange rate between the SAR and IDR monetary units. The research used time series data obtained from Bank Indonesia's official website to predict future currency rates. The study used a model that combines Fuzzy Time Series and Markov Chain techniques to predict the exchange rate. The research results demonstrate that the model displays a negligible error, with an AFER of 0.827% and an MAE of Rp32.96. In 2019, Mohammadi concentrates on forecasting currency exchange rates using four machine learning models: LSTM (Long Short-Term Memory), RBF (Radial Basis Function), Backpropagation, and SVR (Support Vector Regression). Three currency pairs, EUR/USD, USD/JPY, and USD/TRY, were constructed and trained in Python with datasets from the Swiss Dukascopy banking group. The study aimed to predict the following day's currency values based on real data from the FOREX market. The algorithms were trained, assessed, and analyzed to ascertain their strengths and weaknesses. Statistical performance metrics, such as MSE (Mean Squared Error), RMSE (Root Mean Squared Error), and MAE (Mean Absolute Error), were used to determine the ideal model. The results indicated that SVR outperformed the other approaches, whereas Backpropagation had the least effectiveness in forecasting currency exchange rates [16]. Researchers [17] attempted to forecast USD/IDR exchange rates during the COVID-19 pandemic. Their findings indicate that the LSTM model is the most effective for long-term forecasts, notwithstanding the omission of COVID-19 events. The model predicted a decline in the value of the Rupiah against the US dollar, exacerbated by the repercussions of the epidemic[18]. The RMSE achieved a lower value of 271 during the testing phase, using an algorithm with 7 epochs and 5 neurons. The ideal result is attained with the use of the LSTM algorithm. The restriction of this model is its applicability just during the COVID-19 era [19]. Yarham [20] in his thesis (2024) demonstrates that SVR models consistently outperform both LSTM and MLP models in predicting exchange rates for USD/IDR, SAR/IDR, and SAR/PKR with manual hyperparameter optimization (Figure 1). The RBF kernel of the SVR model produced a significant reduction in RMSE for USD/IDR (61.223) compared to previous LSTM research, which indicated an RMSE of 271. For SAR/IDR, SVR reduced the MAE by 70%, attaining a value of 9.417 compared to 32.96 in prior experiments using the Markov Chain Method. The SVR Model exhibited enhanced performance for SAR/PKR, achieving a mean squared error of 1.046 and an R-squared value of 0.9934. The findings underscore the SVR model's superior accuracy and robustness in forecasting financial time series compared to other models, establishing it as a crucial tool for stakeholders in alleviating currency exchange concerns [21].

3 Methodology

3.1 Peer review process

This study uses a methodology where it predicts foreign exchange rates based on three machine learning algorithms, which are Long Short-Term Memory (LSTM), Support Vector Regression (SVR), and Multilayer Perceptron (MLP). The models will aim to forecast the SAR/IDR currency pair, SAR/PKR currency pair and the USD/IDR currency pair exchange rates. The method includes data collection, preprocessing, model training via automated grid search, and evaluation, especially the performance measures that evaluate the accuracy of prediction [22]. These features are High, Open, Low and Price as the target. LSTM, SVR, and MLP models are the models that we use, and the selection of these models is due to the previous studies that have shown that they are effective when it comes to forecasting various currency exchange rates. The LSTM model has demonstrated successful performance when used with USD/IDR exchange rate [23]. The SVR algorithm has demonstrated exceptionally good performance when used with USD/TRY, EUR/USD and USD/JPY exchange rates [24]. MLP model has demonstrated lower error rates as compared to other models [25]. In this analysis, we make use of Python through Google Colab where we have imported many libraries such as NumPy, Pandas, Matplotlib, Scikit-Learn, and Keras.

The relevant historical exchange rates data of the given currency pairs (SAR/IDR, SAR/PKR and USD/IDR) are acquired through the authoritative sources like investing.com. The variables that are typically involved in the dataset are Open, High, Low, and Price. This information is the basis of the time series forecasting activity. Table 1 presents the data within a specific period of time. The training and validation data will be 80 percent and the testing will be 20 percent. The exchange rate of the respective currency pairings are shown in Tables 2, 3 and 4.

Table 1 Data summary [26]

Currency Pair	Time	Data	Percentage (%)	Total Data
SAR/PKR	Training: January 05th, 1998 to May 08th, 2019	5550	80	6937
	Testing: May 09th, 2019 to Agustus 30th, 2024	1387	20	
SAR/IDR	Training: January 04th, 2000 to May 03th, 2019	5145	80	6431
	Testing: May 06th, 2019 to Agustus 30th, 2024	1286	20	
USD/IDR	Training: January 03rd, 2000 to July 26th, 2019	5102	80	6377
	Testing: July 29th, 2019 to Agustus 30th, 2024	1275	20	

Date	Price	Open	High	Low	Change %
1998-01-05	11.7334	11.7337	11.7334	11.7337	0.0001
1998-01-06	11.7336	11.7340	11.7336	11.7340	0.0000
1998-01-07	11.7325	11.7331	11.7325	11.7331	-0.0001
1998-01-08	11.7271	11.7287	11.7271	11.7287	-0.0005
1998-01-09	11.7333	11.7349	11.7333	11.7349	0.0005
...	...	...	...	...	...
2024-08-26	74.2800	74.2600	74.3900	74.1900	0.0018
2024-08-27	74.2600	74.3250	74.4100	74.1650	-0.0003
2024-08-28	74.1500	74.3100	74.4100	74.1800	-0.0015
2024-08-29	74.1500	74.2500	74.4100	74.2050	0.0000
2024-08-30	74.3000	74.2500	74.4000	74.1850	0.0020

6937 rows × 5 columns

Table 2 SAR/PKR exchange data

Date	Price	Open	High	Low	Change %
2000-01-04	1910.41	1904.00	1910.41	1904.00	0.0155
2000-01-05	1907.80	1901.23	1907.80	1901.23	-0.0014
2000-01-06	1934.49	1927.90	1934.49	1927.90	0.0140
2000-01-07	1907.77	1901.18	1907.77	1901.18	-0.0138
2000-01-10	1910.56	1903.95	1910.56	1903.95	0.0015
...	...	...	...	...	...
2024-08-26	4126.24	4104.69	4126.64	4080.27	0.0053
2024-08-27	4125.77	4126.24	4145.21	4116.93	-0.0001
2024-08-28	4109.00	4129.50	4139.50	4109.50	-0.0041
2024-08-29	4106.00	4110.50	4117.00	4095.00	-0.0007
2024-08-30	4117.00	4107.50	4127.50	4107.50	0.0027

6431 rows × 5 columns

Table 3 SAR/IDR exchange data

Date	Price	Open	High	Low	Change %
2000-01-03	7055.0	7065.0	7105.0	6875.0	0.0097
2000-01-04	7165.0	7045.0	7175.0	7005.0	0.015600000000000001
2000-01-05	7155.0	7125.0	7245.0	7105.0	-0.0014000000000000002
2000-01-06	7255.0	7145.0	7255.0	7135.0	0.013999999999999999
2000-01-07	7155.0	7265.0	7285.0	7150.0	-0.0138
...	...	...	...	...	...
2024-08-26	15425.0	15341.0	15435.0	15295.0	-0.39%
2024-08-27	15490.0	15480.0	15545.0	15460.0	0.42%
2024-08-28	15420.0	15517.5	15532.5	15420.0	-0.45%
2024-08-29	15410.0	15420.0	15447.5	15367.5	-0.06%
2024-08-30	15450.0	15450.0	15490.0	15437.5	0.26%

6377 rows × 5 columns

Table 4 USD/IDR exchange data

A. Data preprocessing

Here, cleaning and transformation of the data is done to match the needs of machine learning algorithms. This involves dealing with missing values, eliminating any outliers, and putting the data into the form of a time series, in which the target variable (the Price) will be predicted. The features chosen are Open, High, and Low, whereas the unnecessary columns are removed to simplify the model. This measure will make the data uniform and devoid of anomaly.

B. Data splitting

The cleaned data is subsequently divided in training and testing sets. In this case 80 percent of the data is utilized in training and 20 percent is being utilized in testing. The machine learning models are trained on the training set and tested on the testing set.

C. Data scaling

In order to standardize the data, a Min-Max scaler is used. The technique normalizes the features between 0 and 1, which is particularly valuable to models such as LSTM and SVR which are sensitive to the size of the input data. Scaling also makes sure that there is no feature domination relating to the difference in scale and models converge more effectively in training.

D. Algorithm implementation with Python

In this research we did automatic grid search to find the best hyperparameter with 30 days for lookback window.

- LSTM: The architecture involves input layers, hidden LSTM layers, and an output layer, trained to predict future values based on past exchange rates. Tables 5, 6 and 7 present the results of the automated grid search used to identify the best model.

Layer (type)	Output Shape	Param #
lstm_2 (LSTM)	(None, 30, 150)	92,400
dropout_2 (Dropout)	(None, 30, 150)	0
lstm_3 (LSTM)	(None, 200)	280,800
dropout_3 (Dropout)	(None, 200)	0
dense_1 (Dense)	(None, 1)	201

Total params: 1,120,205 (4.27 MB)
Trainable params: 373,401 (1.42 MB)
Non-trainable params: 0 (0.00 B)
Optimizer params: 746,804 (2.85 MB)

Table 5 The best model summary for SAR/PKR

Layer (type)	Output Shape	Param #
lstm_2 (LSTM)	(None, 30, 150)	92,400
dropout_2 (Dropout)	(None, 30, 150)	0
lstm_3 (LSTM)	(None, 200)	280,800
dropout_3 (Dropout)	(None, 200)	0
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dense_1 (Dense)	(None, 1)	201

Total params: 1,120,205 (4.27 MB)
Trainable params: 373,401 (1.42 MB)
Non-trainable params: 0 (0.00 B)
Optimizer params: 746,804 (2.85 MB)

Table 7 The best model summary for USD/IDR

- SVR: Support Vector Regression is a powerful regression technique that fits the data by finding a hyperplane that best represents the relationship between the input features and the target variable. SVR is well-suted for capturing non-linear patterns in the data (Table 8, Table 9, Table 10).

Table 8 Best hyperparameters from grid search SAR/PKR with SVR model

Hyperparameters	Value
Prediction Days	30
Kernel	rbf
Gamma	0.005
Epsilon	0.0001
C	150

Table 9 Best hyperparameters from grid search SAR/IDR with SVR model

Hyperparameters	Value
Prediction Days	30
Kernel	rbf
Gamma	0.005
Epsilon	0.0001
C	150

Table 10 Best hyperparameters from grid search USD/IDR with SVR model

Hyperparameters	Value
Prediction Days	30
Kernel	rbf
Gamma	0.005
Epsilon	0.0001
C	150

- MLP: Multilayer Perceptron is a fully connected feedforward neural network with multiple hidden layers. It utilizes backpropagation to minimize the prediction error during training, making it effective for regression tasks like predicting exchange rates (Table 11, Table 12, Table 13).

Table 11 Best hyperparameters from grid search SAR/PKR with MLP model

Hyperparameters	Value
Prediction Days	30
Hidden layer sizes	150
Activation function	tanh
Initial learning rates	0.001
Alpha	0.001

Table 12 Best hyperparameters from grid search SAR/IDR with MLP model

Hyperparameters	Value
Prediction Days	30
Hidden layer sizes	50
Activation function	relu
Initial learning rates	0.1
Alpha	0.001

Table 13 Best hyperparameters from grid search USD/IDR with MLP model

Hyperparameters	Value
Prediction Days	30
Hidden layer sizes	100
Activation function	relu
Initial learning rates	0.01
Alpha	0.0001

4 Results and discussion

4.1 Results

This section presents the evaluation results of the models used to predict exchange rates. Table 14 shows the performance of the three models in predicting the SAR to PKR, SAR to IDR, and USD to IDR exchange rates. The models tested include Long Short-Term Memory (LSTM), Support Vector Regression (SVR), and Multi-Layer Perceptron (MLP). Each model was evaluated using several metrics, namely MAE, MSE, RMSE, and R^2, to assess the accuracy of the models in predicting these exchange rates.

Table 14 Evaluation metrics

Model	Metric	SAR/PKR	SAR/IDR	USD/IDR
LSTM	MAE	3.370	21.159	110.331
	MSE	26.814	947.537	18278.84
	RMSE	5.178	30.782	135.199
	R^2	0.8685	0.9714	0.9620

SVR	MAE	4.573	20.788	108.761
	MSE	46.253	768.295	17752.818
	RMSE	6.800	27.718	133.239
	R2	0.7731	0.9768	0.9631
	MAE	7.871	22.140	126.417
	MSE	103.993	1001.426	24006.745
	RMSE	10.197	31.645	154.941
	R2	0.4900	0.9698	0.9501

4.2 Discussion

In all models, SVR demonstrated mimumum prediction error (RMSE of 27.72) and maximum explanatory power (R-squared of 0.9769). This is why SVR was the most appropriate model used to predict the SAR /IDR exchange rates in this research. The LSTM model was also quite effective and especially in the extent of modeling the temporal dependencies, but it was poorer than the SVR. Although effective in certain applications, MLP presented the worst error and the least R -squared value and thus it is not as applicable in this task of forecasting a financial time series.

LSTM model provided the best predictive power in SAR/PKR exchange rates. It also had the lowest MAE (3.37) and RMSE (5.18) and the highest value of R-squared (0.8685) which depicts a good ability to represent the trends and fluctuations of the exchange rate. With the currency pair prediction, LSTM was superior to SVR that had been performing well in the preceding forecasts. The bigger errors in SVR (RMSE of 6.80 and R-squared of 0.7732) indicate that it might not have been as useful to capture the specific complexities of SAR/PKR. The MLP model was unsatisfactory, and its error measures were high and the R-squared was only 0.4900, which means that it could not evidentiate more than half of the data.

The SVR produced the minimum MSE (17,752.82), RMSE (133.24) and MAE (108.76) and the highest value of R-squared (0.9631) gave the best results on predicting USD/IDR exchange rates. The potential of SVR to use non-linear relationships and its high effectiveness in regression processes qualifies it as a good predictor of the USD/IDR exchange rate. The LSTM model, although a little less precise, followed closely after, showing a good ability to deal with the sequential time-series data with R-squared value of 0.9620. Nevertheless, MLP lost to both LSTM and SVR with much higher error rates and lower R-squared value (0.9502), which means that it was not as effective in the modeling of exchange rate dynamics.

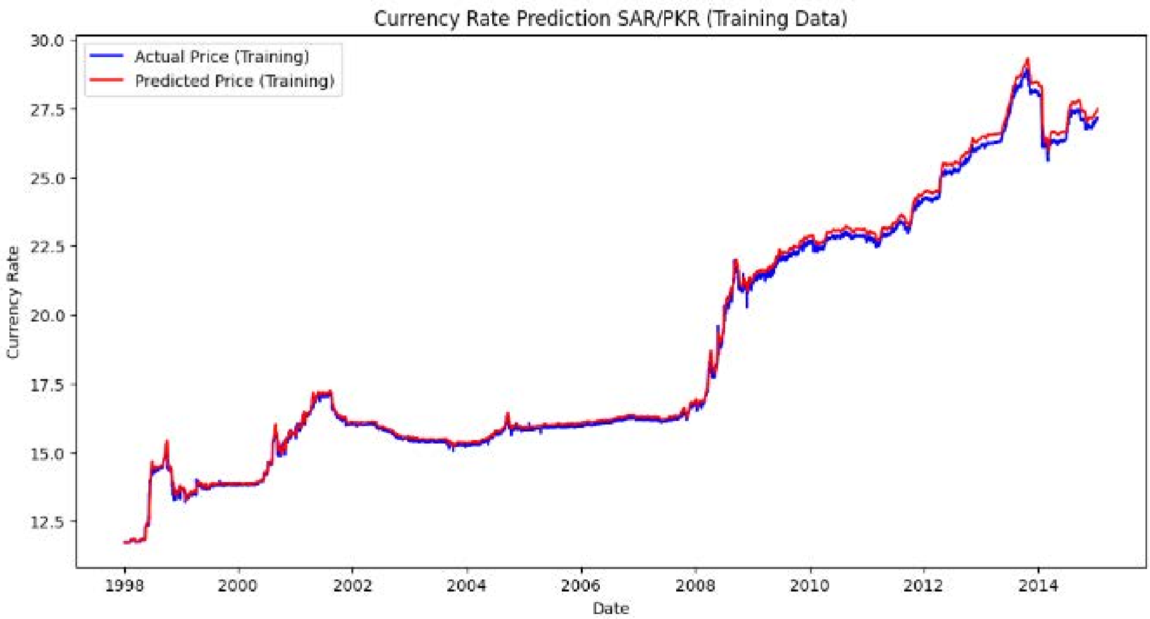

Figure 2 SAR/PKR training predicted using LSTM model

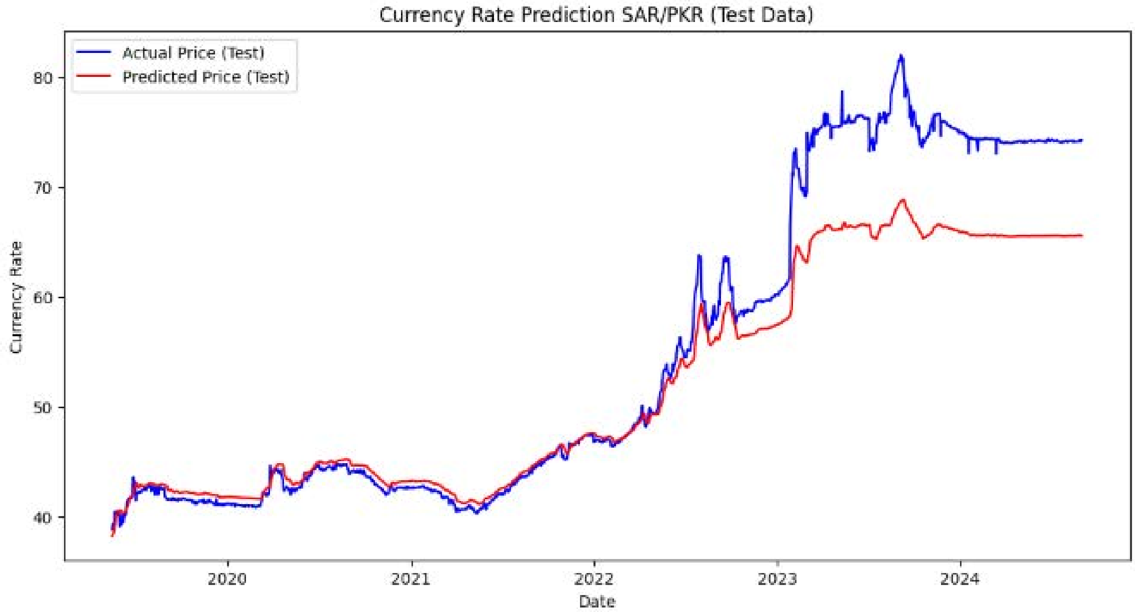

Figure 3 SAR/PKR testing predicted using LSTM model

Figure 2 indicate that The LSTM model is not bad and the predictions are almost perfect in terms of accuracy during the training process. Figure 3 depict the model as effective in capturing short-term trends but with severe changes such as the enormous spike in 2023. This points to the challenge of forecasting large and unpredictable happenings or changes in currency markets through historical data only.

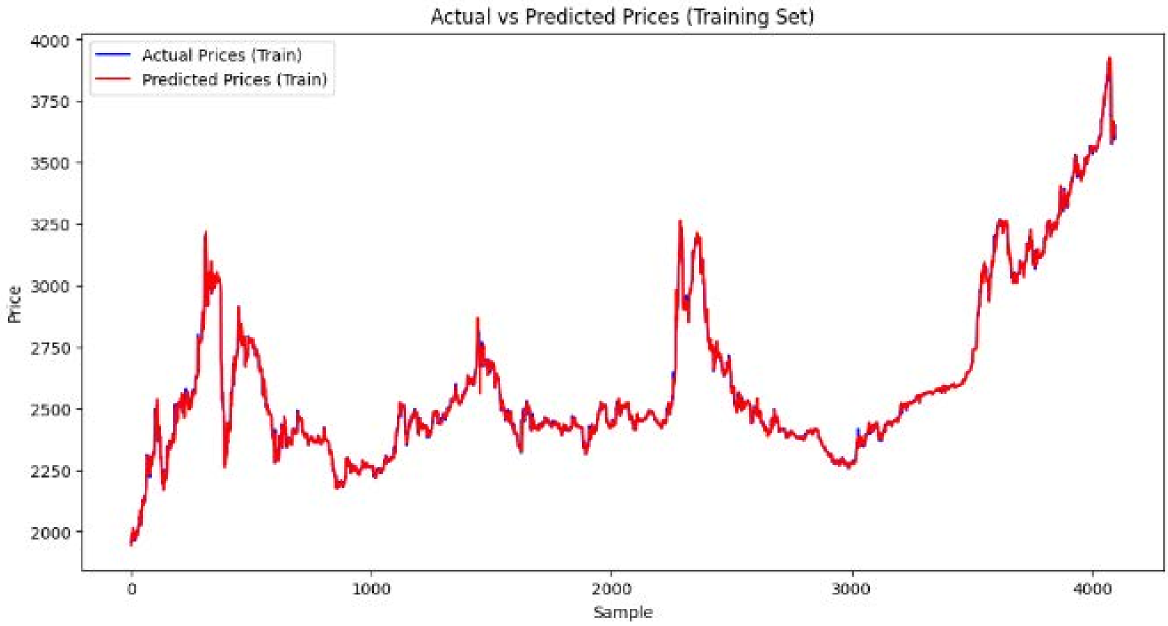

Figure 4 SAR/IDR training predicted using SVR model

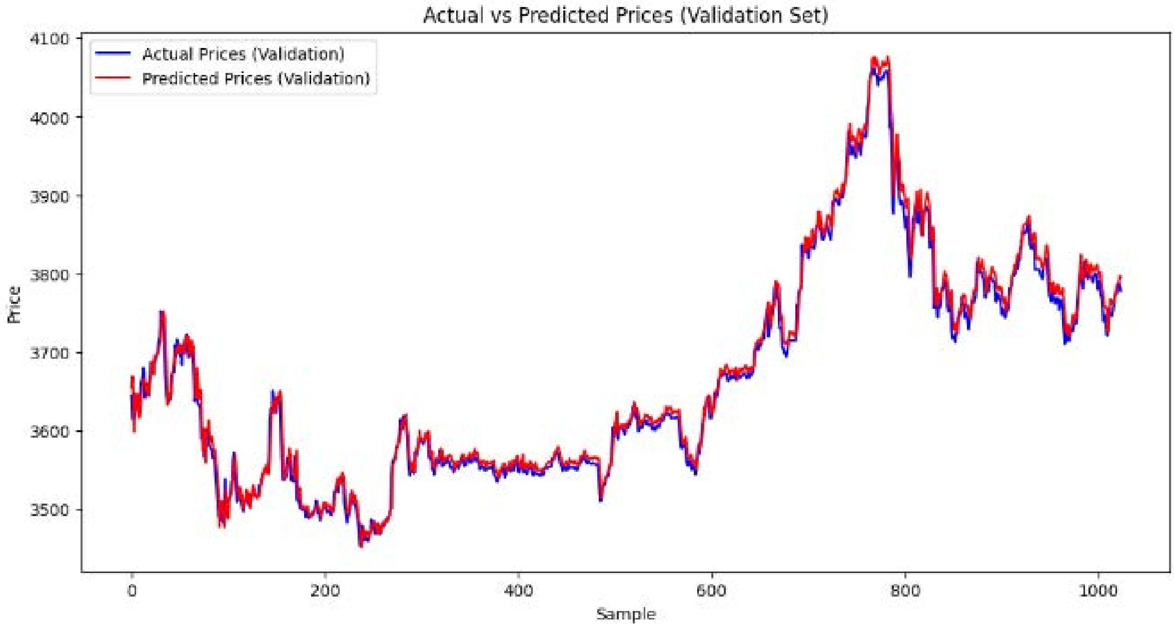

Figure 5 SAR/IDR validation predicted using SVR model

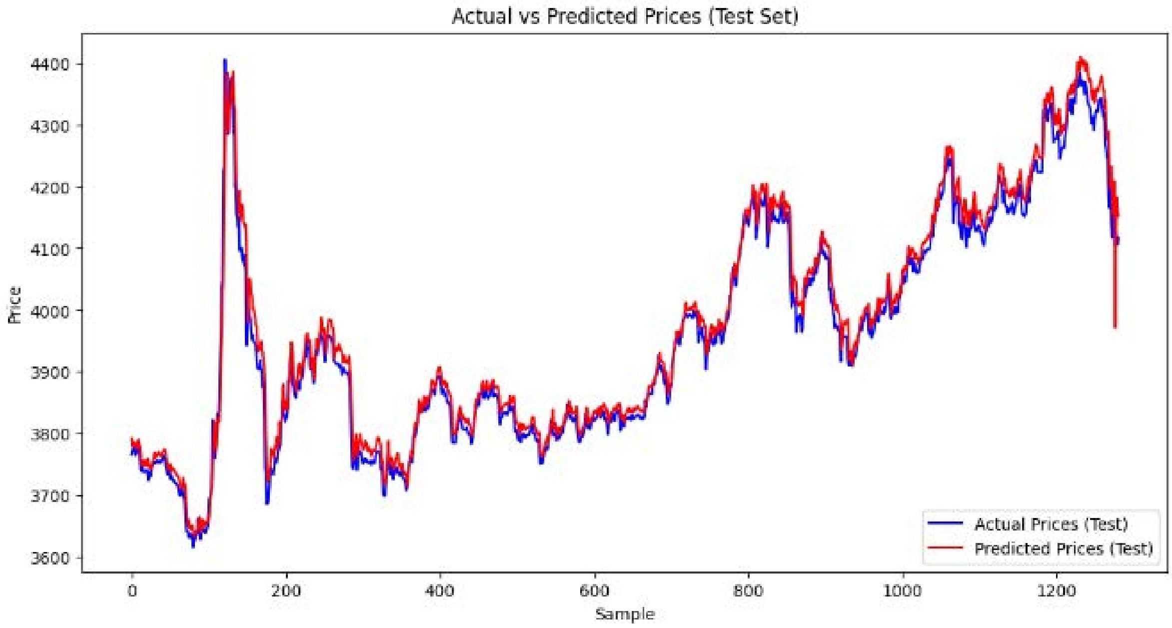

Figure 6 SAR/IDR testing predicted using SVR model

Figures 4, 5 and 6 indicate that the model is very consistent in its work with both training, validating and testing datasets. This consistency means that this model has a high generalization capacity and is not overfitting to the training data.

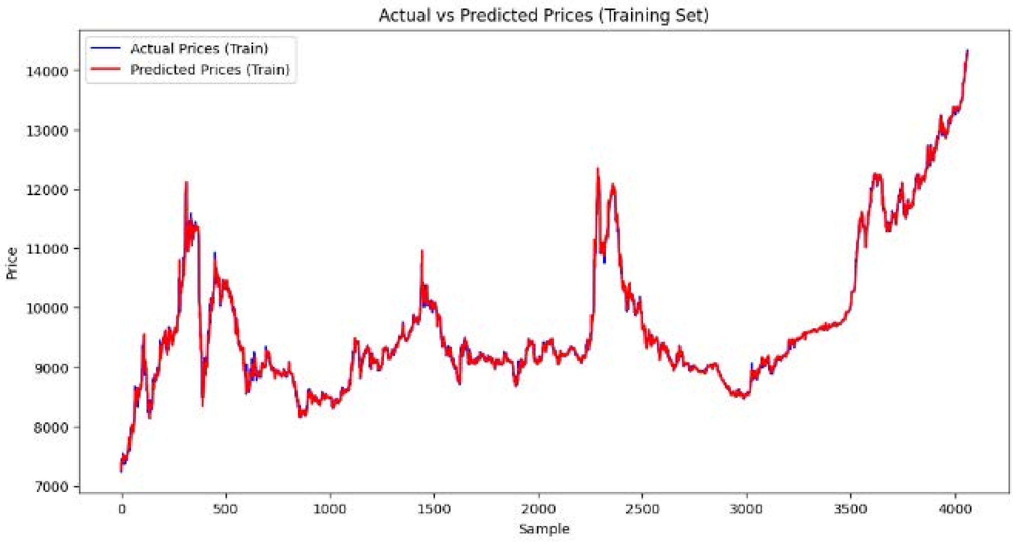

Figure 7 USD/IDR testing predicted using SVR model

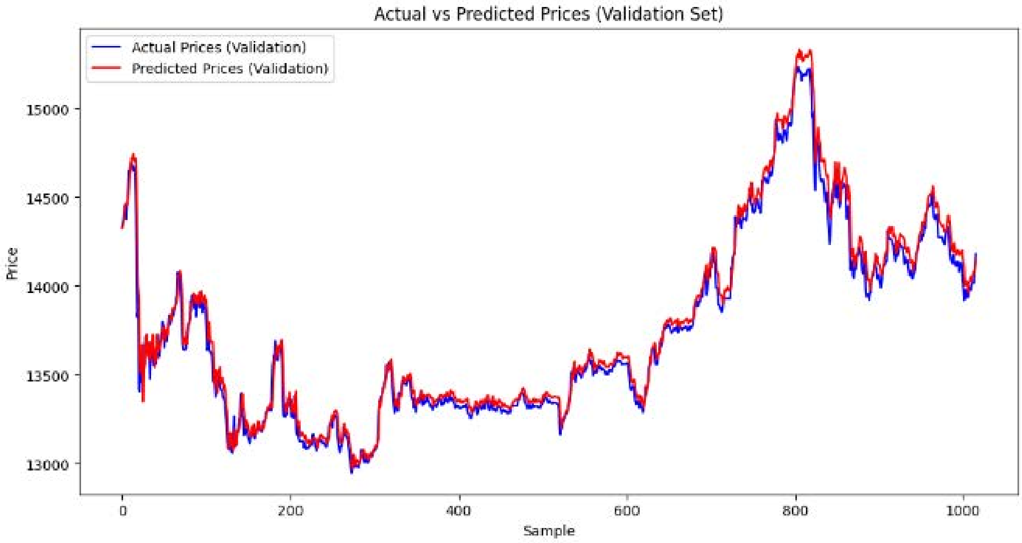

Figure 8 USD/IDR testing predicted using SVR model

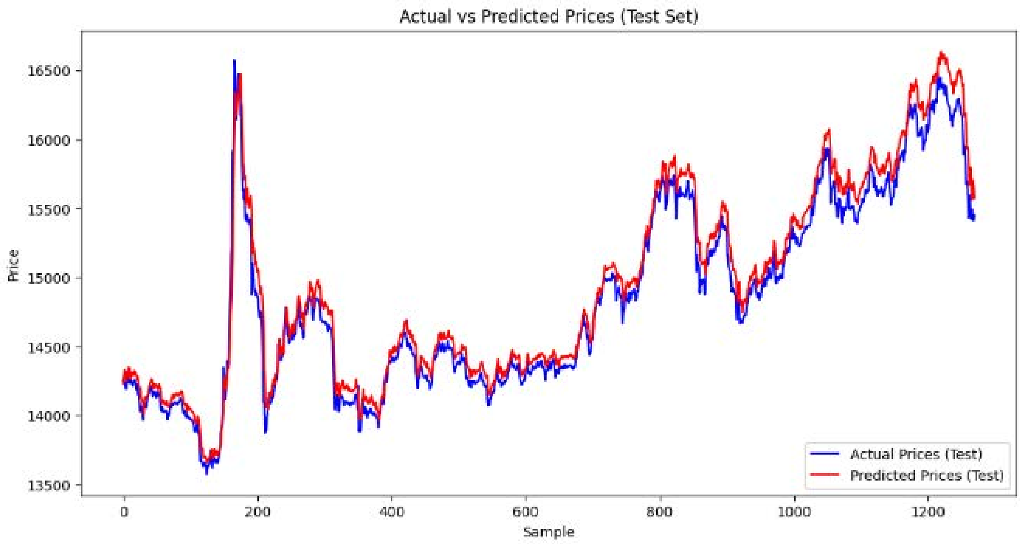

Figure 9 USD/IDR testing predicted using SVR model

Figures 7, 8 and 9 show that SVR model performs best to predicted USD/IDR. Demonstrating that in most instances SVR can be used more successfully than LSTM and MLP and that LSTM can be used more effectively than SVR in relation to certain currency pairs, this study can provide useful advice to researchers and practitioners in choosing the best model to use in the time series forecasting, especially in the financial market.

5 Conclusions

The results of this comparative study indicate that LSTM is better suited to SAR/PKR exchange rate forecasting owing to its ability to better represent time series data as well as the capability to model long-term dependencies. The best and most reliable model in general and in particular with the SAR/IDR and USD/IDR exchange rates was the SVR. It gave the least error rates and the highest R-squared values suggesting that it was able to model the intricacies of these exchange rates with a high level of accuracy. Nevertheless, MLP showed a sustained poor performance in all pairs of currencies with larger errors and less R-squared values, which means that it could not be successfully used without additional optimization. Future research may further investigate more features, may be aimed at improving these models or may investigate ensemble techniques or sophisticated tuning strategies to further enhance the overall performance of these models.

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Logistics service quality, consumer trust, and product judgments in cross-border e-commerce

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Keywords: cross-border e-commerce, consumer trust, product judgments, logistics service quality, cross-border logistics.
Abstract: In emerging markets, cross-border e-commerce (CBEC) depends on consumer trust and product judgments under conditions of logistics complexity, information asymmetry, and cross-border flow uncertainty. This research investigates the collective impact of platform attributes (information, system, and e-service/logistics service quality), value perceptions (price competitiveness, product uniqueness), and national psychological factors (affinity, ethnocentrism, animosity) on trust, product assessments, and cross-border purchasing flows involving U.S. and Chinese products purchased by Vietnamese consumers. Two online surveys were administered to CBEC users assessing U.S. (N = 1,041) and Chinese (N = 1,013) products. Using PLS-SEM and artificial neural networks, the results show that platform quality affects purchasing behavior mainly through trust and product evaluations rather than direct transactional mechanisms. For Chinese products, information quality and logistics-related e-service quality play a more prominent role, reflecting differences in logistics service execution. Price competitiveness and product uniqueness emerge as key value-driven determinants of product evaluations. Affinity strengthens trust and product evaluations, whereas ethnocentrism weakens them; animosity is largely insignificant in routine CBEC logistics flows. Trust is more influential for U.S. goods, while perceived value is more critical for Chinese goods. The study frames CBEC platforms as digital logistics systems coordinating information and service flows, and provides implications for cross-border logistics and platform design in emerging economies.

1 Introduction

In emerging nations, cross-border e-commerce (CBEC) has evolved into a vital conduit transforming consumer access to global items, facilitating cross-border flows of goods, information, and transactions through digital platforms. In Vietnam, CBEC represented approximately 37% of overall e-commerce transactions in 2023, with projections indicating sustained growth until 2025, driven by enhanced logistics capability and platform dependability. Vietnamese consumers are progressively acquiring American products, which are perceived as premium quality, via Amazon and eBay, while Chinese goods, known for affordability and diversity, are purchased through platforms such as Alibaba and TaoBao [1]. Considering that China is Vietnam's foremost import partner [2] and the United States its primary export destination [3], the competition between items from these two nations in Vietnam's digital marketplace is both fierce and strategically important. This context positions CBEC not merely as a retail channel but as a digitally mediated logistics system coordinating material and information flows across borders.

Despite increasing involvement in CBEC, current research presents contradictory findings about the impact of attitudinal elements on product assessments. Social identity theory, via categories such as ethnocentrism, elucidates national bias towards foreign products [4], whereas contemporary research uncovers contextual subtleties [5]. Numerous research indicate that consumer ethnocentrism and antagonism adversely influence evaluations of foreign products and intentions to purchase [6,7]. Nevertheless, alternative studies indicate more intricate or inconsistent patterns. Hostility indirectly diminishes purchase intention by decreasing perceived product quality [8], but an absence of a significant association between animosity and brand image [6]. These mixed results suggest that attitudinal effects may depend on platform-mediated information flows and logistics service execution rather than operate as direct drivers of behavior. Moreover, most prior studies rely on linear modeling approaches, which may overlook complex and non-linear decision mechanisms inherent in digital commerce environments, particularly those shaped by logistics uncertainty and information asymmetry.

Accordingly, this study investigates the determinants of Vietnamese consumers' trust and product evaluations toward U.S. and Chinese products in CBEC, integrating emotional, cultural, and platform quality dimensions. Social identity theory is employed to explain consumer bias, while the S-O-R framework and the Information Systems Success model are combined to capture how platform quality and logistics-related service flows influence trust and satisfaction.

This study contributes by: (1) offering a comparative analysis of U.S. and Chinese products within Vietnam's CBEC market from a logistics flow perspective; (2) clarifying inconsistent findings regarding attitudinal factors; (3) advancing methodological rigor by integrating PLS-SEM and Artificial Neural Networks to capture both linear and non-linear relationships; and (4) providing practical insights for the design of CBEC platforms as digital logistics systems.

2 Theoretical framework and hypothesis development

2.1 Theoretical background

Understanding cross-border consumer behavior requires a solid grounding in interdisciplinary theoretical frameworks that account for the psychological, sociocultural, and technological forces shaping decision-making in digital commerce. This study draws upon three foundational theories: Social identity theory, the Stimulus-Organism-Response (S-O-R) framework, and the Information system success model; to build an integrated conceptual foundation for investigating how Vietnamese consumers evaluate and engage with U.S. and Chinese products in CBEC settings. Social identity theory posits that individuals derive part of their self-concept from their membership in social groups, often leading to preferential attitudes toward in-group symbols and skepticism toward out-group representations. In the context of CBEC, this framework helps explain how national origin cues may activate identity-based preferences or resistance. Constructs such as consumer ethnocentrism, a belief that buying domestic products is morally preferable, are key manifestations of this theory in consumption settings, along with consumer affinity and animosity, which reflect emotional alignment or opposition toward countries [4].

The S-O-R model conceptualizes consumer behavior as a chain of influence whereby external stimuli, such as website interface, brand origin, or product pricing, affect internal states like emotion, perception, or cognitive appraisal, which in turn guide behavioral outcomes. This model provides a useful lens for interpreting how the design and presentation of CBEC platforms elicit psychological responses that may shape trust and purchase-related judgments [3]. Platform functionality and user-centered design drive satisfaction and behavioral intentions, according to the information system success model. This approach emphasises information, system, and service quality as major determinants of consumers' evaluative responses to digital storefronts without physical inspection or interpersonal interaction [9].

2.2 Consumer affinity, national identification, and their effects on trust and product evaluation

Consumer affinity is a positive view of a foreign country based on personal experiences, cultural adoration, and affective connection with its ideals. Affinity reinforces a consumer's sense of belonging and admiration for a national group in cross-border consumption [10]. This psychological alignment affects trust and product evaluations, especially when sellers or products are far away. According to social identification theory, consumers choose foreign products from countries they identify with because they symbolically validate their aspirational or cultural in-group affiliation. Norwegian, Japanese, and Southeast Asian samples showed that national affiliation increased product-related trust [11]. Besides trust, affinity has been connected to greater product ratings, with customers evaluating goods from favorite countries higher in quality, design, and value alignment. These theoretical and empirical grounds suggest the following hypotheses:

H1a. Consumer affinity positively influences consumer trust in cross-border e-commerce platforms.

H1b. Consumer affinity positively influences product judgments of foreign goods.

2.3 Consumer ethnocentrism, national identity, and their impact on trust and product evaluation

Consumer ethnocentrism is the view that buying foreign goods is immoral and bad for the domestic economy. Based on Social identity theory, this concept shows a protective orientation toward the national in-group, sometimes manifested as loyalty to home products and resistance to foreign alternatives [12]. Nationalism and patriotism increase these sentiments, dividing local and imported goods perceptions. Ethnocentrism makes customers distrust foreign brands' quality, relevance, and compatibility with national values [10]. Given Vietnam's nationalist identity and fast globalizing market, the following hypotheses are proposed:

H2a. Consumer ethnocentrism negatively influences consumer trust in cross-border e-commerce.

H2b. Consumer ethnocentrism negatively influences product judgments of foreign goods.

2.4 Consumer animosity, intergroup hostility, and their influence on trust and product evaluation

Consumer hostility is deep-seated hatred of a foreign country, usually caused by political, historical, or economic strife. Unlike situational discontent, enmity is long-lasting and typically arises from unresolved intergroup conflicts like territorial disputes or colonial histories, which form consumer rejection to hostile nation products [13]. A psychological response to perceived intergroup threat, animosity reinforces national in-group loyalty and generates enmity toward out-groups. This causes consumers to emotionally oppose products from the hated country, often leading to purchase hesitancy or rejection. Apart from product rejection, antagonism lowers consumer trust. Hostile customers question product integrity, ethical sourcing, and safety, especially when national identity is at stake [14]. Anger creates cognitive distance that hinders trust building. Anger may affect trust and evaluation in CBEC as an emotional and cognitive filter. These hypotheses are proposed:

H3a. Consumer animosity negatively influences consumer trust in cross-border e-commerce.

H3b. Consumer animosity negatively influences product judgments of foreign goods.

2.5 Information quality, digital content assurance, and their role in trust and product evaluation

Online content correctness and completeness are crucial to user experience in digital commerce, especially in CBEC, where there is no physical product interaction. Information quality, the extent to which system-generated information is timely, relevant, accurate, and complete [9], affects consumer perceptions of product credibility and platform reliability. Product descriptions, pricing clarity, return procedures, and visual content indicate authenticity and value in CBEC. High information quality decreases uncertainty and enables confident decision-making, especially in foreign transactions where cultural, legal, and logistical unfamiliarities increase risk [15]. Customers that receive clear, consistent, and personalized information are more likely to trust the platform and vendor. According to the information system success model, information quality influences system utilization, user happiness, and behavioral intention [9]. CBEC increases trust and product assessments as customers use existing information to infer quality, performance, and suitability [16]. Thus, information quality builds trust and enables evaluation in CBEC platforms. Well-designed products satisfy utilitarian and emotional demands, encouraging positive customer behavior across cultures and nations.

H4a. Information quality positively influences consumer trust in cross-border e-commerce.

H4b. Information quality positively influences product judgments of foreign goods.

2.6 System quality, platform stability, and their effects on trust and product evaluation

In CBEC, system quality refers to the technical performance and user-friendliness of a digital platform, including features such as usability, reliability, responsiveness, and adaptability. Fast page loads, smooth navigation, and platform stability improve user experience with high system quality. Technical fluency promotes professionalism and operational reliability, which build. System failures (errors, crashes, or slow response) signify inefficiency and increase transactional uncertainty, lowering consumer confidence [13]. Behaviorally, intuitive solutions reduce cognitive stress and search costs, letting consumers focus on product evaluation rather than technical navigation [17]. This increases product value since system quality indicates the seller's dependability and reputation. In CBEC contexts with physical and cultural distance, system quality provides operability and communicates the supplier's legitimacy and service commitment [18]. Overall, system quality is crucial to CBEC consumer trust and product perceptions. These hypotheses are proposed:

H5a. System quality positively influences consumer trust in cross-border e-commerce.

H5b. System quality positively influences product judgments of foreign goods.

2.7 E-service quality, relational signals, and their influence on trust and product evaluation

CBEC defines e-service quality as consumers' perceptions of online assistance, transaction ease, delivery speed, and post-sale support. It shows how platforms and vendors meet consumers' timeliness, reliability, and care requirements. This study defines e-service quality as (1) functional support, (2) logistical efficacy, and (3) post-purchase service. High service quality builds satisfaction, loyalty, and trust, especially when cultural or physical distance hinders direct verification [19]. E-commerce studies suggest that quick and personalized services increase product value perceptions, which affects behavioral intent. Service experiences boost trust. Service quality signals care and dedication in CBEC, where seller unfamiliarity is significant). E-service quality builds consumer trust and improves product assessments, especially in high-context emerging countries like Vietnam. The following hypotheses are proposed:

H6a. E-service quality positively influences consumer trust in cross-border e-commerce.

H6b. E-service quality positively influences product judgments of foreign goods.

2.8 Price competitiveness, perceived value, and its role in shaping product judgments

Price competitiveness in CBEC means consumers think a product is cheaper than alternatives, especially after shipping, tariffs, and foreign exchange discrepancies. It shows a supplier's capacity to attract price-sensitive consumers in global digital markets with attractive value propositions. Foreign vendors can undercut domestic competitors in CBEC transactions due to structural cost advantages such favorable tax regimes, lower labor costs, and economies of scale. Utility-maximizing behavior and strong price sensitivity make these pricing advantages especially attractive in growing markets like Vietnam.Consumers feel good about buying a product and getting a good deal. Consumers make better product decisions and are happier with purchases when pricing is fair [13]. Competitive pricing boosts product appeal, consumer trust in the transaction process, and brand favorability, especially in CBEC where physical inspection is not possible. The following hypothesis is proposed:

H7. Price competitiveness positively influences product judgments of foreign goods.

2.9 Product uniqueness, symbolic value, and its impact on product evaluation

Consumers are drawn to CBEC by more than price or convenience. They increasingly seek unique things not available domestically. Psychological research shows that uniqueness drives purchase behavior. This is especially true in civilizations that emphasize individuality and expression [20]. This feature motivates consumers to prefer rare or novel things that help them stand out. This increases brand loyalty and international platform exploration [21,22]. This behavioral trend is even more apparent in CBEC scenarios when a product's perceived uniqueness matches the consumer's aspirations or self-image. Uniqueness boosts a product's hedonic and symbolic utility, according to perceived value theory. Thus, CBEC platforms with unique products tend to receive better reviews and increase purchase motivation. Given this, the following theory is proposed:

H8. Product uniqueness positively influences product judgments of foreign goods.

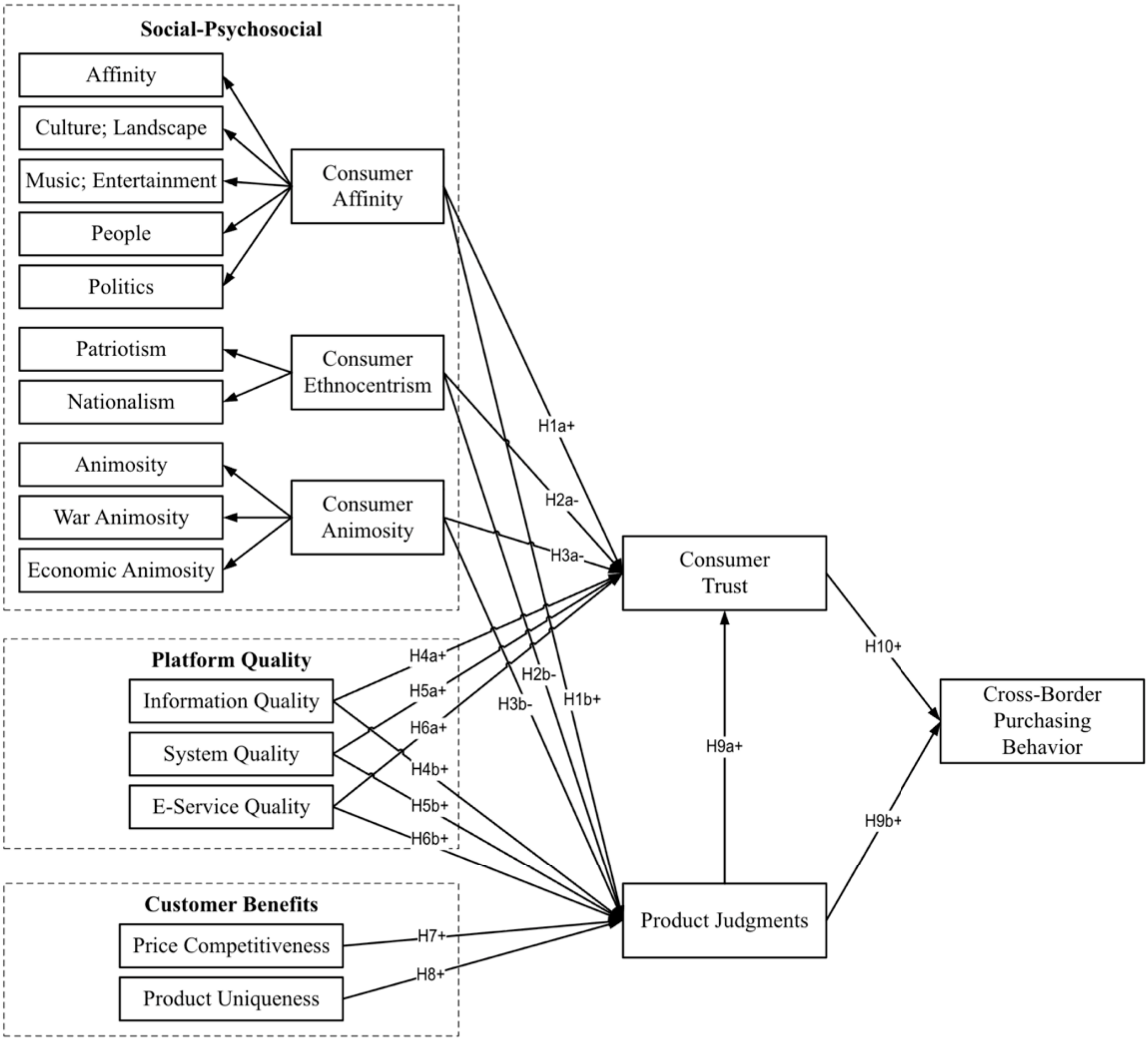

Figure 1 Research model

2.10 Product judgments and cross-border purchasing behavior

Consumers evaluate foreign items based on price, design, innovation, quality, durability, technical advancement, and production capacities [23]. Digital cues, platform knowledge, and brand reputation drive CBEC product evaluations, when consumers cannot physically inspect things. Trust and product ratings are linked. Foreign product quality and value increase consumer trust in the vendor or platform. Superior product features increase perceived reliability. Product value boosts cognitive and affective trust [24]. This link is crucial in CBECs. Consumers trust platforms more when they think foreign products are valuable [15]. When a product meets quality, uniqueness, or perceived benefit expectations, consumers are more likely to buy. In international e-commerce, perceived product value drives purchase behavior.

Given these data, the following possibilities are proposed:

H9a. Product judgments have a positive relationship with consumer trust.

H9b. Product judgments have a positive relationship with cross-border purchasing behavior of consumers.

2.11 Consumer trust and cross-border purchasing behavior

Online commerce depends on consumer trust, especially in cross-border environments where consumers experience increased uncertainty. It shows customers trust the platform, sellers, and trust reduces digital transaction hesitancy and risk [18]. Trust is considerably more important in CBEC. Lack of physical touch, foreign delivery, payment processing, and platform unfamiliarity increase consumer trust as a risk-reduction tool [19]. This is supported by data. For instance, mobile CBEC platform trust significantly increases purchase intention [25]. Information quality moderates trust's favorable effect on cross-border purchase behavior [26]. These findings imply that trust is essential for cross-border purchasing, especially in emerging economies like Vietnam. We suggest the following hypothesis:

H10. Consumer trust has a positive relationship with cross-border purchasing behavior of consumers.

Research model is presented in Figure 1.

3 Research methodology

3.1 Instrument development and qualitative pre-testing

The study used a qualitative pre-test to verify content and context. All constructs were forward-backward translated into Vietnamese using cross-cultural adaption approach. To ensure clarity and contextual relevance, 14 industry professionals from CBEC platforms, exports, logistics, retail tech, branding, trade law, payments, consulting, and international business research assessed the draft questionnaire. Expert criticism led to minor phrasing and layout changes. Validated scales were used to measure all constructs on a five-point Likert scale (1 = strongly disagree, 5 = strongly agree).

Social-psychological factors (affinity, ethnocentrism, animosity), platform quality (information, system, e-service quality), customer benefits (price competitiveness, product uniqueness), consumer trust, product judgments, and cross-border purchasing behavior were covered in the final instrument. A pilot test with 14 experienced CBEC users showed internal consistency with Cronbach's alpha over 0.7 for all constructions.

3.2 Sampling procedure and data collection

Non-probability purposive sampling was employed to target Vietnamese online consumers with prior experience in purchasing foreign products via CBEC platforms. Data were collected through an online survey distributed between September 2023 and May 2024. Measures to prevent duplication included IP checks and mandatory entry of unique email addresses. After data cleaning, two separate but parallel datasets were retained for analysis:

Study 1 (U.S. product context): n = 1,041

Study 2 (Chinese product context): n = 1,013.

3.3 PLS-SEM analysis

The two-step Hair et al. (2019) approach was used for SmartPLS 4's core quantitative analysis:

Assessment of measurement models: Indicator reliability (loading > 0.708), internal consistency reliability (CR > 0.7), and convergent validity (AVE > 0.5) were guaranteed for reflective constructs. Discriminant validity was confirmed by Fornell-Larcker criterion and HTMT ratio (all < 0.85). If relevant, redundancy analysis and multicollinearity checks (VIF < 5) were performed on formative constructs.

Evaluation of structural models: Model fit and predictive power were assessed using R^2, Q^2 (blindfolded), path coefficient t-values (bootstrapping with 5,000 samples), and effect sizes (f^2). All path coefficients were evaluated for significance and directionality in both product-country settings. Model diagnostics confirmed multicollinearity was not a concern (VIF < 5), and Durbin-Watson statistics (≈2) ruled out residual autocorrelation.

3.4 Post-hoc predictive validation using artificial neural network

To complement the explanatory power of SEM and enhance out-of-sample predictive validity, an Artificial neural network analysis was performed. Significant SEM predictions were employed as input neurons in an MLP model using hybrid SEM-ANN technique [27]. Data were split by 90% training and 10% testing. ANN model performance was evaluated using RMSE and predicted R^2. Normalized importance was used to rank predictors using sensitivity analysis. Qualitative study results (Table 1).

Table 1 Qualitative study results

Company's industry field	Positions	Social-psychological -> Trust	Social-psychological -> Judgments	Platform quality -> Trust	Platform quality -> Judgments	Customer benefits -> Judgments	Judgments → Trust	Judgments → Behavior	Trust → Behavior	Other insights provided
01. CBEC platform	Head of Product	✓		✓	✓				✓	Suggested cultural proximity as a mediating variable.
02. Consumer goods exporter	Export Manager					✓	✓	✓	✓	Raised concern on overreliance on platform cues; suggested UX consistency as moderating factor.
03. Logistics provider	Operations Director			✓	✓	✓	✓	✓	✓	Emphasized return policy as an overlooked trust factor.
04. Retail technology	Chief technology officer			✓	✓	✓	✓	✓	✓	Suggested integrating trust seals or certifications as variables.
05. University research center	Senior Researcher	✓	✓	✓	✓	✓	✓	✓	✓	Proposed comparison between Gen Z and Millennials in affinity strength.
06. Cross-border payment firm	Compliance Lead			✓			✓	✓	✓	Noted the role of local influencers in mitigating animosity.
07. Global brand marketing	Marketing Strategist	✓	✓	✓	✓	✓	✓	✓	✓	Recommended dynamic pricing as potential moderator between uniqueness and judgment.
08. B2C marketplace ops	Marketplace Manager	✓		✓	✓	✓		✓	✓	Suggested adding loyalty behavior as a follow-up outcome.
09. Digital marketing consultant	Principal Consultant	✓	✓	✓		✓		✓	✓	Proposed factoring time spent browsing as a moderator.
10. Consumer behavior research	Behavioral Analyst	✓	✓	✓		✓		✓	✓	Suggested comparing inbound vs outbound CBEC flows.
11. International business school	Lecturer in IB	✓	✓	✓		✓		✓	✓	Recommended distinguishing between hedonic and utilitarian products.
12. Product sourcing firm	Procurement Manager			✓		✓			✓	Suggested testing gender as a control variable.
13. Global trade association	Policy Analyst			✓					✓	Warned about data quality issues with Gen AI-generated reviews.
14. IT systems integration	Tech Architect			✓	✓				✓	Proposed assessing perceived risk as indirect path to purchase.

4 Data analysis and results

Customers who were aware of cross-border e-commerce (CBEC) participated in the study conducted in Vietnam. In Study 1, 1,041 respondents assessed American-made products, while in Study 2, 1,013 respondents evaluated Chinese products. The demographic characteristics of the samples are summarized in Table 2.

Table 2 Demographic characteristics of samples

Demographics	Category	Study 1: United States Products			Study 2: China Products		
		Frequency (N = 1.041)	Valid percentage	Cumulative (%)	Frequency (N = 1.013)	Valid Percentage	Cumulative (%)
Gender	Female	561	53.9%	53.9%	470	46.40%	46.40%
	Male	480	46.1%	100.0%	543	53.60%	100.00%
Education	Undergraduate	497	47.7%	47.7%	234	23.10%	23.10%
	University	332	31.9%	79.6%	674	66.54%	89.63%
	Postgraduate	212	20.4%	100.0%	105	10.37%	100.00%
Occupation	Student	198	19.0%	19.0%	170	16.78%	16.78%
	Part-time	186	17.9%	36.9%	108	10.66%	27.44%
	Employed	657	63.1%	100.0%	735	72.56%	100.00%
Experience in CBEC	< 1 month	177	17.0%	17.0%	114	11.25%	11.25%
	1-6 months	319	30.6%	47.6%	215	21.22%	32.48%
	6-12 months	304	29.2%	76.8%	332	32.77%	65.25%
	> 1 year	241	23.2%	100.0%	352	34.75%	100.00%

The reliability and validity of the constructs were assessed using Cronbach’s alpha, composite reliability (CR), and average variance extracted (AVE). In this study, three exogenous latent constructs, namely consumer affinity, consumer antagonism, and consumer ethnocentrism, were modeled as higher order constructs (HOCs) using the hierarchical component model (HCM) approach in PLS-SEM.

As part of the reflective measurement model assessment, indicator loadings were examined. Items with loadings below the recommended threshold of 0.708 were removed. Specifically, in Study 1, the indicators ANI1, CAF4, CAF9, CET2, and CET6 were excluded. In Study 2, the indicators ANI1, CAF1, CAF2, and CAF11 to CAF19 were excluded.

After re-estimation, all remaining constructs demonstrated satisfactory internal consistency, with Cronbach’s alpha, composite reliability, and AVE values exceeding the recommended thresholds. These results, presented in Table 3, confirm the reliability and convergent validity of the measurement model.

Table 3 Construct reliability and validity

Constructs	Identifi-cation	United States Products (Study 1)			China Products (Study 2)		
		Cronbach’s alpha	Composite reliability (rho_c)	AVE	Cronbach’s alpha	Composite reliability (rho_c)	AVE
Consumer affinity	CAF	0.950	0.955	0.558	0.941	0.951	0.707
Affinity		0.834	0.923	0.858			
Culture; Landscape		0.832	0.888	0.665	0.912	0.934	0.739
Music; Entertainment		0.728	0.880	0.786	0.874	0.923	0.799
People		0.879	0.908	0.623			
Politics		0.785	0.875	0.700			
Consumer animosity	ANI	0.923	0.937	0.651	0.934	0.945	0.683
Economic Animosity		0.876	0.910	0.668	0.899	0.925	0.712
War Animosity		0.839	0.903	0.757	0.848	0.908	0.767
Consumer ethnocentrism	CET	0.924	0.941	0.726	0.931	0.943	0.676
Nationalism		0.748	0.888	0.798	0.808	0.887	0.723
Patriotism		0.902	0.932	0.773	0.905	0.929	0.724
Consumer Trust	CT	0.736	0.850	0.655	0.751	0.858	0.668
Cross-border purchasing	CBB	0.838	0.892	0.673	0.855	0.902	0.697
Information Quality	IQ	0.861	0.906	0.706	0.869	0.911	0.719
Price competitiveness	PC	0.796	0.867	0.620	0.816	0.879	0.644
Product judgments	PJ	0.858	0.894	0.586	0.874	0.905	0.613
Product uniqueness	PU	0.722	0.844	0.643	0.802	0.883	0.716
Service quality	SEQ	0.882	0.914	0.679	0.893	0.921	0.701
System quality	SYQ	0.827	0.878	0.591	0.885	0.916	0.686

Convergent validity is established when factor loadings exceed 0.70 and the Average Variance Extracted (AVE) is greater than 0.50. As shown in Table 3, all constructs in this study meet these criteria, confirming that the measurement items sufficiently represent their respective latent variables. The evaluation of discriminant validity utilized both the Fornell-Larcker criterion and the Heterotrait-Monotrait (HTMT) ratio. Table 4 demonstrates that this condition is met for all constructs, signifying sufficient discriminant validity. It is important to note that using the same indicators for both lower-order and higher-order constructs may compromise discriminant validity. However, in this study, the constructs are well distinguished, as evidenced by the AVE square roots being greater than the corresponding inter-construct correlations. This result confirms that the constructs are conceptually distinct and not redundant.

Table 4 Fornell-Larcker's discriminant validity

Study 1: United States Products (N = 1.041 samples)											
Constructs	CAF	ANI	CET	CT	CBB	IQ	PCN	PJ	PUQ	SEQ	SYQ
Consumer affinity	0.747										
Consumer animosity	-0.160	0.807									
Consumer ethnocentrism	-0.504	0.161	0.852								
Consumer trust	0.651	-0.156	-0.582	0.809							
Cross-border purchasing	0.541	-0.183	-0.510	0.656	0.821						
Information quality	0.420	-0.117	-0.532	0.591	0.452	0.840					
Price competitiveness	0.428	-0.184	-0.466	0.555	0.569	0.454	0.788				
Product judgments	0.586	-0.163	-0.647	0.676	0.646	0.628	0.667	0.765			
Product uniqueness	0.406	-0.027	-0.504	0.433	0.459	0.428	0.432	0.656	0.802		
E-service quality	0.129	0.027	-0.137	0.339	0.189	0.208	0.132	0.207	0.183	0.824	
System quality	0.282	-0.111	-0.244	0.436	0.306	0.366	0.282	0.329	0.168	0.136	0.769
Study 2: China Products (N = 1.039 samples)											
Constructs	CAF	ANI	CET	CT	CBB	IQ	PCN	PJ	PUQ	SEQ	SYQ
Consumer affinity	0.841										
Consumer animosity	-0.061	0.826									
Consumer ethnocentrism	-0.255	0.116	0.822								
Consumer trust	0.327	-0.193	-0.408	0.817							
Cross-border purchasing	0.242	-0.141	-0.397	0.653	0.835						
Information quality	0.149	-0.210	-0.314	0.553	0.487	0.848					
Price competitiveness	0.202	-0.174	-0.348	0.580	0.523	0.475	0.803				
Product judgments	0.351	-0.169	-0.478	0.688	0.656	0.566	0.698	0.783			
Product uniqueness	0.137	-0.028	-0.339	0.406	0.443	0.355	0.439	0.630	0.846		
E-service quality	0.107	-0.026	-0.064	0.364	0.213	0.239	0.173	0.339	0.228	0.837	
System quality	-0.056	-0.185	-0.084	0.445	0.339	0.308	0.379	0.286	0.147	0.082	0.828

The mean value of the item correlations across constructs in relation to the (geometric) mean of the average correlations for the items measuring the same construct is known as the heterotrait-monotrait ratio. When HTMT readings are high, discriminant validity issues arise. A threshold value of 0.90 or a lesser threshold value, such 0.85 or 0.90, should be determined based on the study environment. Table 5 demonstrates that all HTMT indicators are below 0.84, suggesting that the concepts are in fact different from one another.

Table 5 Heterotrait-monotrait ratio (HTMT) for discriminant validity

Study 1: United States Products (N = 1.041 samples)											
Constructs	CAF	ANI	CET	CT	CBB	IQ	PCN	PJ	PUQ	SEQ	SYQ
Consumer Affinity											
Consumer Animosity	0.170										
Consumer Ethnocentrism	0.538	0.174									
Consumer Trust	0.778	0.189	0.705								
Cross-Border Purchasing	0.606	0.208	0.578	0.834							
Information Quality	0.464	0.132	0.596	0.740	0.530						
Price Competitiveness	0.491	0.215	0.543	0.725	0.696	0.548					
Product Judgments	0.648	0.183	0.726	0.849	0.761	0.730	0.807				
Product Uniqueness	0.489	0.042	0.617	0.594	0.589	0.542	0.569	0.832			
E-Service Quality	0.140	0.040	0.152	0.420	0.219	0.238	0.156	0.236	0.229		

System Quality	0.318	0.128	0.279	0.559	0.366	0.434	0.346	0.388	0.214	0.159	
Study 2: China Products (N = 1.039 samples)											
Constructs	CAF	ANI	CET	CT	CBB	IQ	PCN	PJ	PUQ	SEQ	SYQ
Consumer Affinity											
Consumer Animosity	0.065										
Consumer Ethnocentrism	0.274	0.124									
Consumer Trust	0.388	0.231	0.487								
Cross-Border Purchasing	0.269	0.158	0.444	0.815							
Information Quality	0.165	0.234	0.348	0.682	0.564						
Price Competitiveness	0.231	0.200	0.397	0.740	0.627	0.563					
Product Judgments	0.388	0.187	0.529	0.849	0.759	0.648	0.826				
Product Uniqueness	0.158	0.046	0.390	0.523	0.534	0.424	0.542	0.753			
E-Service Quality	0.117	0.029	0.071	0.443	0.242	0.269	0.201	0.383	0.269		
System Quality	0.063	0.204	0.101	0.545	0.390	0.350	0.446	0.325	0.174	0.090	

The Q-squared index is computed using the cross-validated redundancy (blindfolding) technique (Q^2). This index offers a more thorough assessment of the exogenous latent variable's predictive indicators. The Q^2 values should be higher than zero for a particular endogenous construct to demonstrate the structural model's prediction accuracy. Q^2 values greater than 0 indicate minor predictive relevance of the PLS-path model, whereas 0.25 and 0.50 indicate medium predictive relevance. According to study 1's findings, the endogenous latent variable of customer trust accounts for 42.5% of the exogenous latent variable's prediction ability, followed by product assessments at 44.2% and cross-border purchasing at 33.8%. Similarly, research 2's findings indicate that 40.5% of the exogenous latent variable's prediction ability may be explained by the endogenous latent variable of consumer trust, 44% by product judgments, and 35.1% by cross-border purchases.

Table 6 The results of R-square, construct cross validated redundancy (blindfolding), and Bayesian information criterion

Constructs	Study 1: United States Products				Study 2: China Products			
	Q2	R2	R2 adjusted	BIC	Q2	R2	R2 adjusted	BIC
Product Judgments	0.422	0.728	0.725	-1291.978	0.440	0.724	0.722	-1244.057
Consumer Trust	0.425	0.656	0.653	-1055.712	0.405	0.613	0.610	-907.684
Cross-Border Purchasing	0.338	0.506	0.505	-714.042	0.351	0.508	0.507	-698.044

Table 6 displays the R^2 and R^2-adjusted results. The scale of cross-border purchase activity has the lowest R^2 indicator, according to both studies' findings. This might be because the residuals outside the model (ε) contain the majority of the significance. However, in both experiments, the scale of product judgments has the highest R^2 indication. This study's structural equation modeling satisfies the specified criteria. Other criteria, including the Bayesian information criterion (BIC), which has also been examined in Table 6, are also available to evaluate out-of-sample prediction without the need of a holdout sample. Further evidence that there is no multicollinearity problem comes from the Durbin-Watson coefficient (d) test, which shows that the model does not have autocorrelation when 1 and the variance inflation factors VIF are both less than 5.

Lastly, utilizing the PLS algorithm offered by SmartPLS 4, the study employed the PLS-SEM technique to evaluate the suitability of the structural model. The 5000-times PLS bootstrapping procedure was used to assess the model's parameters for significance. Figure 2 displays the individual normalized path coefficients and R^2 for study 1, whereas Figure 3 displays the same for study 2. Table 7 provides more information on the path coefficients and R^2 values.

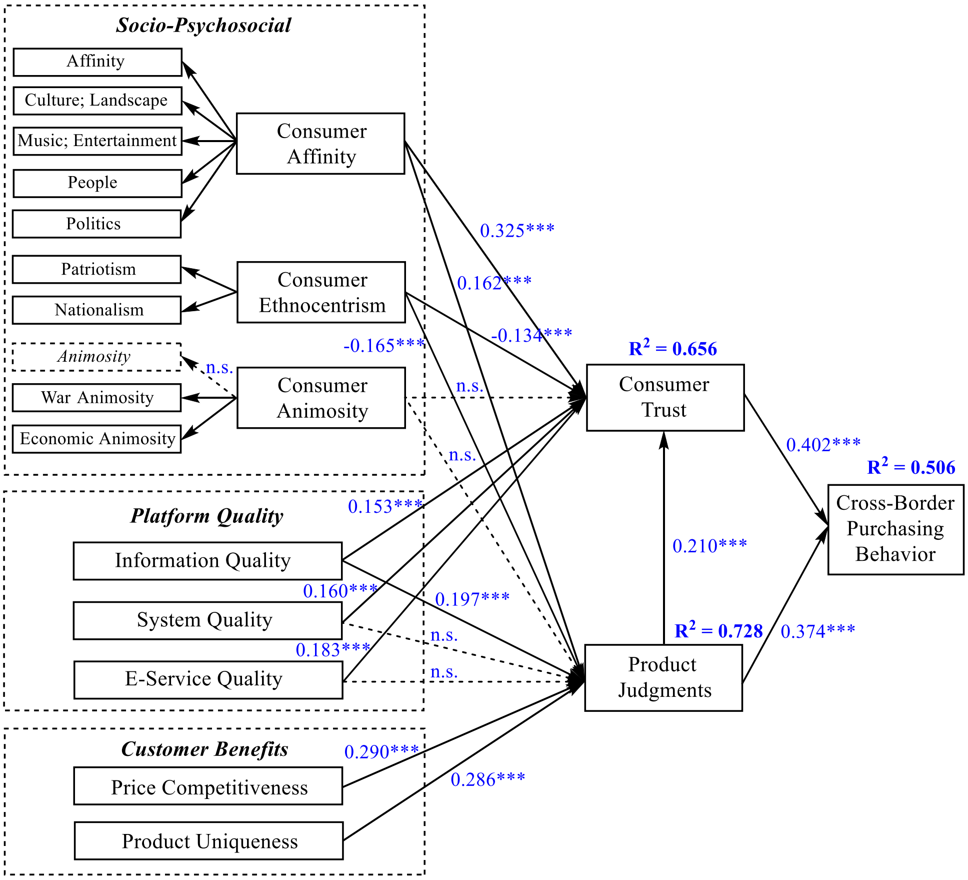

*Figure 2 Model test results in study 1 (United States products) Note: *** p < 0.001*

Table 7 Hypotheses testing (bootstrapping 5,000)

Hypothesis	Relationship-construct	United States Products (Study 1)				China Products (Study 2)			
		Original sample	T Statistics	P Value	Supported	Original sample	T Statistics	P Value	Supported
H1a	Consumer Affinity -> Consumer Trust	0.325	12.147	0.000	Yes	0.146	6.051	0.000	Yes
H1b	Consumer Affinity -> Product Judgments	0.162	7.684	0.000	Yes	0.161	8.585	0.000	Yes
H2a	Consumer Ethnocentrism -> Consumer Trust	-0.134	5.257	0.000	Yes	-0.115	5.042	0.000	Yes
H2b	Consumer Ethnocentrism -> Product Judgments	-0.165	6.975	0.000	Yes	-0.140	7.485	0.000	Yes
H3a	Consumer Animosity -> Consumer Trust	-0.017	0.913	0.362	No	-0.021	1.119	0.263	No
H3b	Consumer Animosity -> Product Judgments	-0.023	1.256	0.209	No	-0.026	1.626	0.104	No
H4a	Information Quality -> Consumer Trust	0.153	4.779	0.000	Yes	0.170	5.546	0.000	Yes
H4b	Information Quality -> Product Judgments	0.197	7.674	0.000	Yes	0.170	7.769	0.000	Yes
H5a	System Quality -> Consumer Trust	0.160	7.266	0.000	Yes	0.274	12.208	0.000	Yes
H5b	System Quality -> Product Judgments	0.034	1.729	0.084	No	0.034	1.685	0.092	No

Hypothesis	Relationship-construct	United States Products (Study 1)				China Products (Study 2)			
		Original sample	T Statistics	P Value	Supported	Original sample	T Statistics	P Value	Supported
H6a	E-Service Quality -> Consumer Trust	0.183	9.008	0.000	Yes	0.158	6.443	0.000	Yes
H6b	E-Service Quality -> Product Judgments	0.028	1.596	0.111	No	0.137	7.695	0.000	Yes
H7	Price Competitiveness -> Product Judgments	0.290	10.976	0.000	Yes	0.361	13.653	0.000	Yes
H8	Product Uniqueness -> Product Judgments	0.286	11.710	0.000	Yes	0.305	11.923	0.000	Yes
H9a	Product Judgments -> Consumer Trust	0.210	6.172	0.000	Yes	0.351	10.440	0.000	Yes
H9b	Product Judgments -> Cross-Border Purchasing	0.374	11.225	0.000	Yes	0.393	10.631	0.000	Yes
H10	Consumer Trust -> Cross-Border Purchasing	0.402	11.905	0.000	Yes	0.383	10.064	0.000	Yes

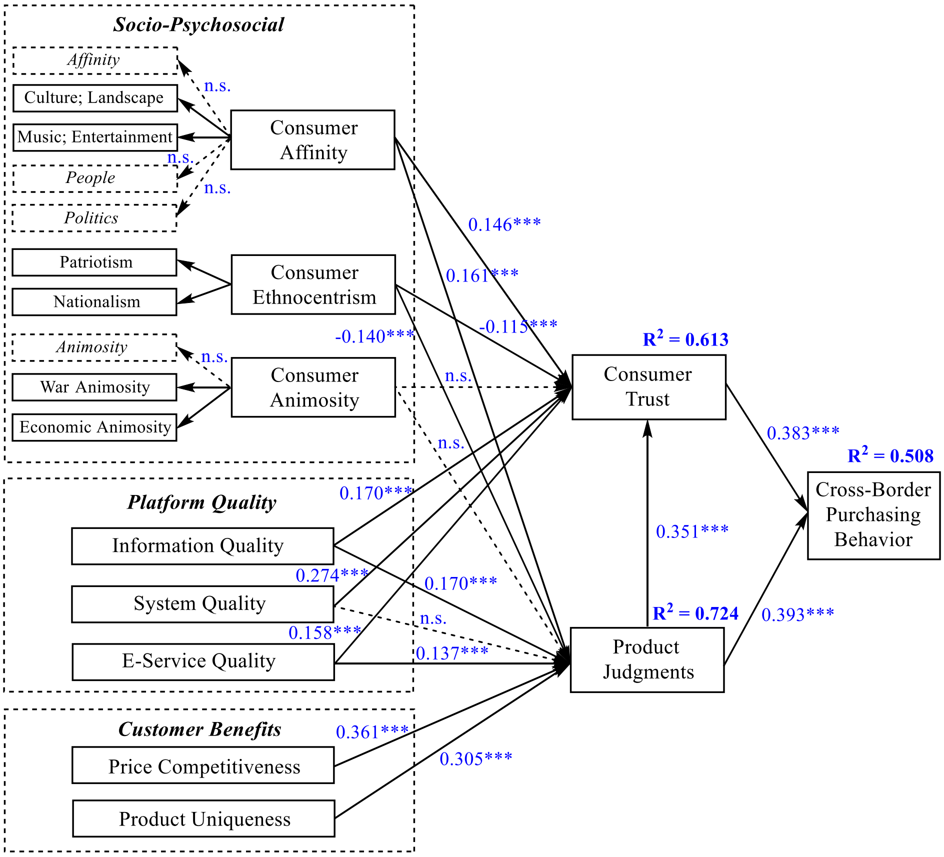

*Figure 3 Model test results in study 2 (China products) Note: *** p < 0.001*

5 Artificial neural network (ANN) analysis

Following the structural model validation through PLS-SEM, an ANN analysis was conducted as a post-hoc phase to improve predictive validity and uncover potential non-linear interactions among key factors influencing cross-border purchasing behavior. This hybrid SEM-ANN approach was motivated by the complex, multidimensional nature of consumer decision-making and the likelihood of non-normal distributions within the dataset [27]. The ANN was particularly suitable for this research context given its robustness against outliers, noise, and sample irregularities, and its capacity to capture both linear and non-linear relationships without assuming data. Moreover, it accommodates noncompensatory relationships, where a decrease in one predictor does not need to be offset by an increase in another. Significant predictors identified via PLS-SEM were used as input neurons across three sub-models in each national context. Each ANN model was trained using a feedforward-backpropagation (FFBP) learning algorithm. Multilayer perceptrons with sigmoid activation functions were implemented for both input and hidden layers. 90% of the samples were allocated to the training set, while the remaining 10% were used for testing. A ten-fold cross-validation method was employed to avoid overfitting and enhance generalizability.

Tables 8 and 9 present the RMSE values for each of the ten ANN runs under each model, corresponding to the U.S. and Chinese datasets, respectively. As shown, the average RMSE values range between approximately 0.094 and 0.119 for the U.S. model and 0.098 and 0.117 for the China model, indicating a satisfactory model fit and strong predictive performance.

Table 8 RMSE values for US model

Neural network	Model A		Model B		Model C	
	Input: Affinity, Ethnocent, InfoQual, PriceComp, ProdUnique		Input: Affinity, Ethnocent, InfoQual, SysQual, ServQual, ProdJudg		Input: Trust, ProdJudg	
	Output: ProdJudg		Output: Trust		Output: CBPurchase	
	Training RMSE	Testing RMSE	Training RMSE	Testing RMSE	Training RMSE	Testing RMSE
ANN1	0.100	0.096	0.097	0.123	0.098	0.123
ANN2	0.123	0.134	0.092	0.118	0.093	0.115
ANN3	0.114	0.128	0.095	0.119	0.098	0.124
ANN4	0.109	0.103	0.091	0.115	0.095	0.126
ANN5	0.091	0.102	0.096	0.122	0.095	0.114
ANN6	0.091	0.102	0.093	0.117	0.089	0.120
ANN7	0.087	0.107	0.098	0.120	0.098	0.112
ANN8	0.120	0.116	0.094	0.116	0.087	0.117
ANN9	0.109	0.112	0.097	0.121	0.090	0.113
ANN10	0.113	0.107	0.090	0.114	0.092	0.125
Mean	0.106	0.111	0.094	0.119	0.094	0.119
SD	0.012	0.012	0.003	0.003	0.004	0.005

Note: Affinity = Consumer affinity; Ethnocent = Consumer ethnocentrism; Animosity = Consumer animosity; InfoQual = Information quality; SysQual = System quality; ServQual = E-service quality; PriceComp = Price competitiveness; ProdUnique = Product uniqueness; Trust = Consumer trust; ProdJudg = Product judgments; CBPurchase = Cross-border purchasing behavior.

Table 9 RMSE values for China model

Neural network	Model A		Model B		Model C	
	Input: Affinity, Ethnocent, InfoQual, ServQual, PriceComp, ProdUnique		Input: Affinity, Ethnocent, InfoQual, SysQual, ServQual, ProdJudg		Input: Trust, ProdJudg	
	Output: ProdJudg		Output: Trust		Output: CBPurchase	
	Training RMSE	Testing RMSE	Training RMSE	Testing RMSE	Training RMSE	Testing RMSE
ANN1	0.086	0.111	0.098	0.117	0.099	0.101
ANN2	0.111	0.129	0.094	0.117	0.094	0.101
ANN3	0.090	0.118	0.099	0.123	0.100	0.107
ANN4	0.102	0.126	0.104	0.106	0.107	0.088
ANN5	0.110	0.113	0.094	0.107	0.093	0.089
ANN6	0.114	0.104	0.094	0.117	0.093	0.100
ANN7	0.102	0.129	0.104	0.113	0.108	0.096
ANN8	0.103	0.128	0.100	0.124	0.101	0.108
ANN9	0.086	0.111	0.092	0.114	0.091	0.097
ANN10	0.101	0.101	0.098	0.110	0.099	0.092
Mean	0.100	0.117	0.098	0.115	0.098	0.098
SD	0.010	0.011	0.004	0.006	0.006	0.007

Note: Affinity = Consumer affinity; Ethnocent = Consumer ethnocentrism; Animosity = Consumer animosity; InfoQual = Information quality; SysQual = System quality; ServQual = E-service quality; PriceComp = Price competitiveness; ProdUnique = Product uniqueness; Trust = Consumer trust; ProdJudg = Product judgments; CBPurchase = Cross-border purchasing behavior.

To further assess the relative importance of each predictor, a sensitivity analysis was conducted (Table 10 to Table 13), where normalized importance values were derived to rank the contribution of each input neuron.

Table 10 Sensitivity analysis for Model A of US model

Neural network	Model A				
	Output: ProdJudg				
	Ethnocent	Affinity	InfoQual	ProdUnique	PriceComp
ANN1	0.230	0.350	0.510	0.980	1.000
ANN2	0.210	0.330	0.490	0.970	1.000
ANN3	0.220	0.340	0.500	1.000	1.000
ANN4	0.240	0.360	0.520	0.990	1.000
ANN5	0.200	0.320	0.480	0.960	1.000
ANN6	0.190	0.300	0.460	0.940	1.000
ANN7	0.250	0.380	0.540	0.980	1.000
ANN8	0.220	0.350	0.510	1.000	1.000
ANN9	0.230	0.360	0.520	0.990	1.000
ANN10	0.260	0.390	0.550	1.000	1.000
Average relative importance	0.225	0.348	0.508	0.981	1.000
Normalized relative importance (%)	22.500	34.800	50.800	98.100	100.000

Table 11 Sensitivity analysis for Model B and Model C of US model

Neural network	Model B						Model C	
	Output: Trust						Output: CBPurchase	
	Ethnocent	InfoQual	SysQual	ServQual	ProdJudg	Affinity	ProdJudg	Trust
ANN1	0.805	0.84	0.925	0.990	1.000	1.000	0.453	1.000
ANN2	0.846	0.83	0.829	0.999	0.784	1.000	0.595	1.000
ANN3	0.812	0.918	0.975	0.927	0.884	1.000	0.575	1.000
ANN4	0.827	0.908	0.973	0.886	0.961	1.000	0.482	1.000
ANN5	0.911	0.904	0.973	0.993	0.986	1.000	0.477	1.000
ANN6	0.884	0.939	0.952	0.872	0.961	1.000	0.478	1.000
ANN7	0.808	0.851	0.905	0.963	0.965	1.000	0.496	1.000
ANN8	0.889	0.985	0.781	0.786	0.854	1.000	0.529	1.000
ANN9	0.751	0.993	0.999	0.934	0.979	1.000	0.515	1.000
ANN10	0.955	0.890	0.774	0.925	0.893	1.000	0.494	1.000
Average relative importance	0.849	0.906	0.909	0.927	0.927	1.000	0.509	1.000
Normalized relative importance (%)	85.165	91.131	91.139	93.444	93.254	100.000	54.041	100.000

Table 12 Sensitivity analysis for Model A of China model

Neural network	Model A					
	Output: ProdJudg					
	Ethnocent	ServQual	Affinity	InfoQual	ProdUnique	PriceComp
ANN1	0.105	0.396	0.438	0.499	0.831	1.000
ANN2	0.093	0.382	0.487	0.465	0.831	1.000
ANN3	0.088	0.376	0.450	0.471	0.845	1.000
ANN4	0.084	0.402	0.429	0.442	0.802	1.000
ANN5	0.060	0.411	0.466	0.459	0.806	1.000
ANN6	0.076	0.409	0.426	0.472	0.829	1.000
ANN7	0.081	0.373	0.454	0.447	0.820	1.000
ANN8	0.111	0.384	0.411	0.478	0.846	1.000
ANN9	0.097	0.397	0.423	0.458	0.822	1.000
ANN10	0.055	0.410	0.454	0.464	0.812	1.000
Average relative importance	0.085	0.394	0.444	0.466	0.824	1.000
Normalized relative importance (%)	8.513	39.484	44.476	46.657	82.596	100.000

Table 13 Sensitivity analysis for Model B and Model C of China model

Neural network	Model B						Model C	
	Output: Trust						Output: CBPurchase	
	Ethnocent	Affinity	ServQual	InfoQual	SysQual	ProdJudg	Trust	ProdJudg
ANN1	0.604	0.751	0.839	0.873	0.886	1.000	0.780	1.000
ANN2	0.616	0.801	0.797	0.858	0.947	1.000	0.800	1.000
ANN3	0.605	0.792	0.762	0.879	0.946	1.000	0.830	1.000
ANN4	0.695	0.772	0.821	0.866	0.875	1.000	0.790	1.000
ANN5	0.647	0.762	0.826	0.943	0.900	1.000	0.780	1.000
ANN6	0.676	0.784	0.806	0.931	0.880	1.000	0.820	1.000
ANN7	0.736	0.844	0.827	0.913	0.878	1.000	0.790	1.000
ANN8	0.637	0.782	0.799	0.937	0.854	1.000	0.820	1.000
ANN9	0.662	0.802	0.802	0.930	0.911	1.000	0.820	1.000
ANN10	0.713	0.820	0.793	0.869	0.900	1.000	0.780	1.000
Average relative importance	0.660	0.790	0.810	0.900	0.900	1.000	0.801	1.000
Normalized relative importance (%)	67.156	81.658	83.651	92.321	92.484	100.000	84.646	100.000

The comparison of PLS-SEM and ANN results for both the U.S. and China models is shown in Tables 14 and 15. For the U.S. model, PLS-SEM path coefficients and the normalized importance scores from ANN yielded consistent rankings across all relationships in Models A, B, and C (Table 14).

Table 14 Comparison between PLS-SEM and ANN results for US model

PLS path	Original sample (O)/path coefficient	ANN results: normalised relative importance (%)	Ranking (PLS-SEM) [based on path coefficient]	Ranking (ANN) [based on normalised relative importance]	Results
Model A					
Output: ProdJudg					
PriceComp → ProdJudg	0.290	100.000	1	1	Match
ProdUnique → ProdJudg	0.286	98.100	2	2	Match
InfoQual → ProdJudg	0.197	50.800	3	3	Match
Affinity → ProdJudg	0.162	34.800	4	4	Match
Ethnocent → ProdJudg	-0.165	22.500	5	5	Match
Model B					
Output: Trust					
Affinity → Trust	0.325	100.000	1	1	Match
ProdJudg → Trust	0.210	93.000	2	2	Match
ServQual → Trust	0.183	93.000	3	3	Match
SysQual → Trust	0.160	91.000	4	4	Match
InfoQual → Trust	0.153	91.000	5	5	Match
Ethnocent → Trust	-0.134	85.000	6	6	Match
Model C					
Output: CBPurchase					
Trust → CBPurchase	0.402	100.000	1	1	Match
ProdJudg → CBPurchase	0.374	54.041	2	2	Match

For the China model, the match between the two approaches was also confirmed across all models (Table 15).

Table 15 Comparison between PLS-SEM and ANN results for China model

PLS path	Original sample (O)/path coefficient	ANN results: normalised relative importance (%)	Ranking (PLS-SEM) [based on path coefficient]	Ranking (ANN) [based on normalised relative importance]	Results
Model A					
Output: ProdJudg					
PriceComp → ProdJudg	0.361	100.000	1	1	Match
ProdUnique → ProdJudg	0.305	82.596	2	2	Match
InfoQual → ProdJudg	0.170	46.657	3	3	Match
Affinity → ProdJudg	0.161	44.476	4	4	Match
ServQual → ProdJudg	0.034	39.484	5	5	Match
Ethnocent → ProdJudg	-0.140	8.513	6	6	Match
Model B					
Output: Trust					
ProdJudg → Trust	0.351	100.000	1	1	Match
SysQual → Trust	0.274	92.484	2	2	Match
InfoQual → Trust	0.170	92.321	3	3	Match
ServQual → Trust	0.158	83.651	4	4	Match
Affinity → Trust	0.146	81.658	5	5	Match
Ethnocent → Trust	-0.115	67.156	6	6	Match
Model C					
Output: CBPurchase					
ProdJudg → CBPurchase	0.393	100.000	1	1	Match
Trust → CBPurchase	0.383	84.646	2	2	Match

Overall, the comparison confirms the complementarity of the two methods: while PLS-SEM offers hypothesis-driven insights and path significance, ANN strengthens the findings by validating predictor importance using a non-linear, data-driven approach.

6 Discussion

The findings confirm that platform quality is central to trust formation and product evaluation in cross-border e-commerce. Across both country models, system quality, e-service quality, and information quality jointly shape how consumers interpret product value through digital information and service flows. In the U.S. case, all three dimensions strengthen trust, while information quality is the only factor that directly affects product evaluations. In the China case, system quality primarily supports trust, whereas e-service quality and information quality influence both trust and evaluations. This suggests that Vietnamese consumers rely more on visible service execution and information transparency when assessing foreign products. ANN results further indicate that system quality acts mainly as an enabling infrastructure rather than a direct trigger of product judgments.

Attitudinal factors grounded in social identity also play a role, though unevenly. Ethnocentrism consistently weakens trust and product evaluations, but its practical effect appears stronger for trust than for evaluation outcomes. In contrast, animosity has no meaningful impact, implying that geopolitical tensions remain largely detached from everyday CBEC purchasing. Affinity toward the exporting country stands out as the strongest positive driver of trust and a key contributor to product evaluations, especially for U.S. goods. Overall, positive country-related feelings and perceived value outweigh negative national sentiments in routine cross-border transactions.

Value-related factors remain decisive. Price competitiveness and product uniqueness strongly shape product evaluations in both models, with price sensitivity being more pronounced for Chinese products. These results align with perceived value theory and the S-O-R framework, indicating that when direct inspection is impossible, consumers infer quality from price–value signals and platform-mediated information. From a managerial perspective, U.S. sellers benefit from emphasizing differentiation and symbolic value, while Chinese sellers may compete more effectively through price advantages combined with selective product differentiation.

Finally, the structural model supports a two-stage behavioral pathway in CBEC, where product evaluation and trust jointly drive purchasing decisions. While both factors matter, their relative importance differs by country of origin: trust plays a more decisive role for U.S. products, whereas perceived value more directly motivates purchases of Chinese goods. This asymmetry reflects differences in perceived risk and logistics reliability, suggesting that CBEC strategies should be aligned with both information flow quality and service execution expectations.

7 Conclusion

This study develops an integrative framework linking platform quality, national attitudes, and perceived value to trust, product evaluation, and purchasing behaviour in cross-border e-commerce. The findings show that information, service, and system quality jointly support trust and evaluation, while system quality mainly functions as enabling infrastructure. Country affinity and perceived value outweigh ethnocentrism and animosity in shaping CBEC decisions. Distinct behavioural patterns emerge across product origins, with trust being more salient for U.S. goods and value perceptions for Chinese goods. These insights highlight the importance of transparent logistics flows, reliable information, and context-sensitive platform and policy strategies in emerging markets.

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Simulation-based optimization of buffer sizing in demand-driven distribution requirements planning

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Keywords: demand-driven DRP, buffer sizing, bullwhip effect, working capital, on-time service.
Abstract: Demand-Driven Distribution Requirements Planning (DDDRP) has emerged as an effective alternative to traditional forecast-driven planning systems by relying on strategically positioned buffers to protect logistics flows against demand and lead-time variability. However, buffer sizing in DDDRP is still largely based on fixed parameters, which may limit its effectiveness in complex multi-echelon distribution networks. This paper proposes a simulation–optimization framework for the tactical calibration of buffer sizes in a demand-driven distribution context. The approach integrates discrete-event simulation, developed using Arena software, with a metaheuristic optimization engine (OptQuest) to dynamically adjust buffer sizing parameters under realistic material and information flow conditions. The model is applied to a multi-echelon distribution network characterized by heterogeneous demand and lead-time profiles. The results demonstrate that the proposed framework significantly improves the trade-off between working capital and service level, which are two primordial indicators for an optimal distribution, while enhancing the stability of downstream and upstream logistics flows. By bridging the gap between theoretical DDDRP sizing rules and their practical implementation, this study contributes to the literature on demand-driven logistics planning and provides decision support for distribution managers. Future research perspectives include the integration of capacity constraints, multi-product flows, and stochastic supply delays.

1 Introduction

In today's volatile and increasingly demand-driven markets, the ability to plan and execute supply chain operations in a responsive manner has become a critical competitive advantage. Traditional planning systems, such as Material Requirements Planning (MRP) and Distribution Requirements Planning (DRP), are primarily structured around forecast-driven logic. Although effective in relatively stable environments, these systems are well known for amplifying variability as demand information propagates upstream along the supply chain—a phenomenon widely referred to as the bullwhip effect (Lee et al., 1997) [1]. To mitigate these limitations, the Demand-Driven MRP (DDMRP) methodology has emerged as a hybrid planning approach that integrates real-time consumption signals, strategically positioned buffers, and decoupling strategies to stabilize material flows and protect service levels (Ptak and Smith, 2016) [2].

At the core of DDMRP lies the concept of strategically positioned inventory buffers, which are dimensioned using predefined, rule-based formulas. These buffers are designed to absorb demand variability and form the foundation of demand-driven planning. However, despite the conceptual clarity of this approach, real-world DDMRP implementations often rely on fixed or heuristically selected sizing parameters. This raises legitimate questions regarding the optimality of buffer configurations under realistic and dynamic operating conditions.

In response to these challenges, recent research has increasingly explored the use of simulation and optimization techniques to enhance the performance of DDMRP-based systems. For instance, Wang et al. (2015) [3] proposed a dynamic drum–buffer–rope model for hospital inventory management, employing Powell search methods to adjust buffer levels based on system feedback. Achergui et al. (2021) [4] addressed the joint problem of buffer positioning and sizing in multi-level environments using constraint programming, while other studies have optimized key sizing parameters—such as the Lead Time Factor (LTF), Variability Factor (VF), and Decoupling Order Cycle (DOC)—through simulation-based Taguchi methods. In parallel, doctoral research and recent studies have demonstrated the potential of hybrid metaheuristics, including genetic algorithms, for fine-tuning buffer configurations across multi-echelon distribution networks (Miclo, 2016) [5].

Foundational contributions by Erraoui et al. (2019) [6] introduced the first formal model dedicated to buffer sizing within a Demand-Driven Distribution Requirements Planning (DDDRP) context. This work was later extended by Erraoui et al. (2022) [7], who embedded the sizing logic within a simulation architecture and demonstrated the performance benefits of adaptive buffer calibration. Together, these studies emphasized the need for integrated simulation–optimization frameworks capable of dynamically adjusting buffer parameters in response to real-world demand and lead-time variability.

Building on this body of literature, the present paper proposes a simulation–optimization framework for tactical buffer sizing in a multi-echelon distribution network. The framework is implemented using discrete-event simulation in Arena software, with optimization performed through OptQuest metaheuristics. The objective is to identify suitable lead-time and variability parameter configurations that minimize inventory-related costs while maintaining a targeted service level. By combining flow-based simulation with performance-driven optimization, the proposed approach provides a practical decision-support tool for improving the effectiveness of DDDRP-based distribution planning.

The remainder of the paper is structured as follows. Section II reviews the theoretical foundations of Demand-Driven Distribution Requirements Planning (DDDRP), with emphasis on its core principles, buffer sizing logic, and identified research gaps. Section III presents the proposed simulation–optimization framework, including the distribution network description, model parameters, simulation logic implemented in Arena, and the OptQuest-based optimization strategy, along with the associated results and discussions. Finally, Section IV concludes the study and outlines directions for future research.

2 Theoretical background

2.1 From push systems to demand-driven distribution

Traditional planning systems in manufacturing and distribution, notably Material Requirements Planning (MRP) and its extension MRP II, have historically operated according to a push-based logic, in which production and replenishment decisions are driven by forecasted demand rather than actual consumption. Initially formalized by Orlicky (1975) [8] and later expanded by Wight (1984) [9], MRP systems provided structured, time-phased planning mechanisms but remained highly dependent on forecast accuracy. This dependency often led to the amplification of demand variability as information propagated upstream along the supply chain—a phenomenon widely known as the bullwhip effect (Lee et al., 1997) [1]. The bullwhip effect is associated with excessive inventory levels, degraded service performance, and operational instability in upstream processes (Figure 1). Subsequent studies, including those by Disney and Towill (2003) [10], further demonstrated the inherent sensitivity of MRP- and DRP-based systems to even minor demand fluctuations.

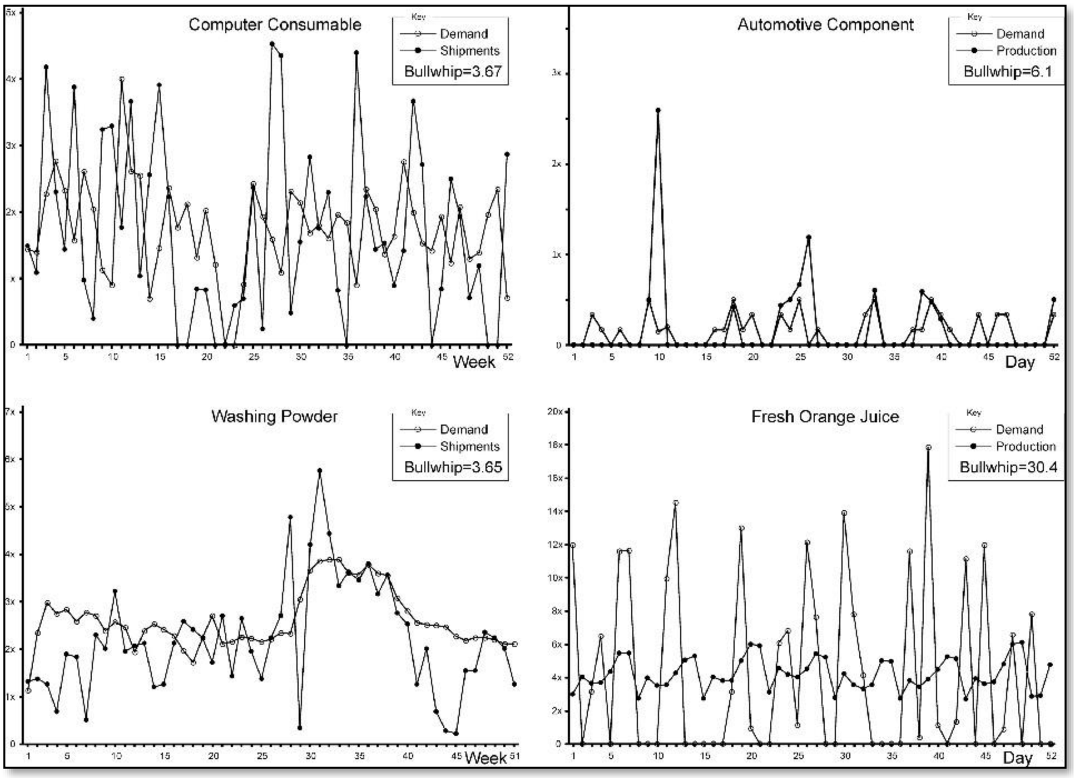

Figure 1 Bullwhip effect in different sectors

In response to these limitations, supply chain planning has progressively shifted toward pull-based and demand-driven strategies that prioritize real-time consumption signals over forecast-driven estimates. Holweg (2005) [11] characterized this transition as a move toward greater responsiveness, in which organizations seek to shorten lead times and reduce their reliance on demand projections. Within this context, Demand-Driven MRP (DDMRP) emerged as a hybrid planning approach that combines the structural discipline of MRP with the adaptability of pull systems. Developed by Ptak and Smith (2016) [2], DDMRP introduces strategically positioned inventory buffers and decoupling points to isolate variability and stabilize material flows. More recently, Uzun et al. (2024) [12] demonstrated the relevance of simulation tools for modeling and evaluating the performance of demand-driven systems under conditions of uncertainty (Figure 2).

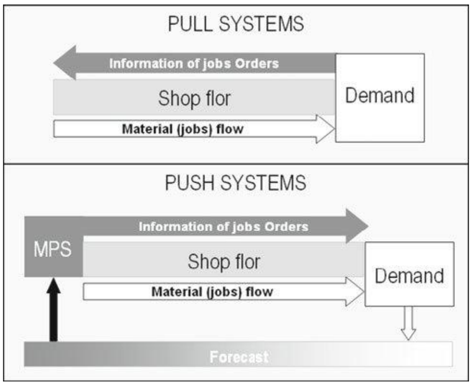

Figure 2 Difference between Push and Pull systems

2.2 Principles of Demand-Driven Distribution Requirements Planning (DDDRP)

Demand-Driven Distribution Requirements Planning (DDDRP) represents a modern evolution of conventional planning approaches, specifically designed to address the limitations of forecast-driven systems such as MRP and DRP. Originating from the work of Ptak and Smith (2016) [2] and further developed by Erraoui et al. (2019) [6], DDDRP adopts a flow-based, decoupling-centered strategy that integrates actual demand signals into the planning and execution processes. Its architecture is structured around five core components, each contributing to improved responsiveness and stability across the supply chain.

a. Strategic Inventory Positioning – T his component focuses on identifying optimal decoupling points within the distribution network. Rather than buffering inventory at every node, DDDRP strategically places buffers where they provide the greatest protection against demand and lead-time variability.

b. Buffer Profiles and Levels – At each decoupling point, DDDRP deploys a three-zone buffer structure composed of a red zone (safety stock), a yellow zone (average consumption over the decoupled lead time), and a green zone (replenishment quantity or order cycle). These zones are calculated using parameters such as Average Daily Usage (ADU), Decoupled Lead Time (DLT), and a variability factor. Erraoui et al. (2019) [6] were among the first to formally model this buffer structure within an analytical framework.

c. Dynamic Buffer Adjustments – Unlike traditional static inventory policies, DDDRP enables dynamic buffer adjustments in response to evolving demand patterns and operational conditions, allowing the system to adapt continuously to changes in variability.

d. *Demand-Driven Planning* – Planning decisions are governed by the Net Flow Position (NFP) (Figure 3), which compares on-hand inventory, open supply orders, and qualified demand. The effectiveness of this mechanism was explored and validated by Erraoui et al. (2022) [7].

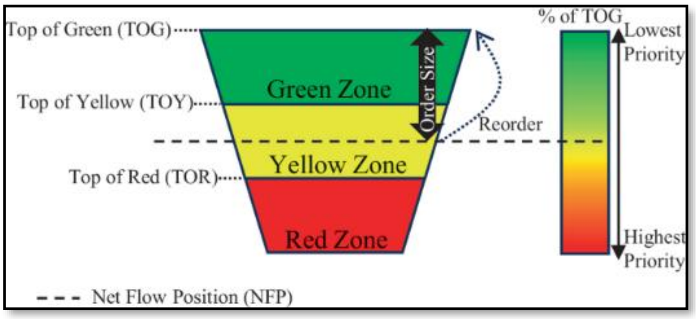

Figure 3 Net Flow Position in a buffer

e. Visible and Collaborative Execution – This component emphasizes operational transparency and coordinated execution across the supply chain, enabling faster decision-making and improved alignment among stakeholders.

2.3 Buffer sizing in DDDRP

Buffer sizing represents one of the most critical tactical decisions in the implementation of DDDRP. Once strategic inventory positions have been defined, each buffered point must be assigned an appropriate buffer profile composed of three zones: the red zone, which provides protection against variability; the yellow zone, which covers average expected consumption over the decoupled lead time; and the green zone, which determines the replenishment quantity or order cycle.

The theoretical foundation of buffer sizing in DDDRP, as described by Ptak and Smith (2016) [2], relies on deterministic relationships based on the Average Daily Usage (ADU) and the Decoupled Lead Time (DLT), combined with two calibration coefficients—the Lead Time Factor and the Variability Factor. These parameters define the buffer zones and ultimately determine replenishment behaviour within the demand-driven planning framework. The corresponding sizing relationships are expressed as follows (1), (2), (3):

$$YZ = ADU * DLT \tag{1}$$

$$GZ = YZ * LT\_Fac\_green \tag{2}$$

$$RZ = YZ * LT_{Fac_{red}} + YZ * LT\_Fac\_red * Var\_Fac \tag{3}$$

Despite their practical appeal, DDDRP buffer sizing rules are often implemented using fixed parameter values, which limit their flexibility and responsiveness. Such static configurations constrain buffer performance, particularly in multi-echelon distribution networks exposed to high demand variability and complex dependency structures.

Recognizing these limitations, Erraoui et al. (2019) [6] were among the first to propose a formal modeling framework for DDDRP buffer sizing, integrating buffer dimensions into a structured analytical formulation. Their work introduced explicit decision variables and mathematical relationships governing buffer behavior, highlighting the role of sizing in stabilizing the Net Flow Position and improving service performance. Building on this foundation, Erraoui et al. (2022) [7] extended the framework by embedding the sizing logic within a simulation-based architecture, enabling dynamic evaluation of buffer behavior under stochastic demand conditions. Their results demonstrated the sensitivity of both service level and working capital to buffer calibration, thereby motivating the use of optimization techniques for parameter tuning.

More recent studies have further explored simulation–optimization approaches to overcome the limitations of traditional DDDRP sizing rules. Wang et al. (2015) [3] developed a dynamic drum–buffer–rope (DDBR) model for hospital inventory management, in which buffer sizes are adapted in response to demand fluctuations using a system dynamics framework combined with a Powell search algorithm. Their approach proved effective in synchronizing inventory decisions across a multi-echelon internal supply chain while reducing stockouts and inventory costs. Similarly, Achergui et al. (2021) [4] addressed the joint optimization of buffer positioning and sizing in complex bill-of-material environments under DDDRP logic. Their enhanced linear model, solved using CP Optimizer, achieved improved computational efficiency and service-level performance, particularly in hybrid make-to-order/make-to-stock contexts. Another notable contribution is provided by Miclo (2016) [5], who proposed a three-phase simulation-based methodology to optimize buffer parameters such as the Lead Time Factor, Variability Factor, and Decoupled Order Cycle. By combining Taguchi experimental design with historical data analytics, their approach significantly outperformed default parameter settings derived from the original DDMRP formulation. Finally, Younespour et al. (2024) [13] presented a comprehensive investigation of DDDRP buffer sizing using simulation-based optimization and heuristic methods, including hybrid genetic algorithms, emphasizing the importance of multi-echelon coherence in buffer calibration and proposing a hybrid DDMRP–hedging strategy that improves service levels while reducing inventory costs.

Building on these contributions, the present study integrates DDDRP buffer sizing logic into a discrete-event simulation model and couples it with OptQuest metaheuristics to identify parameter configurations that minimize inventory-related costs while maintaining target service levels.

2.4 Research gaps and motivation

Although DDDRP provides a powerful conceptual framework for improving supply chain responsiveness, its practical implementation—particularly with respect to buffer sizing—remains largely heuristic and manually driven. In many industrial applications, buffer parameters are still defined using default or experience-based values, relying on fixed lead-time and variability factors as originally proposed by Ptak and Smith (2016) [2]. Such practices lack the adaptability required to address the dynamic and stochastic nature of real-world distribution networks.

Previous work by Erraoui et al. (2019) [6] represented an important step toward formalizing buffer sizing as a quantitative decision problem rather than a static managerial choice. This perspective was further reinforced by Erraoui et al. (2022) [7], who demonstrated the value of integrating simulation-based methods with DDDRP logic to evaluate buffer behavior under uncertainty and network interactions. Nevertheless, despite these advances, there remains a noticeable lack of scalable frameworks that combine discrete-event simulation, optimization techniques, and DDDRP principles in a unified and operationally applicable manner.

This paper addresses this gap by proposing a simulation–optimization framework that leverages Arena software and OptQuest metaheuristics to calibrate DDDRP buffer sizing parameters in a multi-echelon distribution network. By integrating flow-based simulation with performance-oriented objective functions, the proposed approach enables dynamic buffer tuning, leading to improved service levels and reduced working capital requirements under realistic operating conditions.

3 Buffer sizing optimization

The study focuses on a three-echelon distribution network operated by a Moroccan food manufacturing company. Finished products are produced at a central factory and delivered to hypermarkets through one of seven distribution centers (DCs), as illustrated in Figure 4. The empirical data used in this study include:

- historical sales data covering the last five years,
- distribution lead times,
- distribution and inventory-related costs.

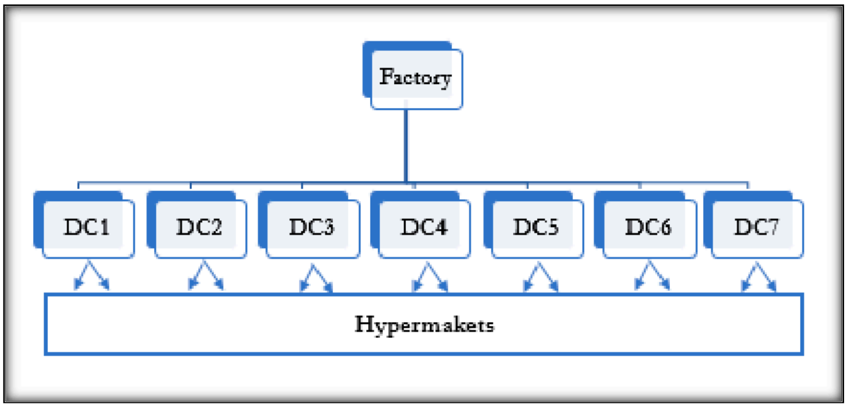

Figure 4 Distribution network of the case study

3.1 Distribution network modeling

Table 1 and figure 5 present the essential parameters for each implementation of the model, as well as the flowchart of DDDRP process.

Table 1 Modeling parameters

Parameter	Description
i	Day of the year
ADU(i)	Average daily usage on day i
Initial_Stock	Initial stock at the distribution point (day 0)
Stock(i)	Stock at the distribution point on day i
FS(i)	Future Spike relative to day i
Qualified_demand(i)	Qualified demand calculated on day i
Open_Supply(i)	Open supply orders on day i
Arrived_Supply(i)	Supply orders that arrived on day i
Demand(i)	Customer demand received on day i
Threshold(i)	Threshold for future Spike calculation on day i
RZ(i), YZ(i), GZ(i)	Buffer dimensions for red, yellow, and green zones respectively on day i
TOR(i), TOY(i), TOG(i)	Top levels of the red, yellow, and green buffer zones on day i
LT_Factor_Red(i)	Lead time factor for the red zone on day i
LT_Factor_Green(i)	Lead time factor for the green zone on day i
Var_Factor(i)	Variability factor of demand on day i

DLT	Decoupling lead time: the longest unbuffered delay between two buffered points
Q(i)	Order quantity set on day i
NFP(i)	Net Flow Position in the buffer on day i
Priority(i)	Planning priority on day i
ABI(i)	Average Buffer Inventory on day i

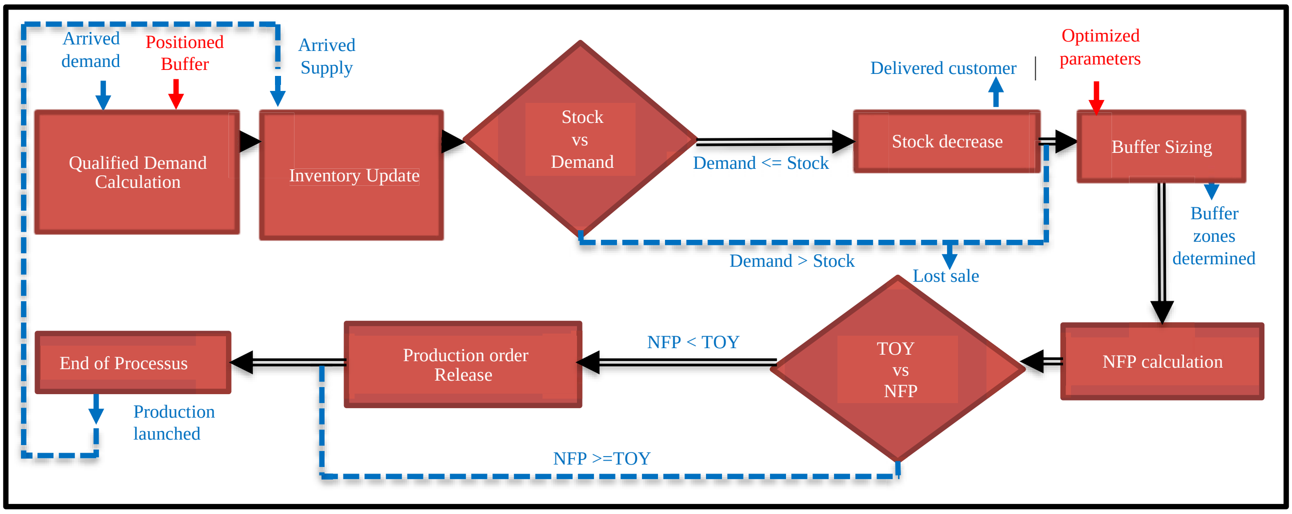

Figure 5 Modeling flowchart

The following algorithm details the blocks of the flowchart, which are numbered from 1 to 8. They describe the execution steps of a demand-based distribution spread over a 365-day horizon. The algorithm is structured as follows:

```
// Bloc 1 :  Qualified Demand Assignment
For (i=DLT; i<=365; i++)
{
       Threshold(i) = RZ(i)/2 ;
       for (k=i+1 ; k<=i + DLT ; k++)
       {
              if Demand (k) >= Threshold(i)
              FS(i)=FS(i)+Demand (k) ;
       }
Qualified_Demand(i)=Demand(i)+FS(i) ;

// Bloc 2 : Stock increasing
Stock(i)=Stock(i)+Arrived_Supply(i) ;

// Bloc 3 and 4 : Comparison between Demand and Stock
If (Demand (i) <= Stock(i))
{
Stock(i) = Stock(i) - Demand(i) ; // the client is delivered
}

// Bloc 5 : Buffer zones Calculation
YZ(i)=ADU(i)*DLT(i) ;
GZ(i)=YZ(i) ∗ LT_Factor_Green(i);
RZ(i)= YZ(i) ∗ LT_Factor_Red(i)+ YZ(i) ∗ LT_Factor_Red(i) ∗FacVar(i);
TOR(i)=RZ(i) ;
TOY(i)= TOR(i)+YZ(i) ;
TOG (i)= TOY (i)+GZ(i) ;
ABI(i)=RZ(i)+GZ(i) ;
```

```
// Bloc 6 : Calculation of Net Flow Position taking in consideration open supplies
for (k=i-1 ; k>=i-DLT ; k--)
{
Open_Supply(i)=Open_Supply(i)+Q(k) ;
}
NFP(i)=Stock(i)+Open_Supply(i)-Qualified_Demand(i) ;
If TOG(i) ≠ 0
{
Priority(i)=NFP(i)/TOG(i) ;
}

// Bloc 7 and 8 : Comparison between net flow position and top of yellow in Buffer
If (NFP(i)<=TOY(i))
{
Q(i)=TOG(i)-NFP(i) ; // A supply is open
}
Open_Supply (i + DLT) = Q (i);
}
```

3.2 Flow simulation logic in Arena software

The simulation model was developed using Arena software and represents the operational dynamics of a demand-driven distribution network (Figure 6). The modeled system consists of one factory, seven distribution centers (DC1 to DC7), and customer demand streams (Figure 7). The simulation implements the core decision logic of the Demand-Driven Distribution Requirements Planning (DDDRP) methodology.

The model is structured into modular blocks that sequentially manage demand processing, buffer sizing, inventory updates, order fulfillment, and factory replenishment decisions. This modular design facilitates the detailed representation of material and information flows across the distribution network and enables the systematic evaluation of buffer-related decision rules.

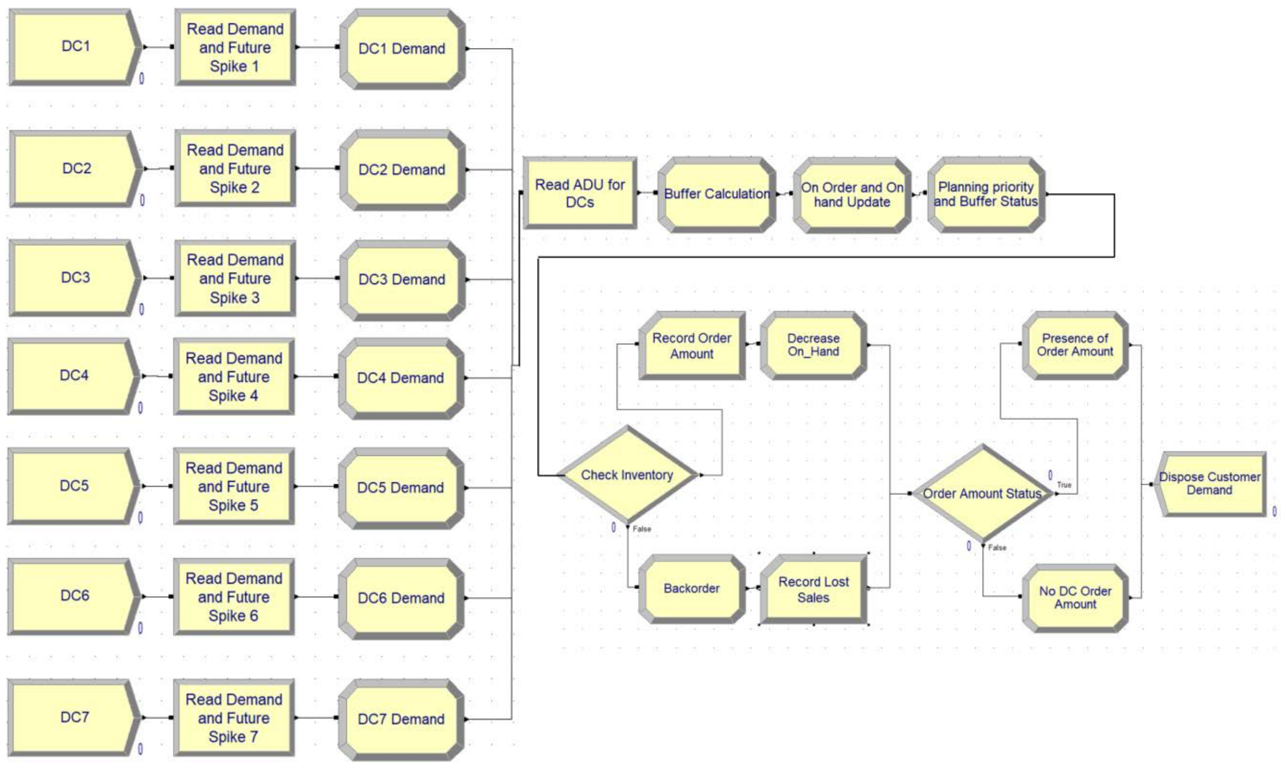

Figure 6 Modeling of process inside the distribution centers

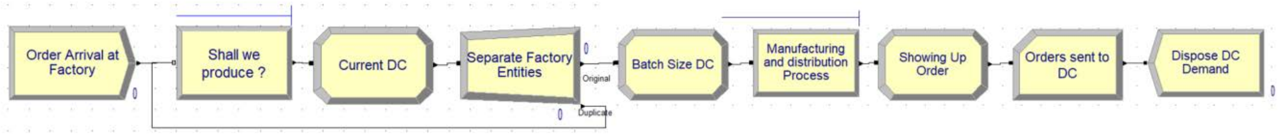

Figure 7 Modeling of process inside the factory

The Arena simulation captures the operational flow of a demand-driven distribution system based on DDDRP principles. The process begins with the collection of daily customer demand and anticipated demand spikes for each distribution center (DC1 to DC7). These inputs are used to compute the qualified demand, which reflects expected requirements by combining actual consumption with short-term variability considerations.

Buffer sizing is then performed using the Average Daily Usage (ADU), lead time factors, variability factors, and the Decoupled Lead Time (DLT). These parameters dynamically determine the dimensions of the red, yellow, and green buffer zones for each distribution center. Following buffer calculation, inventory levels are updated by tracking on-hand stock and open supply orders, which are required to compute the Net Flow Position (NFP), a central control variable in DDDRP logic. Based on the NFP, planning priorities are established and inventory availability is assessed to fulfill customer orders. When sufficient stock is available, orders are delivered and inventory is reduced; accordingly, otherwise, backorders are generated and lost sales are recorded. This logic enables an accurate assessment of service performance at the distribution level.

In parallel, the simulation incorporates a representation of the factory, which responds to replenishment signals generated by buffer consumption at the distribution centers. When NFP values and planning priorities indicate the need for supply, the model evaluates whether production orders should be launched. Replenishment orders are grouped by destination distribution center and processed through manufacturing and distribution stages. Once production is completed, finished goods are dispatched and delivered to the corresponding DCs. This factory-level logic reflects a pull-based supply mechanism aligned with DDDRP principles, where production is initiated based on actual buffer status rather than forecasted demand.

The complete simulation flow enables the evaluation of key performance indicators, including On-Time Service (OTS), Working Capital (WC), Net Flow Position, and Lost Sales. These indicators provide a robust basis for analyzing and comparing alternative buffer sizing strategies under realistic operating conditions.

3.3 Optimization logic and parameters

3.3.1 Objective function

Within the DDDRP approach, buffer size represents the quantity of inventory allocated to protect material flow against demand variability and can therefore be interpreted as protection stock. As illustrated in the DDDRP framework, this quantity must be maintained at an optimal level to avoid shortage situations that negatively affect service performance, as well as excess inventory situations that unnecessarily increase holding costs. Consequently, effective buffer sizing requires a balance between maintaining sufficient inventory levels and achieving a satisfactory service level.

To capture this trade-off, the objective function f incorporates two key performance indicators: On-Time Service (OTS) and Working Capital (WC), which reflects the financial impact of inventory and work-in-process. The formulation of f considers a target service level, denoted as the Desired On-Time Service (DOTS), which represents the company’s service expectations. When the achieved OTS falls below DOTS, penalties are incurred due to insufficient service performance.

It is assumed that each percentage point decrease in OTS below DOTS generates a penalty valued at PEN. Accordingly, the total penalty is expressed as (4):

$$Penalty = PEN * (DOTS - OTS) * 100 \tag{4}$$

This formulation applies only when OTS < DOTS; otherwise, no penalty is incurred. The resulting objective function is therefore defined as (5):

$$f = Min\{WC + MAX(0\,;\,PEN * (DOTS - OTS) * 100)\} \tag{5}$$

The On-Time Service rate is computed as the ratio of achieved sales to total demand, including lost sales (6):

$$OTS = \frac{ACHIEVED\ SALES}{TOTAL\ SALES} \tag{6}$$

In the DDDRP framework, optimal buffer sizes correspond to optimal values of the parameters appearing in Equations (1)-(3), namely the Lead Time Factor, the Variability Factor, and the Decoupled Lead Time (DLT). To identify suitable parameter values, an iterative improvement process was adopted, based on the minimization of the proposed objective function (Figure 8).

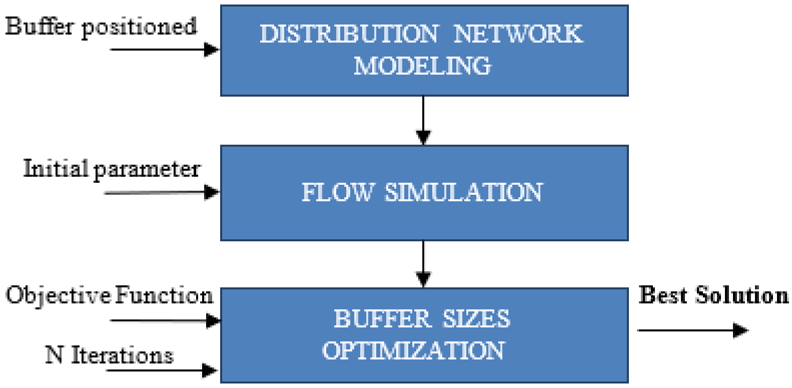

Figure 8 Optimization approach

Once the buffer positioning configuration is established, an initial set of sizing parameters is defined to initiate the optimization process. The discrete-event simulation model developed in Arena software records key performance indicators over the planning horizon, which are subsequently evaluated through the objective function. The optimization is performed iteratively using OptQuest, Arena's built-in optimization engine.

OptQuest integrates several metaheuristic strategies, including tabu search, scatter search, and neural network-based prediction models, to efficiently guide the search for optimal parameter values (Adenso-Díaz and Laguna, 2006; Bartz-Beielstein, 2006; Hong and Nelson, 2006) [14-16]. During the optimization process, parameter values are progressively adjusted across simulation runs until a predefined stopping criterion is reached, such as a maximum number of iterations. The procedure terminates by selecting the parameter configuration that yields the minimum objective function value. Table 2 presents the initial parameter values, their variation ranges, and the corresponding optimization steps.

Table 2 Values of initial, margins and steps of optimized parameters

DC	Lead Time Factor				Variability Factor				DLT			
	Initial	Min	Max	Step	Initial	Min	Max	Step	Initial	Min	Max	Step
DC1	**0.5**	**0.1**	**0.9**	**0.01**	**0.5**	**0.1**	**0.9**	**0.01**	**3**	**1**	**4**	**1**
DC2	**0.5**	**0.1**	**0.9**	**0.01**	**0.5**	**0.1**	**0.9**	**0.01**	**3**	**1**	**4**	**1**
DC3	**0.5**	**0.1**	**0.9**	**0.01**	**0.5**	**0.1**	**0.9**	**0.01**	**3**	**1**	**4**	**1**
DC4	**0.5**	**0.1**	**0.9**	**0.01**	**0.5**	**0.1**	**0.9**	**0.01**	**3**	**1**	**4**	**1**
DC5	**0.5**	**0.1**	**0.9**	**0.01**	**0.5**	**0.1**	**0.9**	**0.01**	**3**	**1**	**4**	**1**
DC6	**0.5**	**0.1**	**0.9**	**0.01**	**0.5**	**0.1**	**0.9**	**0.01**	**3**	**1**	**4**	**1**
DC7	**0.5**	**0.1**	**0.9**	**0.01**	**0.5**	**0.1**	**0.9**	**0.01**	**3**	**1**	**4**	**1**

3.3.2 Optimization execution and termination

The optimization process begins with the evaluation of the objective function for an initial parameter configuration. OptQuest then iteratively updates the parameters, computing the corresponding objective function value at each iteration and systematically recording both the results and their associated configurations. In the present study, the optimization was conducted over 500 iterations, a limit chosen to balance solution quality and computational effort. Figure 9 illustrates the objective function formulation, the minimum value obtained during the optimization process, and the evolution of objective function values across iterations.

The optimization procedure produced the best combination of four decision variables for each buffered distribution center, resulting in a total of 28 calibrated parameters across the network. Each optimization iteration corresponds to a full-year simulation of distribution flows, from which performance indicators are extracted. In this study, the complete optimization process of 500 iterations required approximately 30 minutes of computation time. The results reveal significant heterogeneity in optimal buffer parameters across distribution centers. In particular, the optimal Lead Time Factors for DC1 and DC5 differ, reflecting differences in replenishment lead times. Consistent with DDDRP principles, longer lead times require lower lead time factors, which result in smaller green zones and promote smaller, more frequent replenishment orders—an advantageous behavior for items with extended replenishment cycles.

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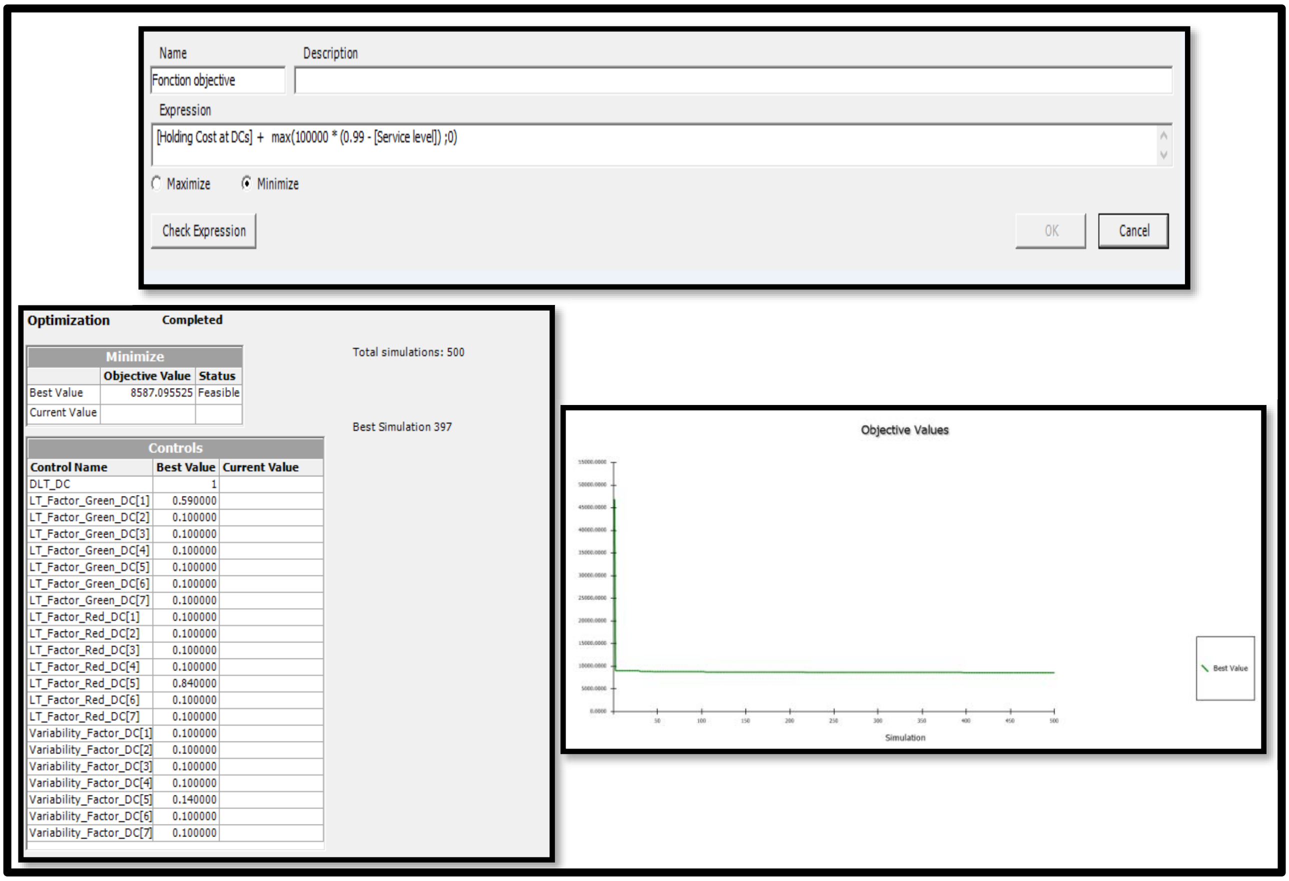

Figure 9 Optimization results with OptQuest

With respect to Variability Factors, deviations were observed primarily at DC5, indicating that products supplied through this distribution center are subject to higher demand or supply variability. This finding suggests the need for increased protection at DC5 and highlights the importance of locally calibrated buffer parameters rather than uniform settings across the network.

3.4 Discussion and future directions

This study evaluated the Demand-Driven Distribution Requirements Planning (DDDRP) approach by first establishing its theoretical foundations through alignment with well-known paradigms such as lean distribution and the theory of constraints. In this context, key DDDRP principles—including demand-driven logic, variability isolation, and protection buffering—were shown to provide a coherent framework for improving flow stability in multi-echelon distribution networks. Building on this conceptual grounding, a tactical buffer sizing model was developed and embedded within a simulation–optimization framework.

The proposed model relies on the Average Daily Usage (ADU) as a central input for buffer sizing, reflecting the consumption rate of an item at a given location. To enhance responsiveness to demand fluctuations, ADU was computed over a short-term horizon, which proved more effective in capturing local variability. In addition, the Decoupled Lead Time (DLT), defined as the cumulative distribution lead time across the network—including parent nodes—was incorporated to reflect structural dependencies within the distribution system. Buffer positioning decisions were evaluated through total storage cost minimization while considering broader return-on-investment (ROI) perspectives, recognizing that effective buffer placement aims not only at cost reduction but also at improving flow protection and responsiveness.

With buffer positions fixed, buffer sizing optimization was conducted using a dual-objective perspective that balances working capital (WC) and on-time service (OTS). The optimization results confirmed the relevance of this approach, as optimal parameter values varied significantly across distribution centers, reflecting heterogeneity in local demand patterns and lead-time characteristics. In particular, lower lead time factors were found to be more appropriate for nodes with longer replenishment cycles, as they generate smaller green zones and encourage more frequent, lower-volume replenishment orders. Conversely, higher variability factors were required in specific locations—such as DC5—where demand or supply uncertainty was more pronounced. These findings clearly indicate that uniform parameter settings are suboptimal in distributed networks and that buffer sizing should be locally adapted based on operational conditions.

Furthermore, the integration of discrete-event simulation with metaheuristic optimization provided a robust evaluation environment that simultaneously considers cost-related and service-level indicators over a full planning horizon. Compared with static, rule-based DDDRP sizing approaches, the proposed framework enables more informed and data-driven decision-making, supporting the alignment of tactical buffer management with strategic supply chain objectives.

Despite these contributions, several directions for future research remain. First, the current model assumes infinite storage capacity at distribution centers, which simplifies the analysis but limits realism. Future extensions could incorporate finite capacity constraints to better represent space limitations and the associated trade-offs between buffer size and available storage. Second, real-world distribution networks typically manage multiple product families with distinct flow characteristics. Extending the model to handle multiple products would improve its applicability and allow the investigation of shared resources, prioritization rules, and flow interference effects. Third, while this study primarily focused on demand variability, additional sources of uncertainty—such as supply variability and managerial variability—should be considered. Incorporating unreliable suppliers, transportation delays, and human resource constraints would further enhance the realism of the model. Finally, scalability issues associated with large networks may require linearized formulations and alternative solution techniques. Although OptQuest proved effective in this study, future research could benchmark it against other metaheuristic approaches, such as genetic algorithms, simulated annealing, or particle swarm optimization, to compare solution quality, convergence speed, and computational efficiency.

4 Conclusion

This paper proposed a simulation–optimization framework for the tactical sizing of inventory buffers within a Demand-Driven Distribution Requirements Planning (DDDRP) environment. Grounded in established supply chain principles—such as lean distribution, the theory of constraints, and flow protection—the study developed a buffer sizing model based on Average Daily Usage (ADU) and Decoupled Lead Time (DLT) as core inputs. The framework was implemented using discrete-event simulation in Arena software and optimized through OptQuest metaheuristics, with the objective of balancing working capital (WC) and on-time service (OTS).

The results demonstrate that optimal buffer parameters vary significantly across distribution nodes, reflecting local lead-time structures and variability profiles. In particular, the findings confirm that static, uniform sizing rules are inadequate for heterogeneous distribution networks. By contrast, the proposed dynamic sizing approach improves service performance without generating excess inventory, highlighting the benefits of locally adapted buffer calibration. The use of simulation enabled a realistic representation of logistics flows over a full planning horizon, while OptQuest effectively guided the search toward high-performing parameter combinations.

From a practical logistics perspective, this study provides decision-makers with a structured methodology to calibrate DDDRP buffers based on operational data rather than fixed heuristics. The framework supports more responsive and resilient distribution planning by aligning tactical buffer decisions with strategic objectives related to inventory efficiency and service reliability.

Despite these contributions, several avenues for further research remain. Future work could incorporate finite storage capacity constraints to better reflect physical limitations in distribution centers. Extending the framework to multi-product or product-family environments would enhance its applicability in real-world networks. In addition, future studies should consider broader sources of variability, including supply disruptions and managerial or organizational factors affecting flow execution. Finally, although OptQuest proved effective in this study, comparative analyses with alternative metaheuristic optimization methods—such as genetic algorithms or simulated annealing—could provide further insights into solution quality and computational performance under increasing network complexity.

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Mechanisms of digital logistics: how e-commerce SMEs improve logistics service quality and competitiveness

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Keywords: competitiveness, digital logistics management, digital maturity, e-commerce, service quality.
Abstract: This study examines how logistics digitalization in small and medium-sized enterprises (SMEs) engaged in e-commerce shapes customer satisfaction and business competitiveness through specific operational mechanisms. Using a structured narrative review, the research integrates conceptual findings into an analytical framework. The methodology consists of a bibliographic search (2020-2025), followed by a thematic synthesis of 69 abstracts selected after applying exclusion criteria. The analysis shows that digital logistics practices create value when they activate four mechanisms: visibility, synchronization, accuracy, and efficiency/automation. These mechanisms enhance customer satisfaction by improving transparency, reliability, personalization, and service speed, while strengthening competitiveness through cost reduction, scalability, and market differentiation. The findings also reveal that the effectiveness of these mechanisms depends on digital maturity, cultural adaptability, and absorptive capacity, as well as on broader institutional conditions. Limited investment, skill shortages, regulatory gaps, and infrastructural inequalities constrain SMEs' ability to fully scale digital tools, underscoring that technological adoption alone is insufficient without organizational readiness and institutional support. By articulating a framework of mechanism-based pathways linking digital practices to customer satisfaction and competitiveness, the study advances theoretical understanding beyond descriptive taxonomies and toward explanatory models of digital logistics. The study concludes by proposing a staged digital maturity model as a supporting tool to identify the current level of logistics capabilities of SMEs and to project scaling pathways toward higher levels of integration, automation, and analytical sophistication.

1 Introduction

Digital transformation stands as a key driving force in 21st century business evolution, profoundly reshaping how organizations operate and deliver value to customers through e-commerce. This process spans from product design to raw material management, manufacturing, distribution, and after-sales service, posing particular challenges for small and medium-sized enterprises (SMEs), which must rapidly adapt to a highly competitive and technologically demanding environment [1-2]. In this context, emerging technologies such as artificial intelligence, machine learning, the Internet of Things, and Big Data analytics reconfigure logistics operations, requiring new technical competencies and an organizational culture oriented toward innovation [3-4].

Digital logistics management emerges as a key strategy to coordinate business operations, optimize resources, and respond to growing expectations for traceability, personalization, and delivery times [5-6]. Several studies demonstrate that practices such as real-time tracking, automation, and dynamic reconfiguration of the supply chain directly influence customer satisfaction and loyalty [7-8]. However, SMEs face structural barriers that hinder technological adoption, including financial constraints, shortages in human capital, and organizational resistance to change [9-10]. Regarding competitiveness, the literature agrees that e-commerce and logistics digitalization can act as catalysts for sustainability and growth, provided a minimum level of digital maturity is in place [11-12].

While literature advances in identifying key practices and technologies associated with Logistics 5.0, a gap remains in understanding how these tools translate into tangible and sustainable competitive advantages for SMEs in emerging economies. Within this context, the present study aims to map and synthesize the impact of logistics digitalization in e-commerce SMEs on customer satisfaction and business competitiveness, considering the operational mechanisms involved. Accordingly, the study seeks to answer the central research question: How do digital logistics practices in e-commerce SMEs generate impact mechanisms that influence customer satisfaction and business competitiveness? To address this, the research offers a dual contribution. First, it develops an integrative framework linking digital practices with logistics mechanisms such as visibility, synchronization, accuracy, and automation through organizational outcomes. Second, it proposes a typology of practices and barriers to guide managerial decision-making in digital transformation processes.

Given the emerging and multidimensional nature of digital logistics management in e-commerce SMEs, this study adopts a structured narrative review as its methodological approach, aimed at conceptual synthesis and the mapping of relevant logistics practices. This type of review enables a critical articulation of the state of the art by integrating heterogeneous findings, identifying thematic patterns, and constructing an analytical framework that links digital practices with operational mechanisms and organizational outcomes, prioritizing interpretive conceptualization over statistical synthesis. Unlike a systematic review, this approach does not seek quantitative exhaustiveness but rather interpretive coherence and methodological transparency, grounded in explicit criteria for information search, selection, and organization. Its purpose is to foster a transversal reading of the academic corpus, facilitating comparative analysis across levels of digital maturity, logistics capabilities, and performance in competitiveness and customer service.

Accordingly, the study draws on a sample of 69 peer-reviewed articles indexed between 2020 and 2025, selected through thematic criteria and organized into a conceptual cartography that visualizes the causal thread connecting digital logistics practices to their corresponding operational mechanisms and to their outcomes in satisfaction and competitiveness within SMEs.

This study contributes to existing literature in three ways. First, it offers a consolidated synthesis of fragmented digital logistics frameworks, addressing the conceptual dispersion that characterizes current research. Second, it advances theoretical understanding by articulating mechanism-based pathways linking digital practices to customer satisfaction and competitiveness and, lastly, it proposes an integrative model of staged digital maturity tailored to the realities of e-commerce SMEs, as a preliminary tool for diagnostics and planification.

2 Literature review

Digital logistics management in e-commerce SMEs has gained prominence as a strategic axis for addressing the demands of traceability, efficiency, and personalization from contemporary consumers. However, the specialized literature reveals significant conceptual dispersion, lacking integrative frameworks that systematically link digital practices with the operational mechanisms that support them and the organizational outcomes they generate. This study addresses that gap by proposing a theoretical framework articulated across three dimensions: digital logistics management practices, logistics mechanisms, and outcomes. These dimensions, derived from thematic analysis of the academic corpus, enable the mapping and synthesis of the impact of logistics digitalization on customer satisfaction and business competitiveness.

2.1 Digital logistics management practices

Digital logistics management practices are defined as the set of actions, processes, and technologies aimed at planning, executing, and controlling logistics operations through digital tools [13]. These practices optimize supply chain efficiency, traceability, flexibility, and responsiveness, in alignment with the growing demands of e-commerce [14]. Key enabling technologies include real-time tracking, warehouse automation, and predictive logistics [6].

These practices can be classified in the following way [14-15]:

- Logistics Function: inventory management, distribution, reverse logistics
- Technological Level: low, medium, or high automation
- Expected Impact: cost reduction, delivery speed, service personalization
- SME Type: retail, food service, professional services

This classification enables the contextualization of practices according to industry sector and level of technological maturity, facilitating comparative analysis. From a strategic standpoint, the implementation of digital logistics solutions serves as a pathway to competitive differentiation for SMEs, particularly in saturated markets [12].

2.2 Logistic mechanisms

Logistic mechanisms can be understood as operational processes that mediate between technological adoption and organizational outcomes, facilitating visibility, synchronization, and automation across the supply chain. These mechanisms enable the translation of digital capabilities into competitive advantages, particularly in volatile and highly disruptive environments [16]. Within the scope of this research, these mechanisms function as impact vectors, helping to explain how logistics technologies influence customer experience and business competitiveness.

The identified mechanisms include:

- Visibility: the ability to monitor the status of orders, inventories, and logistics routes in real time
- Synchronization: dynamic alignment between supply, demand, and logistics operations
- Accuracy: precision in data management, delivery times, and product availability
- Automation: replacement of manual tasks with digital processes that enhance efficiency and reduce errors

These mechanisms act as mediators between technological adoption and expected outcomes, and their activation depends on the firm's level of digital maturity [11]. Empirical literature demonstrates that practices such as continuous monitoring and personalized deliveries enhance the perceived value of service [7-8].

2.3 Organizational outcomes

The organizational outcomes derived from digital logistics management concentrate on two key dimensions: customer satisfaction and business competitiveness. The former relates to the firm's ability to deliver agile, traceable, and personalized shopping experiences, while the latter is associated with operational efficiency, logistics resilience, and adaptability to changing environments.

Recent studies show that the quality of logistics services directly influences customer loyalty, particularly among consumer segments that value traceability and delivery flexibility [5, 7]. Regarding competitiveness, logistics digitalization has been shown to act as a catalyst for growth and sustainability, provided that a minimum foundation of technological and organizational capabilities is in place [10,12].

This theoretical framework offers a structured view of the relationship between digital practices, logistics mechanisms, and organizational outcomes, providing a conceptual basis for comparative analysis and managerial decision-making regarding the digital maturity level and innovation capacity of SMEs. By articulating these three dimensions, this study contributes to understanding how logistics digitalization in e-commerce SMEs functions as a strategic lever for enhancing customer satisfaction and business competitiveness, addressing a research gap that remains unresolved in the specialized literature.

3 Methodology

The review was conducted in two complementary stages, following a structured narrative review approach oriented toward conceptual synthesis and thematic mapping. First, a bibliographic search was carried out in December 2024 and July 2025, targeting peer-reviewed articles published in English between the first half of 2020 and the first half of 2025. The search was conducted across the Web of Science (WoS), Scopus, and ErihPlus databases using the following Boolean operators: (Logistics management OR Logistical management) AND digital transformation AND (ecommerce OR electronic commerce). This strategy yielded an initial corpus of 475 academic articles in English. The selected time frame corresponds to the post-COVID-19 surge in e-commerce, a period marked by intensified digital transformation processes in logistics management and a significant increase in relevant scientific output.

To delimit the scope of analysis, thematic exclusion criteria were applied to filter out studies focused on sustainability, environmentalism, green information technologies, health, education, public policy, taxation, and cryptocurrencies, as these topics fall outside the scope of a review centered on digital logistics management in SMEs. These criteria were operationalized through the identification of exclusionary keywords in titles, abstracts, and descriptors, complemented by manual screening to ensure thematic relevance. After removing duplicates and applying these filters, a final sample of 69 articles was selected for analysis.

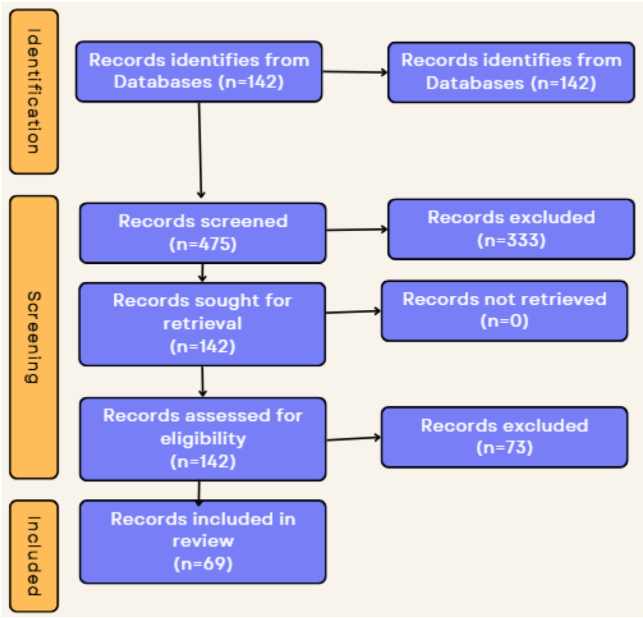

Figure 1 Identification of studies via databases and registers
Source: Figure developed by the author.

Second, the titles, abstracts, and keywords of the selected articles were thematically analyzed and narratively synthesized to identify recurring digital practices and conceptual challenges that present themselves as research gaps. This synthesis enabled the construction of a conceptual framework that clusters logistics practices and mechanisms according to their operational and strategic orientation, understood as the intended impact, and subsequently allows for linking the identified challenges to the digital maturity level of the firms. The framework proposed in the discussion responds to these gaps by providing an integrated reading of the state of the art as outlined in the theoretical review, contributing both to comparative research and to managerial decision-making in digital transformation processes.

4 Results

The study's findings are presented through a descriptive synthesis aimed at identifying and characterizing the main emerging themes within the analyzed corpus. This phase organizes empirical evidence and establishes patterns that serve as a foundation for the subsequent discussion, in which an interpretive synthesis will conceptually integrate the findings with the theoretical framework.

4.1 Practices and mechanisms identifies in SMEs dedicated to ecommerce

Digital logistics management in e-commerce is conceived as a set of actions, processes, and technologies designed to plan, execute, and control logistics operations through digital tools [13]. These practices function as enablers of efficiency, traceability, and responsiveness, and are articulated through specific mechanisms that influence both competitiveness and customer experience. The most relevant practices include:

- Collaborative Planning, Forecasting, and Replenishment (CPFR): data integration among supply chain actors to anticipate demand and adjust inventories via digital platforms
- Automated Inventory Management (VMI, JIT): replenishment systems based on actual consumption and predictive algorithms to minimize stockouts and overstock
- Warehouse Digitalization (WMS): use of sensors, QR codes, and RFID for real-time tracking and flow visualization through interactive dashboards
- Enterprise Resource Planning (ERP) and Supply Chain Management (SCM) System Integration: connection between procurement, production, and distribution through integrated systems and real-time monitoring of key performance indicators (KPIs)

These practices respond to the demands for differentiation in saturated markets and operational efficiency [12], as well as to customer satisfaction and loyalty through traceability, personalization, and delivery flexibility [7-8].

Table 1 summarizes, for each study, the dominant logistics mechanism (V/S/A/E), the expected impact, and the main implementation challenge, serving as a bridge to the practices–indicators linkage presented in Table 3.

Table 1 Conceptual framework of logistics mechanism, intended impact, and implementation challenges

Dominant logistic mechanism (V/S/A/E)*	**Intended impact**	**Challenges**
IA, blockchain, IoT, cloud	Improved efficiency, traceability	Heterogeneous adoption depending on digital maturity [13]
Big data, autonomous vehicles Visibility	Route optimization, operational visibility	Implementation costs [6]
IA, IoT, blockchain, ML	Strategic classification by logistics function	Low technological integration [14]
Real time tracking Accuracy	Customer loyalty, impact on Generation Z	Continuous service requirement
Traceability, flexibility Synchonization	Personalization, customer loyalty	Lack of sectoral standardization [7-8]
General digitalization Automation	Reduction of operational costos	Lack of digitally skilled human capital [9]
Resilient logistics Synchronization	Regional adaptability, sustainability	Territorial inequality in technological adoption [10]
Digital platforms Visibility Efficiency	Market Growth, Resilience Cost reduction	Limited digital capabilities in SMEs Organizational and technological barriers [11-12]

**V = Visibility, S = Synchronization, A = Accuracy, E = Efficiency/Automation*
Source: Author's own elaboration.

Table 1 presents a framework designed to classify the selected articles according to the contributing authors; the logistics mechanisms, understood as digital logistics management practices; the intended outcomes of their implementation—focused on customer service and competitiveness through operational cost reduction, route optimization, among others; and, finally, the most common implementation challenges.

4.2 Impacts and outcomes on customer satisfaction and business competitiveness

Building on the synthesis presented in Table 1, Table 2 operationalizes these impacts into measurable indicators of customer satisfaction and business competitiveness.

Table 2 Practices and indicators of customer satisfaction and business competitiveness in SMEs

Logistics Practices	Customer Satisfaction Indicators	Business Competitiveness Indicators	N° of studies
Inventory management, transportation, tracking, and delivery (Big Data, AI, IoT, drones, omnichannel strategies, smart warehousing, TOE frameworks)	Speed and reliability of delivery Order transparency Service personalization	Operational efficiency Reduction of logistics costs Market differentiation	24
Process automation and digital strategies	Seamless shopping experience Shorter order wait times Greater consistency in service	Operational scalability Flexibility and adaptability to change Innovation in business models	18
Training and competency management for operating disruptive technologies	Faster and more personalized customer service Greater customer trust in service	Development of internal capabilities	27

Source: Author's own elaboration.

The analysis of the data presented in Table 2 reveals that inventory management, transportation, tracking, and delivery—supported by technologies such as Big Data, Artificial Intelligence, IoT, drones, omnichannel strategies, and smart warehousing—constitute the most extensively studied core in the literature, with 24 studies. These practices are directly associated with improvements in customer satisfaction by ensuring faster and more reliable deliveries, enhanced order traceability, and personalized service. In parallel, they are linked to business competitiveness indicators such as operational efficiency, reduction of logistics costs, and market differentiation in highly competitive environments.

Secondly, process automation and the implementation of digital strategies are supported by 18 studies, highlighting their role in generating smoother shopping experiences, with fewer errors and greater consistency in service delivery. From a competitive perspective, these practices enable SMEs to scale operations, adapt more flexibly to environmental changes, and explore innovations in their business models.

Finally, the literature also emphasizes the importance of training and talent management for operating disruptive technologies, with 27 studies underscoring their impact on customer satisfaction through faster and more personalized service, as well as the development of customer trust. In terms of competitiveness, the formation of internal capabilities is recognized as a key factor in sustaining digital transformation over time and ensuring that logistics innovation translates into stable and scalable organizational advantages.

4.3 Integrative insights

Figure 2 illustrates the number of studies addressing challenges related to internal digital transformation, internal cultural transformation, and external factors beyond the company.

The implementation of digital logistics management is conditioned by a set of interdependent organizational and institutional factors that influence the extent to which digital tools become improvements in customer service and business competitiveness. Rather than isolated barriers or challenges, the results of this study reveal a series of integrative dynamics that can explain how digital transformation unfolds within businesses and across their operating environments.

- Digital Maturity as a Foundational Enabler of Logistical Transformation: The adoption of advanced technologies such as Big Data, Internet of Things (IoT), Artificial Intelligence (AI), traceability systems, and personalization tools depends critically on the business' level of digital maturity. This maturity reflects the capacity to invest in, integrate, and scale digital solutions, a condition that remains limited in many small and medium-sized businesses due to structural constraints in technological and operational modernization [17-42]. Consequently, digital maturity functions as a moderating mechanism that determines whether digitalization efforts effectively enhance logistical efficiency, customer service responsiveness, and competitive positioning.
- Cultural Transformation as the Core Mechanism Enabling Technological Adoption: The literature consistently highlights that technological implementation is contingent upon a deeper process of cultural transformation. Openness to innovation, willingness to embrace change, and the development of digital competencies across organizational levels constitute the cultural foundations that enable the effective integration of emerging technologies [20,21,28,29,32,33,38,39,43-52]. Cultural adaptability thus emerges as a central mechanism, shaping

not only the pace of digital adoption but also the capacity of businesses to leverage digital tools for improved customer experience and competitive differentiation.

- Gaps Between Technological Availability and Organizational Absorptive Capacity: A recurring pattern in the literature is the misalignment between the rapid evolution of digital technologies and the limited absorptive capacity of many organizations. This gap appears as insufficient investment, shortages of digital skills, and difficulties in reconfiguring processes to accommodate disruptive tools [17-52]. As a result, the competitive benefits associated with digital logistics such as enhanced traceability, personalization, and operational agility remain unrealized in businesses that lack the dynamic capabilities required to internalize and operationalize technological innovations.
- Institutional Insufficiencies as Systemic Constraints on Digitalization: Beyond internal dynamics, the external environment plays a decisive role in shaping the trajectory of digital transformation. Insufficient legislative support, limited access to infrastructure, and scarce training and funding mechanisms constrain businesses' ability to develop the competencies needed to manage disruptive technologies [37,40,41,47,53-69]. Additionally, regulatory voids concerning ethical, privacy, and cybersecurity requirements hinder the responsible and secure deployment of digital tools. These institutional gaps constitute systemic constraints that restrict the scalability and sustainability of digital logistics initiatives.
- Weak Strategic Alignment Between Digitalization, Customer Service, and Competitiveness: Although digital technologies hold significant potential to enhance service quality and competitive performance, many organizations struggle to align digital initiatives with strategic objectives related to customer experience and market positioning. Cultural, technological, and regulatory limitations hinder the intent to digitalize and the capacity to generate tangible value, resulting in a conceptual and practical gap in both managerial practice and academic research [17-69]. Strengthening this articulation is essential for ensuring that digital logistics investments translate into measurable improvements in customer satisfaction and competitive advantage.

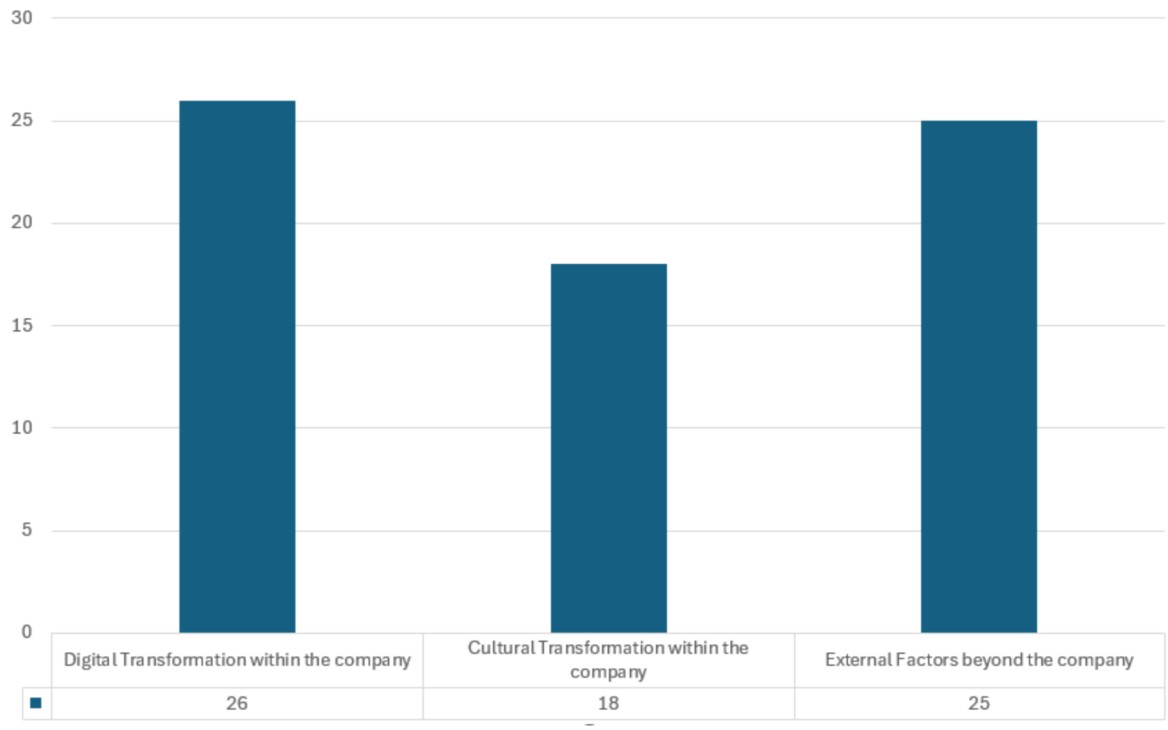

Figure 2 Number of studies categorized by type of challenge

5 Discussion

The structured narrative review reveals a consistent pattern across the analyzed studies: digital logistics practices in SMEs dedicated to e-commerce generate value not through isolated technological tools, but through the interaction of specific logistics mechanisms. These mechanisms: visibility, synchronization, accuracy, and efficiency/automation shape customer satisfaction and business competitiveness. They operate as mediators between technological adoption and performance outcomes, and their effectiveness depends on the organizational and institutional conditions identified in the integrative insights.

5.1 Interpretation of the pattern of results: implications for customer satisfaction and competitiveness

Across the review, customer satisfaction emerges as a factor given by speed, reliability, transparency, and personalization, while competitiveness is driven by operational efficiency, cost reduction, scalability, and differentiation. The results show that digital logistics practices consistently reinforce these dimensions, but their impact is uneven and moderated by digital maturity, cultural adaptability, and absorptive capacity.

Inventory management, transportation, tracking, and delivery, supported by Big Data, AI, IoT, drones, omnichannel strategies, and smart warehousing, constitute the most influential cluster of practices. Their prominence in 24 studies underscores that customer satisfaction in e-commerce logistics is fundamentally operational. This means that customers reward businesses that deliver quickly, transparently, and reliably. These same practices enhance competitiveness by reducing costs, optimizing routes, and enabling differentiation in saturated markets.

Process automation and digital strategies, relevant in 18 studies, contribute to smoother shopping experiences and greater service consistency, reinforcing the idea that operational fluidity is a precursor to customer loyalty. Competitively, automation enables SMEs to scale operations and adapt to environmental volatility, aligning with the literature on dynamic capabilities.

Finally, training and competency development, throughout 27 studies, highlight that human capital remains central to digital transformation. Faster, more personalized service and increased customer trust depend on employees' ability to operate disruptive technologies. Competitiveness, in turn, is sustained when internal capabilities evolve alongside technological change.

Taken together, these patterns confirm that digital logistics practices generate value only when businsses possess the cultural, organizational, and institutional conditions to absorb and operationalize them, which are reflected in five integrative insights.

5.2 Links between logistics mechanisms (V/S/A/E) and outcomes on customer service and competitiveness

The mechanisms identified in Table 1, Visibility (V), Synchronization (S), Accuracy (A), and Efficiency/Automation (E), provide a conceptual bridge between digital practices and performance outcomes. Each mechanism activates a distinct pathway through which digital logistics influences customer satisfaction and competitiveness.

- Visibility (V): Visibility mechanisms are enabled by Big Data, IoT, real-time tracking, and digital platforms and enhance order transparency, traceability, and customer follow-up. In this sense, customers perceive transparent operations as more reliable, which increases trust and satisfaction (Visibility → Trust → Satisfaction) and businesses gain real-time situational awareness, enabling route optimization and cost reduction (Visibility → Operational insight → Competitiveness).
- Synchronization (S): Synchronization mechanisms are supported by CPFR, ERP–SCM integration, and resilient logistics system, which coordinate flows across the supply chain. In this sense, coordinated processes reduce delays and variability, improving perceived service quality (Synchronization → Delivery consistency → Satisfaction), and SMEs can respond more quickly to demand fluctuations and environmental disruptions (Synchronization → Agility and adaptability → Competitiveness).
- Accuracy (A): Accuracy mechanisms are driven by real-time tracking, predictive analytics, and automated inventory systems and ensure precise execution of logistics tasks. As a result, accurate order preparation and delivery reduce errors and enhance customer loyalty, especially among digitally demanding segments such as Generation Z (Accuracy → Reliability → Satisfaction), and precision minimizes operational losses and strengthens cost efficiency (Accuracy → Reduced waste and rework → Competitiveness).
- Efficiency and Automation (E): Efficiency mechanisms are enabled by automation, WMS, robotics, and digitalization optimize resource use and streamline operations. This implies that shorter wait times and seamless experiences improve customer perceptions (Automation → Faster service → Satisfaction) and automated processes support growth and reduce labor-intensive bottlenecks (Automation → Scalability and cost reduction → Competitiveness).

The effectiveness of the mechanisms examined is inherently conditioned by the organizational and institutional context in which they are implemented. First, the organization's level of digital maturity determines the extent to which visibility and automation tools can be fully implemented, directly shaping their operational reach and depth. Cultural transformation also plays a central role in enabling synchronization and accuracy, as it fosters openness to new practices, technologies, and competencies. Similarly, absorptive capacity emerges as a critical factor, as it defines the organization's ability to translate technological availability into concrete operational improvements. This process is not automatic; it requires cognitive structures, routines, and prior learning that allow digital knowledge to be internalized and exploited. In parallel, institutional support influences the scalability of these practices, particularly for SMEs that often face regulatory, financial, or infrastructural constraints limiting the full adoption of digital solutions.

5.3 Supporting diagnostic: digital maturity model

Strategic alignment acts as an integrating element that prevents the mechanisms from being implemented as isolated tools. Instead, embedding them within a coherent value-creation logic enables them to contribute synergistically to organizational objectives.

Understood as a whole, these elements show that the mechanisms of visibility, synchronization, automation, and standardization do not operate independently or within a purely technical domain. Rather, they are embedded in a socio-technical system in which organizational readiness and institutional conditions determine their actual capacity to enhance customer satisfaction and strengthen competitiveness.

The analysis reveals that the implementation of digital logistics management is not constrained by isolated barriers but by the interactión and articulation of organizational maturity, cultural adaptability, absorptive capacity, and institutional support. Digital maturity and cultural transformation emerge as foundational mechanisms that condition the extent to which technological investments translate into improvements in customer service and competitiveness. At the same time, the persistent gap between technological availability and organizational capabilities, together with systemic institutional insufficiencies, limits business' ability to scale and sustain digital initiatives. These dynamics highlight a broader strategic misalignment between digitalization efforts and value creation objectives, suggesting that the competitive potential of digital logistics depends less on the mere adoption of technologies and more on the coherence between internal capabilities, cultural readiness, and the external regulatory environment. This integrative perspective provides a basis for discussing how businesses and policymakers can strengthen the conditions necessary for digital logistics to generate meaningful and sustained competitive advantages.

Figure 3 illustrates the interrelations between digital transformation and cultural transformation, and how these converge in strengthening the organizations' capacity for innovation and coordination, oriented toward the consolidation of strategic projects.

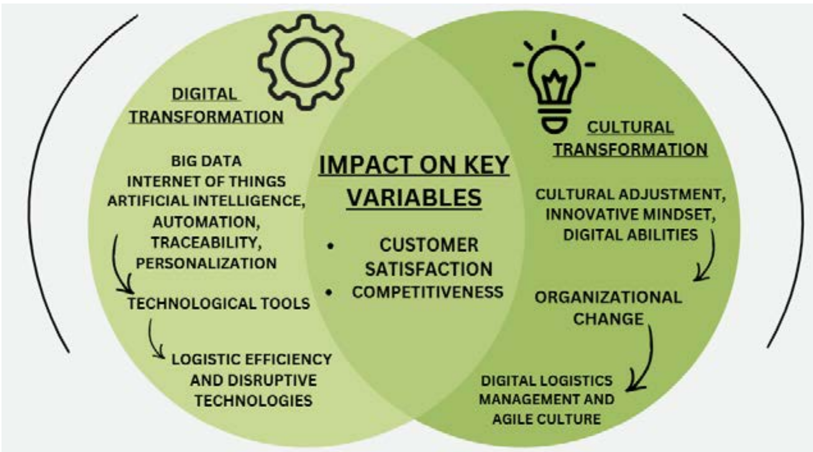

Figure 3 Articulation of implementation challenges in digital logistics management focused on customer service and competitiveness
Source: Author's own elaboration.

Figure 3 illustrates that both digital transformation and cultural transformation are essential for scaling the digital maturity of firms, as the supporting elements for a diagnostic tool to diagnose digital maturity in Table 3. In Figure 3, each axis impacts customer service and competitiveness; however, they face distinct challenges. On one hand, cultural transformation requires organizational change, managing change and fostering a willingness to reconfigure agile mindsets are significant barriers that firms must overcome. On the other hand, digital transformation demands key investments in both operational technologies and machinery, aimed at improving logistics efficiency and mastering disruptive technologies.

In this sense, firms must develop differentiated competencies according to their resources and context, with strategic management, innovation, and continuous training being critical factors for organizational survival and sustained growth [68,69]. This need becomes increasingly urgent in business cycles that are shorter and more complex, shaped by technological acceleration and market volatility.

The willingness to embrace change and the development of digital competencies across all levels of the firm must confront the reconfiguration of values, practices, and mindsets among employees throughout the organizational structure, in order to respond effectively to the constant evolution of emerging technologies [17-42].

During the growth stage, firms require financing and commercial strategies that enable them to attract customers and investors, achieve economies of scale, and compete with established players. The management phase is associated with financial stability, allowing for strategic decisions regarding investment or divestment based on competitive positioning. However, the lack of continuous adaptation may lead to organizational decline, evidenced by decreasing sales and the need for structural adjustments.

This process is directly linked to digital transformation, which demands significant technological and operational investments. Firms acknowledge the need to incorporate advanced tools such as Big Data, Internet of Things (IoT), Artificial Intelligence (AI), traceability systems, and personalization technologies, all aimed at optimizing logistics efficiency and sustaining competitive advantages in dynamic environments. These technological solutions target operational effectiveness and organizational productivity, yet their implementation faces a major challenge: limited investment in digitalization and operational modernization processes, particularly within the context of small and medium-sized enterprises [20,21,28,29,32,33,38,39,43-52].

The survival phase, understood from a Darwinian perspective, requires adaptive capacity through innovation, strategic alliances, and product renewal. It is worth noting that, in adverse contexts, firms that strategically adapt through partnerships, progressive digitalization, and an innovative culture are more likely to advance toward growth and consolidation stages. However, on their path to consolidation, firms must respond to external pressures that directly affect their viability and are not always within their control [37,40,41,47,53-69].

The external pressures faced by SMEs in logistics digitalization processes manifest across three critical dimensions: regulatory-political, sociocultural, and technological. On the regulatory front, fiscal, labor, and technological changes directly affect operational costs and strategic planning. In particular, regulations concerning e-commerce, data protection, and cybersecurity have become increasingly relevant in digital contexts, demanding both operational efficiency and ethical responsibility in the use of disruptive technologies.

From a sociocultural perspective, shifts in consumer preferences, alongside demographic dynamics such as population aging, migration, and demands for inclusion, compel firms to reassess their business models and redefine their target markets.

In the technological domain, the rapid evolution of tools such as Artificial Intelligence (AI), Internet of Things (IoT), and big data analytics imposes constant pressure to adapt. However, many SMEs face significant gaps in infrastructure and human capital development, which limit their effective access to these technologies. The accelerated obsolescence of traditional processes and the need for ongoing reinvestment create a challenging environment that demands strategic vision and organizational transformation capacity.

This aligns with the classification of firms by degree of innovation, categorized into three levels, leading, modest, and non-innovative enterprises [70,71]. This classification corresponds to the observed levels of digital maturity and is directly related to the barriers to open innovation in firms, which are explained across three dimensions: cognitive, behavioral, and institutional. These levels reflect that logistics innovation does not depend solely on technological availability, but also on organizational culture, leadership, and internal incentives. This implies the need for a preliminary stage prior to the implementation of digital tools, one that relates to the maturity levels of entrepreneurs, which condition their openness to innovation, understanding of its benefits, and motivation to adopt it.

Once the need to access technology and pursue digital transformation and adaptive capacity is understood, it becomes essential to recognize that external factors, such as access to financing, regulatory frameworks, and institutional support, also influence the viability of innovation processes, particularly during the early stages of the business lifecycle.

Based on this articulation between theory and empirical evidence, a diagnostic tool is proposed to structure logistics innovation capacity according to the level of digital maturity. The model in Table 3 is organized as a scaled typology, ranging from a Basic level, characterized by incipient digitalization and low adaptability, to a Transformative level, marked by adaptive logistics, intelligent personalization, and intensive use of emerging technologies. Each level incorporates technological, operational, and analytical dimensions that enable the evaluation of an organization's innovative capacity and its competitive potential in digital environments.

Table 3 Staged digital maturity model

Digital maturity level	Degree of innovative adaptability
1. Basic	Use of isolated tools, low automation
2. Intermediate	Partial system integration, functional automation
3. Advanced	Technological synergy between areas, predictive analysis and traceability
4. Transformational	Use of AI, IoT, Big Data, Adaptive Logistics, and Personalization

Source: Author's own elaboration.

In Table 3, the progression from a Basic level to a Transformative one reflects not only technological adoption, but also the degree of integration, automation, and analytical sophistication that enables logistics innovation. The configuration of these levels is grounded in the business lifecycle stages [70] and aims to offer a preliminary definition to help entrepreneurs recognize the level of innovative capacity afforded by their firm's digital maturity, guiding them on how to scale toward greater capabilities and reach in terms of competitiveness and customer service.

Within this model, the Basic level is characterized by incipient digitalization and low adaptability. This means that digital tools are used in isolation, such as spreadsheets or non-integrated software, among others. As a result, its innovative capacity is limited. Low automation hinders process optimization, data-driven decision-making, and agile responses to environmental changes. Consequently, logistics operations are reactive, with limited traceability and a reliance on manual processes.

At the Intermediate level, functional automation and partial connectivity are present. This level is defined by partial integration of systems (ERP, WMS, CRM), enabling some degree of interoperability and coordination across departments. Accordingly, its innovative capacity is moderate, allowing for the automation of specific functions such as inventory or dispatch, which improves operational efficiency. In this context, useful information begins to be generated for decision-making, although gaps in data communication and limitations in adaptability still persist.

The Advanced level is characterized by technological synergy and predictive analytics, enabled by interconnection across logistics areas through digital platforms, with capabilities for predictive analysis and real-time traceability. As a result, its innovative capacity is high, reflected in the organization's ability to anticipate demand, optimize routes, and manage resources dynamically. This consolidates a data-driven intelligent logistics system that enables proactive responses and continuous improvement.

Finally, at the Transformative level, logistics becomes adaptive and intelligent personalization is achieved. This is defined by the intensive use of emerging technologies such as Artificial Intelligence (AI), Internet of Things (IoT), and Big Data. Its innovative capacity is very high, as logistics become adaptive, able to personalize services, predict behaviors, and respond in real time to environmental changes. This leads to a sustainable competitive advantage, with customer-centered, resilient, and scalable logistics models.

6 Conclusion

This study examined the digital logistics practices adopted by SMEs engaged in e-commerce and analyzed their impacts on customer satisfaction and business competitiveness through a mechanism-based lens. The methodology employed consisted of a structured narrative review in two phases: a bibliographic search across indexed databases (WoS, Scopus, and ERIH Plus) from 2020 to 2025, followed by a thematic synthesis of the selected abstracts. The analysis enabled the construction of a conceptual framework structured by the identification of mechanism-based pathways linking digital practices to customer satisfaction and competitiveness. By articulating how visibility enhances trust, synchronization improves consistency, accuracy reduces service errors, and automation enables scalability, the study provides a conceptual model that clarifies how and why digital logistics practices generate value in e-commerce contexts. This mechanism-oriented approach advances theoretical understanding of digital logistics beyond descriptive taxonomies and toward explanatory models.

The findings show that digital logistics management is most effective when practices such as automated inventory systems, real-time tracking, omnichannel strategies, and integrated ERP–SCM platforms activate four key logistics mechanisms: visibility, synchronization, accuracy, and efficiency/automation. These mechanisms, in turn, shape customer satisfaction through transparency, reliability, personalization, and service speed, while enhancing competitiveness through cost reduction, operational scalability, and market differentiation.

The study also reveals that the value of these mechanisms is contingent on business' digital maturity, cultural adaptability, and absorptive capacity, as well as on the broader institutional environment. Limited investment, skill shortages, regulatory gaps, and infrastructural inequalities constrain the ability of SMEs to fully leverage digital tools. This underscores that the effectiveness of digital logistics practices is not inherent to the technologies themselves but emerges from the interaction between visibility, synchronization, accuracy, efficiency/automation mechanisms and the business's digital maturity, cultural adaptability, and absorptive capacity.

The study also highlights the systemic role of institutional conditions, including regulatory support, infrastructure, training programs, and ethical guidelines, in shaping the scalability and sustainability of digital transformation in SMEs. This insight contributes to institutional theory by emphasizing that digital logistics capabilities are embedded in broader ecosystems that can either enable or constrain innovation.

Ultimately, the study highlights that the competitive potential of digital logistics lies not in technology alone, but in the coherence between technological adoption, organizational readiness, and institutional support. As supporting elements, to generate value in the context of e-commerce, a staged model for digital maturity (Table 3) is proposed as a diagnostic tool for SMEs.

Managerial implications

From a practical standpoint, the findings provide strategic inputs for decision-making in digital transformation contexts. First, it is recognized that SMEs face persistent structural barriers such as insufficient infrastructure, resistance to change, financial constraints, and shortages in human capital. These challenges must be addressed with consideration for the organizational lifecycle and institutional environment, as they directly affect the viability of innovation processes and the sustainability of technological investments. Managers can use the mechanism-based framework to prioritize investments that strengthen visibility, synchronization, accuracy, and automation, while policymakers can leverage institutional insights to design targeted interventions that reduce capability gaps and promote equitable digital adoption across regions and sectors. This approach facilitates the prioritization of investments, the selection of appropriate technologies, and the alignment of internal and external capabilities.

Second, it is emphasized that improvements in customer satisfaction and business competitiveness do not rely solely on the adoption of disruptive technologies, but rather on the organization's ability to integrate them strategically. This requires overcoming gaps in training, leadership, and organizational culture, as well as confronting regulatory and economic challenges. Factors such as inflation, interest rates, and access to credit directly influence SMEs' capacity for investment and expansion, particularly in economically volatile environments.

Finally, the need for public policies that promote subsidies, accessible training programs, and certifications in digital logistics management is underscored. Such measures can foster virtuous linkages between the productive sector, academic institutions, and government agencies. This articulation has the potential to strengthen a culture of collaborative innovation, enabling SMEs to compete in the digital economy in an ethical, inclusive, and sustainable manner.

It is worth noting that this emerging conceptual framework offers a preliminary definition oriented toward business practice and opens the possibility of advancing toward integrative and comparative reviews, both regional and national, that allow for the contrast of digital maturity patterns and innovative capacities across different contexts. In doing so, gaps and opportunities can be identified for future research that deepens the relationship between logistics digitalization, competitiveness, and service quality, contributing to the academic debate as a complement to previous theoretical syntheses in the field.

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