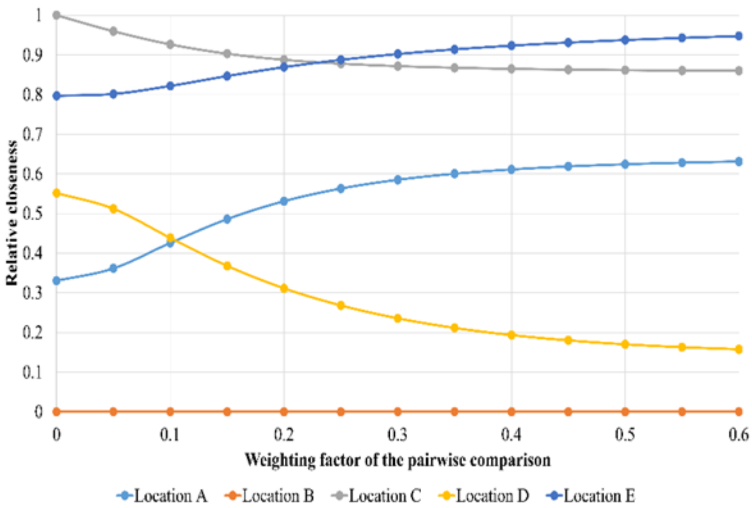

Questions

Procedures

Methods

Results

Application

18th International Doctoral Students Workshop on Logistics, Supply Chain and Production Management

17 June 2025, Magdeburg

Institute for Engineering of Products and Systems

Conference Proceedings

OTTO VON GUERICKE UNIVERSITÄT MAGDEBURG

&

Promotionszentrum Sozial-, Gesundheits- und Wirtschaftswissens

INSTITUT FÜR ENGINEERING VON PRODUKTEN UND SYSTEMEN

18th International Doctoral Students Workshop on Logistics, Supply Chain and Production Management

June 17, 2025
Magdeburg

Editors:
Prof. h. c. Dr.-Ing. Dr. h.c. (UCLV) Elke Glistau
Prof. Dr.-Ing. Sebastian Trojahn
Prof. Dr.-Ing. Fabian Behrendt

Impressum

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Institute for Engineering of Products and Systems (IEPS)
Otto von Guericke University Magdeburg

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Otto von Guericke University Magdeburg

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Foreword

Dear Ladies and Gentlemen,

Colleagues and Friends,

this volume contains the scientific contributions of the 18th International Doctoral Student Workshop on Logistics, Supply Chain and Production Management in Magdeburg 2025.

The annual doctoral student workshop offers a very good working platform to discuss the topic and focus of one's own doctoral thesis, to sharpen the research questions, to align one's own approach in a scientifically correct and at the same time very efficient way. The scientific discussions fertilise your own scientific work and create a good basis for further international cooperation between the participating colleges and universities.

The doctoral workshop offers the opportunity to present and discuss the initial results to an international panel of experts.

This year, in addition to many interesting individual topics, there are also three major focal points: These are supply chain management in the food and medical sectors, logistics planning of distribution centres and the subject area of Industry 4.0 and Logistics 4.0.

One of the purposes of our workshop is to create strong networks between the participating national and international doctoral students.

We use different form, e.g. a joint dinner the evening before, the technical discussions in the room and the breaks and individual discussions spent together on the day of the workshop serve to get to know each other. In this way, the dissertation as an individual doctoral candidate should be accompanied by a stronger sense of togetherness. Joint online meetings or appointments for conferences are also typical.

The exchange of people via Erasmus +, the Eastern Partnership Programme, the Pannonia Programme, DAAD Scholarship and other research projects can subsequently be used to deepen and consolidate the relationship.

If you – our reader -are also interested to participate next year, please contact us!

Looking ahead, we eagerly anticipate hosting the

19th International Doctoral Students Workshop on Logistics, Supply Chain and Production Management on 15. & 16. June 2026 at Magdeburg (Germany).

We sincerely hope to have the pleasure of welcoming all of you to Magdeburg, the captivating capital city of Saxony-Anhalt, next year.

On behalf of the entire workshop team

Prof. h. c. Dr. Ing. Dr. h. c. (UCLV) Elke Glistau

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Scientific Papers

Shared Autonomous vehicles - systematic review on case studies

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Abstract

Mobility in rural areas is dominated by motorised individual transport and is therefore particularly harmful to the environment. In contrast to urban centres, public transport is generally not an attractive option. Shared autonomous vehicles (SAVs) represent a disruptive technology that could change this status quo and eliminate the dependence on private cars. However, past studies on the implementation of SAVs focus in particular on urban centres and prioritised the implications that could arise here. It therefore seems necessary to highlight the potential of implementing SAVs in rural areas in order to steer the debate in this direction and highlight the potential for saving greenhouse gases. In order to investigate the suspected gap, a piloting systematic literature review is carried out in this article. The research takes into account peer-reviewed journal articles from Scopus. It can be stated that a stronger focus on the combined consideration of different SAV types is necessary to map intermodal routes and that the potentials of rural areas are only marginally considered

1. Introduction

In the face of climate change it is imperative to reduce greenhouse gas (GHG) emissions within the European transport sector (TS). In contrast to all other sectors, GHG emissions from the TS have continued to rise (EUROSTAT; 2024a). Therefore, the TS is now the sector with the highest emissions within the European Union (EU) (Earl, 2024). Consequently, it is necessary to identify possible fields of action for GHG emission reduction in the TS and to take measures as soon as possible.

Motorised individual transport (MIT) accounts for the largest share of GHG emissions. Around 60% of GHG emissions from the European TS are attributable to MIT (EUROSTAT, 2024b). The high proportion of GHG emissions from the TS caused by MIT can be traced back to the increasing amount of vehicle miles travelled (VMT) and MIT vehicles in the EU. Accordingly, the number of vehicles per 1,000 inhabitants in the European Union rose from 506 to 570 between 2014 and 2023 (EUROSTAT, 2025). Hence, the high number of MIT vehicles represents great potential for GHG emission reduction in the TS.

The reduction of GHG emissions from MIT in rural regions needs to be addressed. Around 137 million (24.3%) people in the EU live in rural areas (World Bank, 2023). At the same time this population causes disproportionately high GHG emissions. For instance, 70% of all trips in German rural areas are realised via MIT, while conventional public transport (PT) is used for only 5% of trips resulting in GHG emissions per capita being 60% higher in rural areas compared to urban areas (VCD, 2021). Obstacles to the use of more environmentally friendly mobility alternatives must therefore be focussed in the context of rural areas.

For many people in rural areas, conventional PT is no viable alternative to MIT. Due to a lack of direct connections, inadequate frequency of journeys, excessively long journey times and distant stops PT is not attractive (VCD, 2021). However, scaling up conventional PT to a service quality similar to that in urban regions is not financially viable due to the low settlement density and the poor bundling of routes (Herget et al., 2021).

This problem is exacerbated by demographic change. PT services are financed by the municipalities and focus on ensuring functional school transport (Kersten et al., 2020) leading to restrictions for other potential user groups (VDV, 2024). As young people are leaving rural regions in the wake of demographic change, the number of inhabitants in the regions is steadily decreasing (Augère-Granier & McEldowney, 2020). As a result, a lower allocation of financial resources in municipal budgets reduces the quality of PT services. The attractiveness of rural areas decreases and a positive feedback loop is created, which pushes people out of rural areas and into urban centres (VDV, 2024). This reinforcing loop is additionally accelerated by increasingly poor municipal budgets. Exemplary, the financial deficit of municipalities in Germany rose by 17.3 billion Euro within the year of 2023 alone (DESTATIS, 2025). The interplay of these developments engenders a self-perpetuating cycle of MIT dependency in rural regions. Consequently, there is an urgent need for action to create an attractive and sustainable PT system in rural regions in order to break this vicious circle.

The application of shared autonomous vehicles (SAV) in a mobility-as-a-service (MaaS) framework represents a disruptive technology in a new type of PT system. The elimination of the necessity for human drivers facilitates flexible fleet management, thereby giving rise to novel PT systems that could challenge MIT dominance in rural areas (Pflanz, et al., 2022)

Yet, the potential effects of SAV integration on transport is the subject of controversial debate in research. Since real-world SAV application is in a premature stage, due to various technological and juridical impediments, the effect of a large-scale rollout of the technology is approximated by models. While according to some studies SAVs promise the potential to reduce MIT other studies point to possible negative effects, such as an increase of VMT, longer trip times and a shift away from conventional PT leading to higher cost for society. (Fielbaum & Pudane, 2024).

The effects of SAVs that have been simulated since 2014 were comprehensively synthesized in a systematic literature review (SLR) conducted by Karolemeas et al. (2024). On the basis of the SLR results it is noticeable that the effect of SAV implementation

- On rural areas in general
- And models involving
  - A user-focused, agent-based consideration of intermodal routes as well as
  - The simultaneous application of different SAVs (bikes, micro mobiles, cars, buses)

seem to be researched scarcely (Karolemeas et al., 2024).

These observations emphasise the need for an up-to-date insight in study designs allowing for a precise contextualization of the various study results and identification of research gaps in this context. The social significance of the topic is very high due to the urgent implications of demographic change, rural exodus, urbanisation, climate change and intergenerational justice. Due to the high degree of novelty of artificial intelligence and its potential to influence the technical feasibility of SAVs, the discussion is very lively, yet heterogenous as various research topics in this overall context are discussed simultaneously.

The author's dissertation project is currently in the initial phase of clarifying the topic and therefore specifying the research question (RQ). Therefore, a pilot SLR is to be carried out below in order to specify the RQ and delimit non-relevant aspects.

Using the PICO method (Heil, 2020) the following preliminary RQ was derived for the SLR presented in this article:

Which agent-based simulation study designs, (Population | P), are used to evaluate the (traffic) effects (Outcome | O) of the introduction of road-bound, shared autonomous vehicles (Intervention | I) in a case-study area compared to the status quo (Comparison | C)?

In order to answer the RQ the identified articles are considered in more detail regarding the following five focal points (FP) of study design:

- Model type, model paradigm (related to P)
- SAV scope (related to I)
- Study area classification (related to C)
- Evaluation parameter (related to O)
- Assumptions and limitations

Extraction criteria were derived on the basis of the defined FP in order to systematically uncover research gaps and develop up-to-date knowledge.

2. Research Methodology

To answer the RQ, a reproducible, documented SLR was carried out. The SLR therefore is based on the PRISMA 2020 framework (Page et al., 2021). In the following, the steps of the conducted SLR are shown sequentially with their respective results.

2.1. Eligibility criteria

In a first step, eligibility criteria were defined. These were used to include or exclude studies in the search process and thus enable a standardised and focused search that facilitates comparability (Carrera-Rivera et al., 2022).

Table 1: Eligibility criteria

	Inclusion	Exclusion
Period	2023 – open-end	before
Language	English, German	other
Type of source	peer-reviewed journal article	other
Accessibility	open access	any closed-access

In addition, the selection bias is reduced by formulating the criteria ex-ante for conducting the search itself (Durach et al., 2017; Mengist et al., 2020). Taking into account the recommendations for criteria from (Carrera-Rivera et al., 2022; Durach et al., 2017; Mengist et al., 2020) the eligibility criteria presented in Table 1 were defined for the SLR.

As the aim of the search was to identify potential up-to-date research gaps, only novel publications were considered. Thus, the scope for this SLR was set to include 2023 to “open-end” (25-03-10). Since the author of this work can fluently speak English and German, yet no other languages, the languages considered eligible are these two. Accordingly, synonyms and aliases are considered in both of these languages in chapter 2.2. To ensure the academic integrity and reliability of the results, only journal publications that have successfully passed a peer review process were included. For this reason, this SLR waives to include an explicit quality assessment checklist as suggested in Carrera-Rivera et al. (2022). Only open-access articles were considered eligible for the SLR displayed.

2.2. Data search

The second step of the SLR was to define where to search and what exactly to search for. For this SLR the digital and scientific literature databases “Scopus” was chosen. No checks were carried out in other databases such as “Web of science”, “IEEE Xplore” or “Google scholar”. This limitation offers potential for improvement for a more in-depth investigation.

2.2.1. Search strategy and pilot-search

For an SLR, it is advisable to first carry out a broader, unsystematic pilot-search in order to build up a general understanding of the topic and to understand the relevance of the keywords (Howe et al. 2014; Mengist et al., 2020). In the pilot-search, the current (25-03-10) associated research topics were identified in the context of SAVs. This identification allows to derive terms for topics that can be excluded from the search in order to enable an efficient search for articles related to the RQ. The topics identified in the context of SAVs that are not explicitly related to the pursuit of the RQs of this thesis were:

- studies applying analytical, optimization models
- studies on use in aviation, military, agriculture and maritime sectors and
- studies regarding mechatronics, sensorics and information and communication technology
- studies focusing power grid integration
- empirical studies regarding acceptance, intention to use, demand, safety and the perception of safety.

As a result of the pilot-search, frequently mentioned keywords and terms as well as associated synonyms and aliases were consolidated for the RQ. In order to ensure the consideration of all relevant aliases and synonyms the Large Language Model “GPT-4o” was used for complementation suggestions. There are no limitations with regard to relevant extraction criteria resulting from the FP, such as study area (e.g.: ‘rural’) or SAV definition (e.g.: ‘-bike’).

Based on the titles of the articles in the pilot search, the author decided to search in two separate search queries and consolidate the results. The first search query focuses on simulative studies on autonomous vehicles in the context of mobility. The second search query focuses on simulative studies on MaaS.

2.2.2. Search application

The first search query is divided into five complexes (see Figure 1). The first complex includes the set of terms around the term ‘autonomous’ and assumes that this is present in the title. The second complex assumes that a form of a road-bound vehicle is present in the title. The third complex assumes that there is a mention of the word family ‘simulation’ in the abstract, title or keywords (method). The fourth complex requires that the results are in the field of mobility. The fifth complex eliminates all articles that contain words in the title that refer to studies that are not explicitly linked to the RQ.

(TITLE (auton* OR autom* OR self* OR driverless OR selbst*)

AND TITLE (vehicle* OR car* OR bus* OR bike* OR taxi* OR cab* OR motorcycle* OR scooter* OR public* OR fahr* OR roller*)

AND TITLE-ABS-KEY (*simulat*)

AND TITLE-ABS-KEY (*mobilit* OR *transport* OR traffic OR reise* OR pendel* OR verkehr* OR öpnv OR "Öffentlicher *Nahverkehr" OR geteilte* OR gemeinsame* OR ride* OR shar* OR pt OR trans* OR travel* OR comm* OR traffic)

AND NOT TITLE (optim* OR motiv* OR adopt* OR inten* OR factor* OR behav* OR preference* OR willing* OR concern* OR trust OR pedestrian OR survey OR opinion OR expert OR risk OR cybersecurity OR accident* OR percept* OR attitude* OR accept* OR safety OR security OR crash* OR power* OR electricity OR airport OR aerial OR air OR armored OR farm* OR *water OR image OR control* OR fault OR diagnosis OR characteriz* OR visibil* OR navigation OR trajectory OR lateral OR sensor* OR path OR monitoring OR detect*))

AND PUBYEAR > 2022 AND PUBYEAR < 2026 AND (LIMIT-TO (OA , "all")) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (DOCTYPE , "ar"))

Figure 1: Advanced first search query in Scopus

The application of this first enquiry resulted in 306 documents found (2025-03-10). The application of the second enquiry (see Figure 2) resulted in 20 documents found (2025-03-10) while 2 duplicates occurred, leading to a total of 324 articles viable for screening.

(TITLE ((mobility AND service) OR "mobility-as-a-service" OR maas) AND TITLE-ABS-KEY (*simulat*)) AND PUBYEAR > 2022 AND PUBYEAR < 2026 AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (SRCTYPE , "j")) AND (LIMIT-TO (OA , "all"))

Figure 2: Advanced second search query in Scopus

As part of the PRISMA 2020 screening, the title, abstract and keywords of all articles found were manually checked for relevance to the RQ. In the process, 292 articles were determined to be unsuitable for the review. The high number of unsuitable articles results from the specific RQ and at the same time a very intensive academic debate in the context of autonomous vehicles in many other research questions. For example, a large proportion of the excluded articles related to issues of mechatronics & sensor technology and the interaction between human-controlled and autonomous vehicles. To prevent this, further narrowing down the search queries would have possibly reduced the relative number of items to be removed, yet would have increased the risk of excluding relevant items already during the search process.

2.3. Extraction criteria

The extraction criteria are ex-ante defined in strict accordance with the FP taking into account recommendations by (Mengist et al., 2020). The extraction criteria are displayed inTable 2: Extraction criteria

	ID	Extraction criteria
Model	1.1	Objective
	1.2	Type, paradigm
	1.3	Tool
	1.4	Data bases and input parameters
	1.5	Assumptions
	1.6	Limitations and gaps
	1.6.1	PT-Intermodality
	1.6.2	Operation mode
SAV	2	SAV scope
Study area	3	Study area classification
Evaluation	4.1	Evaluation criteria
	4.2	Scenarios & Sensitivity
	4.3	Evaluation method
General	5.1	Key findings
	5.2	Future research

.

Table 2: Extraction criteria

	ID	Extraction criteria
Model	1.1	Objective
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SAV	2	SAV scope
Study area	3	Study area classification
Evaluation	4.1	Evaluation criteria
	4.2	Scenarios & Sensitivity
	4.3	Evaluation method
General	5.1	Key findings
	5.2	Future research

The aggregation of knowledge on the objective, modelling paradigm, tool, databases and limitations is intended to provide an overview of current issues, means of implementation and limitations. For the boundaries, it is explicitly examined whether only monomodal routes or also intermodal routes via PT integration are modelled, if and how a shift to SAVs from existing transport modes is mapped and which operating modes the vehicles map (demand-responsive, fixed-route etc.). The SAV (car, bike etc.) referred to in the articles are recorded. The study area is classified as urban, sub-urban, rural or diverse/undefinable. In order to gain an explicit insight into the evaluation mechanisms of the implementation of SAVs evaluation criteria are consolidated. It is recorded whether scenarios were generated in the study or whether a sensitivity to the alternation of certain control variables was checked. Evaluation methods are recorded. Central findings and possibilities for future research are summarised. To verify the information gathered manually, these were checked using the Large Language Model "GPT-4o". If discrepancies were found, a second review was carried out to alter the information consolidated.

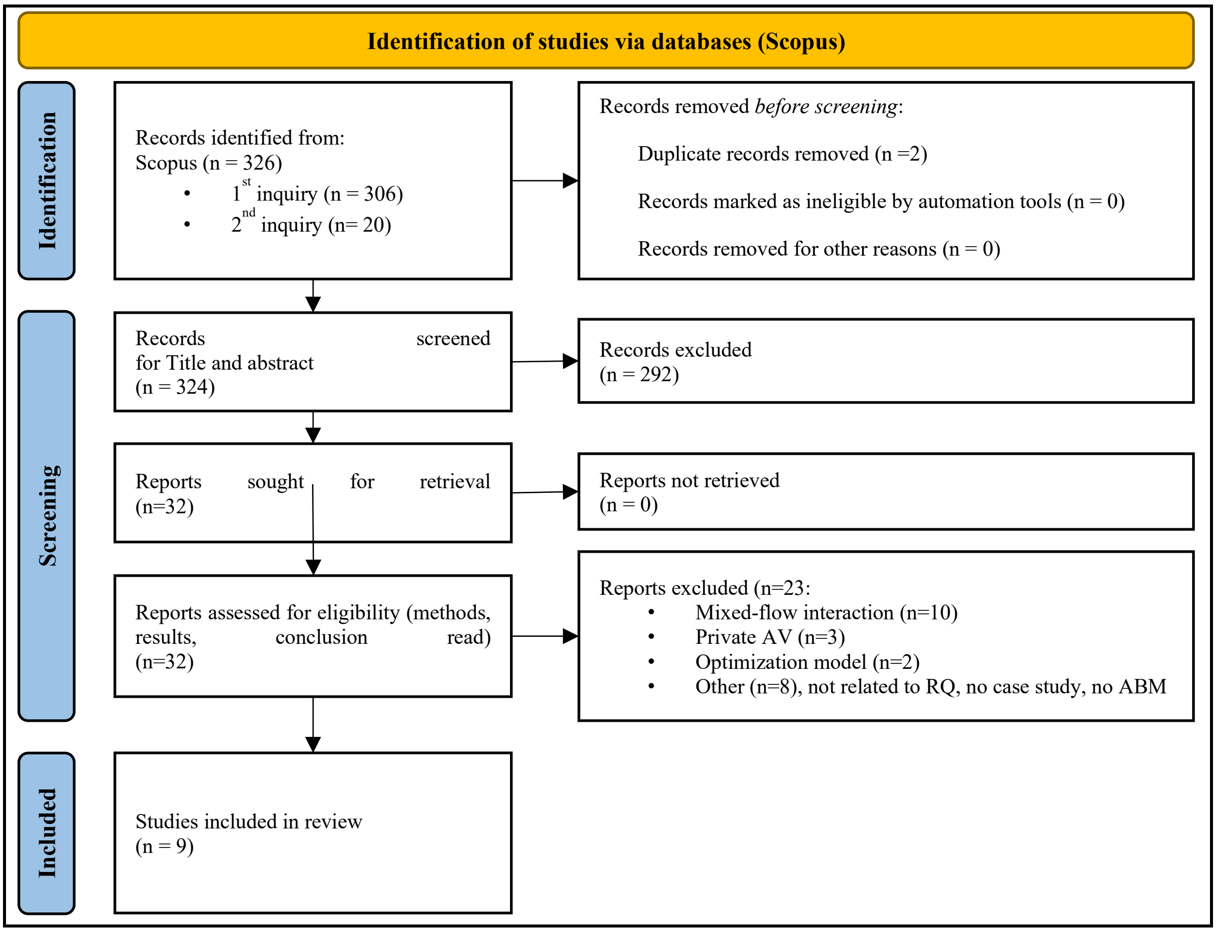

Figure 3: PRISMA 2020 flow diagram, based on Page et al. (2021)

3. Results and Discussion

Table 3: Extracted data from the studies included in the SLR, vehicle capacity (c); excerpt

Article	Tool	Inter-modality	Operation modes	SAV scope	Study area	Evaluation criteria	Future research
Carreyre et al. (2024)	MATSim	Yes	DRT, FR	Car (c=4) shuttle bus (c=8)	Berlin, urban	Travel time traffic density emissions cost	intermodality life cycle assessment
Cheong et al. (2023)	Own framework	Only implicit	DRT	Car (c=4) Car (c=6)	London and periphery, urban/ sub-urban	Travel time waiting time declined rides energy-consumption cost	intermodality, customer demand integration

Fidanoglu et al. (2023)	Own framework	Only implicit	FS	Car (c=4)	Bursa, sub-urban	Travel time, waiting time, energy-consumption	vehicle capacity and heterogeneity
Fujita et al. (2023)	Own framework	Yes	DRT, FS, FR	Car (c unspecified) eScooter	Miyata, urban; Toyama, sub urban	Travel time waiting time demand satisfaction rate	Tool influence, shared infrastructure
Haj Salah et al. (2024)	AnyLogic	Only implicit	FS	bicycle	Magdeburg, urban	Service level energy cost total cost	Failure rate integration
Ma et al. (2024)	MATSim	Yes	DRT	Car (c unspecified)	Shanghai, urban	Travel time energy-consumption	Additional parameters
Nguyen-Phuoc et al. (2023)	Sim Mobility	Only implicit	DRT	Car (c=4), Car (c=6)	Singapore, urban	Waiting time Passenger kilometers	Rebalancing integration, implications for PT
Peer et al. (2024)	MATSim	Yes	DRT	Car (c=4)	Vienna, urban	Travel time, emissions	Charging integration, urban sprawl
Tiwari et al. (2024)	MATSim	Only implicit	DRT, FS	Car (c=4)	Melbourne, urban	Travel time occupancy emissions service equity	SAV variety, reallocation of inquiries, ML for prioritization

3.1. Results

Of the 32 articles that were considered relevant after reviewing the abstract and title, all full texts could be retrieved (see Figure 3). By reviewing the methods section, the results and the conclusion, further studies could be checked for relevance to the RQ and excluded. All studies that examined the interaction of SAVs in a mixed flow in microscopic form were excluded, as this is not explicitly relevant for the RQ. After excluding all non-relevant studies, 9 studies remained, which are included in the review.

Table 3 shows an excerpt of the most important extraction criteria for these. The tools used in the studies are heterogeneous, but most studies use MATSim (Multi-Agent Transport Simulation). MATSim is an open-source tool for agent-based simulation of large systems at the microscopic level using a queueing model at node and edge level. MATSim is easily extendable by various modules and can simulate very large areas with millions of agents in a reasonable time due to the high degree of abstraction compared to microscopic traffic simulations with vehicle sequence models.

Some studies such as (Cheong et al.,2023) or (Fujita et al., 2023) use tools such as MATSim or SUMO to derive their own specific frameworks, while (Carreyre et al., 2024) have integrated a module for MATSim, to map Demand-Responsive Transport (DRT) more accurately. The explicit mapping of intermodal routes is only possible on the basis of these tools. This also enables (Carreyre et al., 2024; Fujita, 2023) to comprehensively vary the operating modes of the SAVs in the form of DRT, fixed-route (FR) and feeder system (FS) combinations. The scope of what is to be considered an SAV is inhomogeneous. While most studies focus on cars or shuttle buses, (Haj Salah et al., 2024) also consider autonomous bicycles as micro-vehicles in an FS. The study areas comprise exclusively urban and sub-urban areas.

3.2. Discussion

The findings from the review by (Karolemeas et al., 2024) and the results of this SLR coincide with regard to the areas of investigation, which are predominantly urban. With regard to the integration of intermodality, it can be stated that new approaches are being developed in MATSim and own frameworks. (Carreyre et al.,2024) point out that the consideration of intermodal routes is essential for a holistic assessment of the impact of SAVs, especially due to the versatile operation modes. Against this background, it also seems important to consider combinations in which different vehicle types (bus, car, bicycle) track different operation modes (FR, DRT, FS). (Fidanoglu et al.,2023) also points out this need to integrate different vehicles.

4. Limitations and Conclusion

Although the SLR carried out is methodologically sound, it requires a larger scope and an adaptation of the search strategy and the screening strategy in order to guarantee a reliable identification of the research gap.

Therefore, building on this pilot SLR, an iteration will be carried out in which further databases will be consulted. The search terms will be re-evaluated on the basis of the high number of articles considered to be non-eligible. For example, models that use the cellular automaton or vehicle-following models are excluded, as they pursue different research questions, although they also serve as agent-based models.

The author finds it particularly interesting to derive a strategy for dimensioning an SAV fleet with different vehicles and different specific operation modes and to assess its potential, taking into account relevant evaluation criteria. A rural area would be a possible study area. The evaluation of emissions at the level of a life cycle analysis, as proposed by (Carreyre et al., 2024), seems equally interesting. In this way, the question of the extent to which sustainable mobility is possible in rural areas (from a holistic perspective) and how it should be organised could be investigated for a specific case.

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7. Information on application of AI

Process	Tool	Scope	Comment
Search Synonyms	GPT-4o, Perplexity	Recommendations	manually adapted
Extraction	GPT-4o, Perplexity	Verification	manually checked
Translation	DeepL, DeepL-write	Translation	manually adapted

Optimization for Adaptive Logistics Distribution Centers

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Abstract

The optimization of distribution centers (DCs) is a critical element in enhancing the efficiency and resilience of global supply chains. This paper presents a comprehensive methodological framework for planning, evaluating, and selecting logistics models adapted to distribution centers, combining quantitative and qualitative tools. The study addresses three primary configuration models: centralized, decentralized, and mixed models. These models are evaluated using decision matrices, the analytical hierarchical process (AHP), and Monte Carlo simulations. The methodology integrates cost, delivery time, flexibility, sustainability, and operational resilience metrics, allowing logistics decisions to be adapted to dynamic and highly uncertain environments. Furthermore, the integration of emerging technologies, such as the Internet of Things (IoT), digital twins, and blockchain, is explored. These technologies are designed to enhance traceability and facilitate real-time decision-making processes. The results obtained from this study allow for the identification of the optimal model according to the operational and strategic conditions of each organization, thereby contributing to the creation of more sustainable, flexible, and resilient logistics networks. Finally, the pending scientific challenges and opportunities for improvement for the development of smart distribution centers, aligned with the objectives of sustainability and operational efficiency, are highlighted.

1. Introduction

In the context of a dynamic global supply chain environment, distribution centers (DCs) have undergone a transformation, evolving from rudimentary warehouses to pivotal strategic nodes that facilitate the seamless connection between production and final consumption. This transformation is driven by increasing market complexity, demand volatility, and disruptive events such as the SARS-CoV-2 virus pandemic or geopolitical conflicts. These events have revealed critical vulnerabilities in traditional logistics networks (Christopher, 2016; Onstein et al., 2019). In response, organizations must optimize their DCs with criteria for operational efficiency, environmental sustainability, and resilience in the face of uncertainty (Gunasekaran et al., 2015).

Conventionally, the determination of the location, design, and operation of DCs has been informed by static cost-oriented parameters (Ballou, 2004; Becerra-Fernandez et al., 2024). However, recent literature advocates for a multi-criteria approach, integrating economic, social, environmental, and technological factors in alignment with the Sustainable Development Goals (Awasthi & Chauhan, 2012; Jamshidi et al., 2019). In this framework, the incorporation of emerging technologies such as the Internet of Things (IoT), blockchain, digital twins, and predictive analytics has expanded the operational capabilities of DCs, enabling greater traceability, automation, and real-time adaptation (Ben-Daya et al., 2019; Cao et al., 2023; Saberi et al., 2019).

Notwithstanding these advancements, a fragmentation persists between strategic logistics planning and operational DC management. A significant body of research has been dedicated to examining these domains independently. On one hand, there are studies that focus on global logistics planning, and on the other hand, there are those that emphasize the internal optimization of distribution centers (Ariyanti & Paramaputra, 2023; Fedtke & Boysen, 2017). This division impedes the optimization of DCs as intelligent and adaptive nodes within supply networks (Hernández-Mejía et al., 2022; Xiao & Watson, 2017). A bibliometric analysis conducted in Scopus and Web of Science

lends further support to this finding, as the analysis revealed that while there are more than 7,500 articles related to "distribution centers" and over 1,200 related to "logistics planning," only 41 publications in the Scopus database and 27 publications in the Web of Science address both subjects simultaneously. This finding underscores a discernible scientific gap in the literature (Ghasemi et al., 2020).
The present article proposes a comprehensive and adaptive methodology to bridge this gap. The methodology employed in this study incorporates both quantitative (AHP, decision matrices, Monte Carlo simulations) and qualitative (PESTEL, SWOT) analysis techniques to assess logistics configurations (centralized, decentralized, and mixed) across a comprehensive set of criteria. Figure 1 illustrates this approach through a Venn diagram that integrates three key dimensions: strategic planning, DC operational management, and emerging technologies. The nexus of these components constitutes the crux of the proposed model, thereby enabling effective decision-making in complex and ever-evolving environments (Huang et al., 2022).

Figure 1: The intersection of key dimensions in the methodological proposal is represented.

This methodology is distinct from conventional approaches that prioritize static route optimization or cost minimization. Instead, it incorporates dynamic variables, sustainability metrics, resilience indicators, and continuous improvement mechanisms such as the Plan-Do-Check-Act (PDCA) cycle. Future research opportunities include the use of artificial intelligence for demand forecasting, real-time simulation via digital twins, and the adoption of circular economy indicators to enhance DC sustainability (Li et al., 2020; Mishra et al., 2024; Wang et al., 2021).
This work addresses both a practical need and a theoretical void. It offers a unified methodological logic that integrates strategic and operational perspectives, rendering it applicable to sectors characterized by volatility—such as e-commerce, retail, and pharmaceuticals. As illustrated in Figure 1, the integration of planning, operations, and technology serves as the foundational framework for the development of intelligent, resilient, and sustainable distribution centers.

2. Methodology and Research Process

The proposed methodology for optimizing distribution centers (DCs) follows a structured process divided into five key phases. This process integrates both quantitative and qualitative instruments, incorporating continuous improvement mechanisms to ensure a comprehensive evaluation and adaptability to diverse logistics contexts. The methodology is designed to assess and select the most appropriate distribution model (centralized, decentralized, or hybrid) based on economic, operational, environmental, and resilience criteria. The figure 2 below provides a Process Flowchart – Overview of Phases, which illustrates the five phases and the key tools utilized in each.

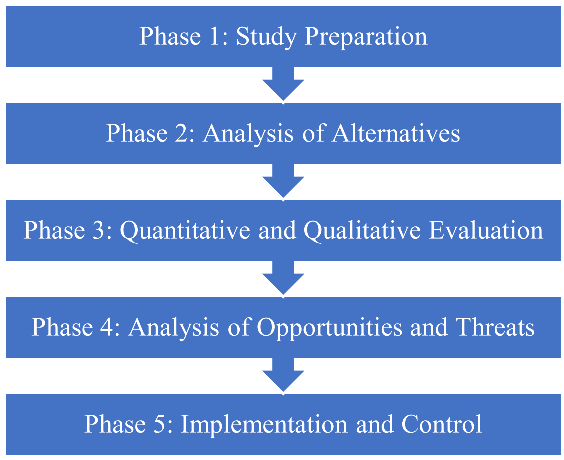

Figure 2: Process Flowchart – Overview of Phases

2.1. Phase 1: Study Preparation

The initial phase entails an examination of the company's internal and external environment. This entails the characterization of the business model, product portfolio, customer base, and geographical reach. In order to assess the logistics system, strategic tools such as PESTEL analysis are employed to evaluate the political, economic, social, technological, environmental, and legal factors that exert influence upon the company (Govindan et al., 2015). Furthermore, conducting a SWOT analysis enables the identification of both internal strengths and weaknesses, as well as external opportunities and threats, thereby ensuring a balanced understanding of the company's positioning.
Customer segmentation is performed using the ABC analysis, which classifies customers and products into high, medium, and low importance categories based on demand and revenue contribution (Govindan et al., 2015). To forecast future demand, time series analysis and multiple regression models are used, correlating demand patterns with factors such as seasonality, economic conditions, and marketing activities (Ghasemi et al., 2020).

The evaluation of existing infrastructure entails the calculation of key performance indicators (KPIs), including warehouse space utilization rate, inventory turnover ratio, and order-to-delivery performance. These metrics provide a baseline assessment of current operational efficiency and capacity utilization.
Phase 1 is foundational to understanding the company's situation and setting strategic objectives. The utilization of data-driven methodologies and analytical tools facilitates enhanced decision-making processes, leading to the optimization of logistics and operational frameworks.

2.2. Phase 2: Analysis of Alternatives

The present phase is oriented towards the evaluation of disparate operational models and the selection of the most suitable one based on cost, efficiency, flexibility, and sustainability. The primary models under consideration are as follows:

- Centralized Model
- Decentralized Model
- Mixed Model

Each model has its advantages and challenges, which will be analyzed using various methodologies and quantitative techniques.

2.2.1. Step 1: Centralized Model

Objective: To evaluate the feasibility of a centralized logistics system, where a single distribution center (DC) serves all regions.
Advantages:

- Lower fixed costs due to economies of scale.
- Better inventory control.
- Reduced complexity in operations.

Disadvantages:

- Higher transportation costs for distant customers.
- Increased lead times.
- Risk concentration (e.g., supply chain disruptions).

Tools & Methods:

- Total Cost Analysis (TCA): Evaluates fixed and variable costs of centralization.
- Linear Programming: Optimizes resource allocation.
- Network Flow Models: Simulate supply chain performance.

Key Metrics & Formulas:
Total Cost Calculation:

$$TC = FC + VC \times Q \qquad (1)$$

TC = Total cost
FC = Fixed costs (e.g., warehouse rent, equipment)
VC = Variable costs (e.g., transportation, labor)
Q = Quantity of goods handled

Inventory Holding Cost:

$$HC = H \times Q/2 \qquad (2)$$

HC = Holding cost
H = Cost per unit of inventory per period
Q = Order quantity

Optimal Central Location (Gravity Model):

$$X_c = \frac{\sum(x_i w_i)}{\sum w_i};\ Y_c = \frac{\sum(y_i w_i)}{\sum w_i} \qquad (3)$$

X_c, Y_c = Coordinates of the optimal location
x_i, y_i = Coordinates of each demand point
w_i = Weight (e.g., demand volume, shipping frequency)

2.2.2. Step 2: Decentralized Model

Objective: To evaluate the feasibility of multiple regional distribution centers, reducing transportation costs and lead times.
Advantages:

- Faster delivery times.
- Lower transportation costs for regional customers.
- Greater flexibility in responding to demand shifts.

Disadvantages:

- Higher fixed costs due to multiple facilities.
- More complex inventory management.
- Risk of inefficiencies in warehouse utilization.

Tools & Methods:

- Break-Even Analysis: Determines profitability of multiple locations.
- Vehicle Routing Problem (VRP): Optimizes transportation efficiency.
- Multi-Echelon Inventory Models: Evaluates inventory allocation across multiple locations.

Key Metrics & Formulas:
Break-Even Point for Multiple Facilities:

$$Q = FC/(P - VC) \qquad (4)$$

Q = Quantity needed to break even
FC = Fixed costs per facility
P = Price per unit
VC = Variable cost per unit

Transportation Cost Savings:

$$\text{Savings} = \sum_{i=1}^{n} C_{\text{Central}} - \sum_{j=1}^{n} C_{\text{decentralized}} \qquad (5)$$

Compares centralized vs. decentralized transportation costs.

Facility Location Optimization (p-Median Model):

$$\text{Minimize} \sum_{i=1}^{n} \sum_{j=1}^{m} d_{ij} X_{ij} \qquad (6)$$

d_{ij} = Distance between facility ii and demand point j

X_{ij}= Binary variable (1 if demand point jj is served by facility ii, 0 otherwise)

2.2.3. Step 3: Mixed Model

Objective: To determine the feasibility of a hybrid centralized + decentralized distribution system.

Advantages:

- Balance between cost efficiency and service speed.
- Redundancy to mitigate supply chain risks.
- Scalability for future growth.

Disadvantages:

- Complex coordination and logistics.
- Higher initial investment.
- Need for advanced technology and tracking systems.

Tools & Methods:

- Heuristic Optimization Models: Find the best combination of centralized and decentralized hubs.
- Network Flow Optimization: Determines optimal product allocation.
- Monte Carlo Simulation: Analyzes risks and uncertainties in the hybrid model.

Key Metrics & Formulas:

Total Distribution Cost in a Hybrid Model:

$$CT = \sum_{i=1}^{n}(FC_i + VC_i \times Q_i) + \sum_{j=1}^{m}(TC_j + SC_j i) \quad (7)$$

FC_i = Fixed cost of central warehouse ii
VC_i = Variable cost of central warehouse ii
Q_i = Demand served by central warehouse ii
TC_j = Transportation cost from distribution center jj
SC_j = Storage cost at distribution center jj

Service Level Analysis (Fill Rate):

$$\text{Fill Rate} = \frac{\text{Orders Fulfilled on Time}}{\text{Total Orders}} \times 100 \quad (8)$$

Measures how efficiently the system meets customer demand.

Risk Assessment in a Mixed Model:

$$R = \sum_{k=1}^{p}(P_k \times I_k) \quad (9)$$

R = Total risk score
P_k = Probability of disruption k
I_k = Impact of disruption k

The Phase 2 evaluates various supply chain models employing cost-benefit analysis, optimization techniques, and risk assessments. The selection of a centralized, decentralized, or mixed model is contingent upon cost efficiency, service levels, and scalability requirements.

2.3. Phase 3: Quantitative and Qualitative Evaluation

The selection of the optimal distribution configuration necessitates a comprehensive multi-criteria evaluation process, integrating quantitative performance indicators with qualitative expert judgments. This evaluation is facilitated by the Weighted Decision Matrix (WDM), a methodology that assesses alternatives based on criteria such as total cost, delivery lead time, flexibility, sustainability, and risk exposure.

The weights assigned to each criterion are determined by their strategic importance, while each alternative is evaluated in relation to the others. To ensure consistency, weights are derived using the Analytic Hierarchy Process (AHP), which compares criteria pairwise to establish their relative importance.

Addressing uncertainty is achieved through the implementation of a Monte Carlo simulation, which models potential variations in demand, transportation costs, and external disruptions. This approach enables the calculation of expected performance under different scenarios, thereby enhancing the robustness of the decision-making process.

2.4. Phase 4: Analysis of Opportunities and Threats

Following the identification of the preferred distribution model, a detailed analysis of opportunities and threats is conducted. This process ensures that external factors, both positive and negative, are incorporated into the final implementation plan.

Opportunities encompass new market segments, technological advancements (e.g., the Internet of Things (IoT) and automation), and regulatory incentives for green logistics. Conversely, threats encompass economic volatility, supply chain disruptions, and increasing regulatory compliance costs.

To address these challenges, a Risk Matrix is developed, in which each identified threat is evaluated based on its probability and potential impact. This results in a Risk Score that prioritizes the most critical threats to be mitigated through contingency planning and operational flexibility.

2.5. Phase 5: Implementation and Control

The final phase of the process entails the execution of the selected configuration and the establishment of a robust monitoring and continuous improvement framework. The PDCA (Plan-Do-Check-Act) cycle is implemented to drive iterative improvements based on real-time performance data.

A digital monitoring system, integrating data from IoT sensors, WMS (Warehouse Management Systems), and transportation management platforms, provides real-time visibility into inventory levels, order fulfillment rates, and transportation costs. This system enables the early detection of deviations from planned performance and triggers corrective actions when necessary.

The continuous improvement process involves the evaluation of key performance indicators (KPIs), including:

- On-Time Delivery (OTD)
- Cost per Order
- Carbon Footprint per Shipment
- Operational Flexibility Index

Each iteration of the continuous improvement process involves the integration of feedback from operational teams, customer surveys, and performance analytics. This systematic process enables the refinement of operational procedures, leading to enhanced efficiency and resilience.

3. Results and Discussion

The proposed methodology is currently under development; consequently, it has not yet been applied in a specific real case. Nevertheless, its design is founded on an innovative integration of quantitative, qualitative, and dynamic approaches, incorporating classical logistics optimization instruments with contemporary risk management methodologies, multi-criteria analysis techniques, and continuous improvement methodologies. This hybrid approach is designed to adapt to a wide range of companies and sectors, representing a significant advance over traditional approaches that are often limited to cost minimization or distance optimization.

Conventional models, which prioritize short-term operational efficiency, are static. In contrast, this methodology incorporates strategic factors, such as network resilience, environmental sustainability, and adaptability to changes in demand or external disruptions. This comprehensive approach enables logistics decision-making to be not only more efficient but also aligned with the company's long-term strategic and sustainability objectives.

3.1. Verification and validation of the methodology

The methodology is still in the development phase. Its initial validation has been carried out through theoretical contrast and conceptual simulation. This process has integrated best practices identified in the academic literature and previous case studies on logistics network optimization. The theoretical-comparative approach has enabled the adjustment of phases, tools, and metrics to ensure the methodology's applicability to diverse logistics environments, ranging from centralized supply chains to decentralized multilevel networks.

To bolster the validity of the proposal, the methodology incorporates internationally recognized tools such as:

Analytic Hierarchical Process (AHP) for prioritization of criteria.

The Weighted Decision Matrix (WDM) is employed for the evaluation of alternatives.

Monte Carlo simulation is employed to assess uncertainty scenarios.

The integration of these tools enhances the traceability and transparency of each decision, empowering logistics managers to substantiate the selection of a particular model, even in volatile and dynamic environments.

The methodology has been thoroughly tested through concrete academic and practical cases. Although not yet implemented in a real case, the methodology is designed to be applicable to companies in different sectors, especially those facing:

High demand uncertainty, such as e-commerce.

Geographically dispersed distribution networks, a common occurrence in the automotive and FMCG sectors, are another area of applicability.

Environmental regulatory requirements, as evidenced by the standards in the food and pharmaceutical industries.

In contradistinction to conventional methodologies that prioritize financial or operational efficiency, this novel approach systematically incorporates sustainability and resilience as pivotal criteria in decision-making. This feature renders it especially pertinent for enterprises that are committed to the Sustainable Development Goals (SDGs) or that operate within markets characterized by stringent environmental regulations.

3.2. Differentiation from other methodologies

The distinguishing characteristic of this methodology is its:

- Comprehensive and multi-criteria approach: It does not merely focus on minimizing costs or delivery times; rather, it considers a comprehensive set of criteria, including operational, economic, environmental, and resilience factors.
- It is dynamic in nature, allowing for adaptation to changing circumstances. It utilizes tools such as Monte Carlo simulation, which enables the adjustment of decisions based on multiple scenarios, a feature that is absent in traditional methodologies, which are predominantly based on deterministic analysis.
- Finally, the incorporation of sustainability is a distinguishing feature of the methodology. It evaluates the environmental impact of each logistics alternative, allowing companies to select configurations that not only optimize costs but also reduce their carbon footprint and contribute to the circularity of the supply chain.
- Resilience integration involves the introduction of specific indicators to assess resilience to disruptions, thereby strengthening decision-making in highly uncertain environments.
- Continuous improvement: It integrates the PDCA (Plan-Do-Check-Act) cycle as an essential part of the implementation, ensuring that the selected logistics model continuously evolves and adjusts to changes in the environment and actual performance.

- Transparent justification: Each decision is traceable and justifiable through the use of decision matrices, AHP weightings, and sensitivity analysis, which improves transparency and facilitates internal and external auditing of the decision-making process.

This methodology has been demonstrated to enhance the quality of logistics decision-making by integrating strategic and operational criteria into a unified process. This integration prevents decisions from being biased toward short-term goals. It enables the visualization of the impact of each decision across different scenarios, thus strengthening proactive risk management. The methodology provides a flexible framework that can be adapted to companies of all sizes, adjusting to varying levels of complexity and available resources. Additionally, it fosters internal communication by leveraging visual tools such as decision matrices, risk matrices, and PDCA diagrams, thereby enhancing the comprehensibility of the process across all areas of the company. Furthermore, it aligns logistics with corporate objectives of sustainability and resilience, creating value that extends beyond mere operational efficiency.

Despite its ongoing development, the proposed methodology signifies a substantial advancement over conventional logistics network optimization methodologies by integrating economic, environmental, and resilience criteria within a flexible, transparent, and adaptable framework. Its future application will allow companies not only to optimize costs and delivery times, but also to increase their ability to adapt to disruptions and improve their competitive positioning in increasingly regulated and demanding markets.

4. Limitations and Conclusion

The proposed methodology is still in the development phase, which introduces certain limitations that must be considered prior to its implementation in a real environment. These limitations reflect not only the inherent technical difficulties, but also the organizational and contextual challenges associated with optimizing complex logistics networks.

- The methodology is dependent on reliable data. The efficacy of quantitative instruments (AHP, Decision Matrices, Monte Carlo Simulation) is contingent on the quality and accessibility of historical data on demand, logistics expenditures, service levels, and external factors. In companies with a low level of digitization or poorly documented logistics processes, the application may be limited.
- The process of assigning weightings is inherently complex. Although AHP allows for hierarchical structuring of decision criteria, the assignment of weights still depends, in part, on the subjectivity of the experts, which may introduce biases or inconsistencies in the evaluation.
- The application's capacity to address the emergence of disruptions is also constrained. While Monte Carlo Simulation is useful for modeling uncertainty, sudden disruptions (e.g., health crises, geopolitical conflicts, or unexpected regulatory changes) are difficult to forecast accurately. This can affect the robustness of the recommendations derived from the methodology.
- The necessity of analytical capabilities is paramount. The effective application of the methodology necessitates the presence of personnel within companies who have received training in quantitative analysis, data management, and simulation tools. This may represent a barrier for SMEs with limited resources.
- The integration of technology is limited: Although the methodology contemplates the integration of technologies such as the Internet of Things (IoT), blockchain, and digital twins, these elements are not yet fully developed within the methodological framework. The implementation of these technologies in the future will be contingent upon their technological maturity and the capacity of each organization to adopt them.

The ensuing discussion will address the primary results, subsequent steps, and opportunities for exploitation. Although the methodology has not yet been applied in a specific real case, its development has already allowed the structuring of a flexible and adaptable framework. This framework is capable of balancing operational efficiency, environmental sustainability, and resilience to disruptions. The framework's primary strengths are evident in its integration of quantitative and qualitative techniques, its incorporation of strategic and environmental criteria into logistics decision-making, and its capacity to utilize simulation tools to model future scenarios. The subsequent steps are focused on conducting pilot tests in key sectors such as retail, the food industry, and e-commerce. These tests will allow for the adjustment of the model to real operating conditions and the validation of its applicability in different contexts. The model's enhancement of technological integration, incorporating real-time data from IoT sensors and logistics management platforms, is expected to bolster its predictive and dynamic adjustment capabilities. At the exploitation level, the methodology demonstrates considerable potential for application in both business and academia, serving as a specialized consulting instrument for companies aspiring to redesign their logistics networks and as a foundational framework for future research on sustainable, resilient, and intelligent logistics.

4.1. Conclusions

- The proposed methodology integrates a holistic and adaptable approach, combining strategic, quantitative, qualitative, and dynamic tools, allowing for a comprehensive assessment of logistics configurations.
- In contradistinction to conventional methodologies, it incorporates sustainability, resilience, and strategic alignment criteria, which enables optimization of the distribution network without losing sight of environmental and long-term objectives.
- The phased structure of the methodology facilitates its application across diverse sectors, ranging from mass consumption and retail companies to highly regulated industries such as pharmaceuticals and food.
- The integration of AHP, weighted decision matrices, Monte Carlo simulation, and PDCA cycle ensures a robust multi-criteria evaluation process and a continuous improvement system, adaptable to market changes and external disruptions.
- The methodology enables the selection of the most optimal logistics configuration and ensures future flexibility and adaptability. It integrates tools and processes that facilitate decision-making in dynamic and highly uncertain environments.
- The multi-criteria and flexible approach of this methodology makes it a key instrument for companies seeking to align their operational efficiency with sustainability and resilience objectives, thereby strengthening.

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Evaluation of potential locations of Urban Consolidation Centers

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Abstract

The initial step in the planning process of Urban Consolidation Centers (UCCs) involves identifying potential locations for centers and evaluating them using various methods. This research aims to compare potential locations based on different voting methods, analyze the results, and assess the strengths and weaknesses of each approach. The ultimate goal is to develop a novel and improved method that enables evaluating and comparing the potential locations of UCCs in a more sophisticated way. The study begins with the definition of the problem and proceeds with a literature review of evaluation methods, including the Condorcet method, the Copeland method, the Date method, the Dodgson method, the Plurality method, and the Weighting method. A hierarchical evaluation criteria framework is then established for the facility location of UCCs to systematically assess these methods. A case study is presented to demonstrate the application of these approaches. The pros and cons of each method are also discussed. Based on these findings, a new evaluation approach is proposed, which aims to address limitations identified in existing techniques and provide a robust solution for decision-making in the first phase of the planning process for facility location. The novel approach is based on the integration of pairwise comparison, weighting, and reference-based evaluation. The proposed framework is expected to contribute to both theoretical advancements and practical applications in UCC facility location.

1. Introduction

An urban consolidation center is a facility located outside city centers where operators consolidate, sort, and prepare goods for more efficient last-mile delivery to urban areas. Such centers typically reduce the number of vehicles entering city centers, improve traffic flow, and mitigate environmental strain by employing cleaner transportation solutions, such as electric vehicles, cargo bikes, or river transport. UCCs are logistics facilities designed to improve the efficiency and sustainability of urban freight transport by consolidating deliveries before final distribution. Their primary goal is to reduce vehicle kilometers, emissions, and congestion in cities (Gillström & Björklund, 2024). However, despite these potential benefits, the practical implementation of UCCs faces several challenges. One key issue is economic sustainability. Many studies highlight that UCCs often fail due to financial constraints, lack of stakeholder engagement, and insufficient incentives for businesses to participate (Björklund & Johansson, 2018). Additionally, the success of UCCs is highly dependent on external factors such as government policies, location selection, and integration with other transport systems (Gillström & Björklund, 2024). Research suggests that private-sector engagement and financial viability remain significant barriers, as many UCCs struggle to cover their operational costs without government subsidies (Björklund & Johansson, 2018). Another challenge is the variability in UCC performance assessments. While some studies report significant reductions in emissions and traffic congestion, others find only marginal improvements (Gillström & Björklund, 2024). This inconsistency is largely due to differences in methods, the scope of studies, and variations in urban environments. A systematic literature review found that the most substantial environmental benefits arise not only from consolidation but also from shifting to environmentally friendly vehicles, such as electric vans and cargo bikes (Gillström & Björklund, 2024). Current research is increasingly focused on optimizing UCC operations through simulation models and data-driven decision-making (Wuennenberg et al., 2023). Discrete-event simulation (DES) and other modeling techniques are being used to evaluate different UCC layouts, material flow strategies, and storage solutions. Additionally, there is growing interest in integrating identification technologies, such as RFID and automated sorting systems to improve operational efficiency (Wuennenberg et al., 2023). Future research should address economic viability, stakeholder collaboration, and methodological standardization (Björklund & Johansson, 2018). By improving these aspects, UCCs can become a more effective solution for urban freight management and contribute to more sustainable city logistics.

1.1. Literature review

We have analyzed the available research results focusing on the facility location problems of UCCs. To search the Scopus database, we used the following keywords: (TITLE (urban AND consolidation AND center) AND TITLE-ABS-KEY (location)) AND (LIMIT-TO (LANGUAGE, "English")), including only research works published in English. Our search was conducted in February 2025, so additional relevant articles may have been published since then. The main research results related to the facility location problems of UCCs include the following key aspects.

(Rudolph et al., 2022) propose a hybrid multi-criteria approach combining AHP and PROMETHEE methods to determine optimal urban micro-consolidation center locations for cargo bike deliveries. Their model, applied in Stuttgart, accounts for demand, land use, and road types, emphasizing the importance of real-world data integration. (Mepparambath et al., 2021) develop a theoretical framework to assess the impact of UCCs on freight traffic, analyzing two location strategies—within or outside retail districts. Their study, based on Singapore data, reveals that UCC participation must reach a critical level to significantly reduce freight trips. (Gogas & Nathanail, 2017) present a two-level evaluation framework for UCC location selection and performance assessment. Their method integrates stakeholder interests, optimizing interconnections between urban and interurban freight networks. (Zhou & Wang, 2014) use experimental economics to analyze decision-making in UCC development, highlighting public-private partnerships and non-central locations as key success factors. Their findings suggest that larger carrier sizes enhance stakeholder benefits. (Nourinejad & Rooda, 2022) introduce a shipper-centric model for UCC location selection, ensuring cost savings for participants. Their study identifies customer density, establishment costs, and fulfillment center proximity as critical factors. (Savall-Manyó & Ribas, 2022) focus on optimizing micro-UCC locations within Barcelona's superblocks, balancing opening and transportation costs. Their approach considers operational constraints to ensure economic viability. (Triantafyllou et al., 2014) examine a UK retail UCC case study in Southampton, assessing operational scenarios and environmental impacts. Their analysis underscores the role of UCCs in reducing urban road congestion and emissions. (Royo et al., 2023) explore the transformation of parking lots into UCCs in Madrid's Living Lab, integrating digital twin technology. Their study demonstrates the feasibility of repurposing urban spaces for sustainable last-mile logistics.

As this brief literature review shows, there is a significant research gap in the mathematical modeling and optimization of the establishment and operation of UCCs. Although numerous mathematical models have been developed for optimizing urban consolidation center (UCC) locations, incorporating various factors such as transportation efficiency, cost minimization, stakeholder interests, and environmental impact (e.g., Rudolph et al., 2022; Savall-Manyó & Ribas, 2022; Nourinejad & Rooda, 2022). These models range from multi-criteria decision-making frameworks (Rudolph et al., 2022; Gogas & Nathanail, 2017) to shipper-centric approaches (Nourinejad & Rooda, 2022) and experimental economic simulations (Zhou & Wang, 2014).

1.2. Research gap identification

However, while these studies provide sophisticated mathematical optimization tools, they often assume a predefined set of candidate locations without an in-depth comparative assessment of their suitability before model application. Existing research either integrates location selection within broader logistics frameworks (Mepparambath et al., 2021) or focuses on case-specific evaluations (Triantafyllou et al., 2014; Royo et al., 2023) rather than developing systematic, pre-optimization methodologies to compare potential sites. This gap highlights the need for a structured comparative analysis of candidate locations before the application of complex mathematical optimization models. Such an approach would enhance decision-making by ensuring that mathematical models operate on a well-refined set of feasible locations, ultimately improving UCC implementation effectiveness.

One important reason for this may be the need to add specific factors into conventional planning models of logistics systems. Within the framework of the PhD research, the focus is on the following research questions:

- How can the application of new location and layout planning methods enhance the efficiency, sustainability, and cost-effectiveness of consolidation centers?
- How can advanced route planning models improve the operational efficiency of consolidation centers while reducing environmental impact and transportation costs?
- How can innovative inventory management and warehouse design methods optimize the performance of consolidation centers in terms of sustainability and cost efficiency?
- How can the adoption of e-mobility and micromobility solutions contribute to the environmental and economic efficiency of consolidation centers?
- How can the implementation of cross-docking, consignment, and postponement strategies

enhance the overall efficiency, sustainability, and cost-effectiveness of consolidation centers?

In this article, we discuss the first research question focusing on the first phase of the facility location problem of UCCs, where the most important task is the evaluation of potential locations.

In our research, we aim to investigate whether the outcomes produced by traditional voting systems are consistent and reliable. Specifically, we explore the need for a novel, integrated evaluation method that can incorporate multiple traditional voting systems. Such an approach would enable a more comprehensive comparison of potential solutions from several perspectives.

The literature offers various methods for solving such comparison tasks, including the Condorcet method, the Copeland method, the Date method, the Dodgson method, the Plurality method, and the Weighting method. In this research, we discuss the advantages and disadvantages of these methods, demonstrate their application through a case study using a potential evaluation framework, and propose the adoption of a new integrative evaluation method. This novel method, by integrating the advantages of the mentioned approaches, provides a more comprehensive assessment of UCC locations.

2. Materials and methods

Before the optimization of the location of a UCC, it is important to evaluate the potential sites to ensure that the chosen location maximizes efficiency and cost-effectiveness. By assessing each site, factors such as transportation access (rail, road, water, or air), proximity to demand areas, and infrastructure quality can be compared to select the best option from different perspectives. This evaluation process helps avoid suboptimal decisions and supports long-term sustainability in urban logistics operations. This chapter presents methods from the literature that are suitable for evaluating potential locations of UCCs. It is divided into three main parts. In the first part, the known voting methods are summarized, which are suitable for evaluating potential locations of UCCs and their pros and cons are discussed. In the second part, a novel criteria framework is described, allowing comparison and evaluation of the potential locations of UCCs. In the third part, numerical case studies demonstrate the process and operation of the mentioned existing voting methods for the selection of the optimal location for a UCC.

2.1. Conventional voting models

In decision-making, different methods help select the best solution, each following a unique evaluation approach (Stanford, 2019). The Condorcet method compares solutions in pairwise matchups, selecting the one that wins the most direct comparisons (Barberà & Bossert, 2025). However, if no single solution dominates all others, additional methods are needed. The Copeland method extends this by assigning each solution a score based on wins and losses in pairwise comparisons. The solution with the highest Copeland index is considered the best, offering a structured ranking (Bhavnani & Schiendorfer, 2022). The Date method also relies on pairwise comparisons but evaluates solutions against a fixed reference point rather than comparing them to each other. This is useful when a standard baseline exists, ensuring that all alternatives are assessed relative to a predefined benchmark. The Dodgson method, like the Copeland method, assigns scores but selects the solution with the lowest cumulative score, favoring the one with minimal opposition (Bossert & Suzumura, 2020). The Plurality evaluation method takes a different approach by allowing evaluators to select one best solution per criterion. The solution receiving the most votes is chosen as the best. While this method is simple, it does not ensure a Condorcet-optimal selection, as it does not account for how each solution compares to others. The Weighted evaluation method introduces a structured approach by assigning weights to criteria based on importance. Solutions are rated on a numerical scale, then scores are multiplied by their respective weights and summed. The highest total score determines the best option, ensuring that more critical factors have a greater influence. Each method provides a different perspective on decision-making, balancing direct competition, scoring systems, reference-based assessments, or simple majority preferences, making them useful in various contexts. The pros and cons are summarized in Table 1. As Table 1 shows, it is not possible to definitively determine which method is the most suitable for comparing potential UCC locations. Therefore, the main objective of our research is to develop a novel integrated approach that, by combining the advantageous features of these known methods, can effectively perform the comparison of potential UCC locations.

2.2. Criteria framework for evaluation

When determining the optimal location for an Urban Consolidation Center (UCC), several key factors must be considered to ensure efficiency, cost-effectiveness, and sustainability. These factors can be grouped into seven main categories, each playing a crucial role in the decision-making process (see Figure 1).

One of the most important aspects is property characteristics, which define the physical attributes of the site. Proximity to highways and railway terminals directly affects accessibility and transport efficiency, while access to ports and river transport enables multimodal logistics. Additionally, the condition and capacity of local roads influence last-mile delivery operations. Ensuring that the site is near truck-designated routes can improve traffic flow and efficiency, while the necessity for new road construction must be assessed to determine additional costs and feasibility.

Table 1: Pros and cons of voting methods

Methods	Pros	Cons
Dodgson Method	• Tries to find the solution closest to the Condorcet winner. • Provides a refined approach to ranking candidates.	• Computationally complex and impractical for large problems. • Requires iterative calculations, making it hard to implement.
Condorcet Method	• The solution preferred by the majority wins. • Reduces the risk of a widely disliked candidate winning.	• May not always produce a clear winner (Condorcet paradox). • Can be complex to compute in elections with many candidates.
Plurality Method	• Simple and easy to implement. • Requires minimal computation.	• Can result a winner who lacks broad support.
Weighting Method	• It is allowed to express varying degrees of preference. • More flexible than a simple plurality method.	• May be susceptible to strategic voting. • Requires careful calibration of weights to avoid unfair influence.
Copeland Method	• Considers all pairwise comparisons and ranks solutions. • Provides a more balanced outcome.	• Can lead to ties, requiring additional tie-breaking rules. • Requires more computation.

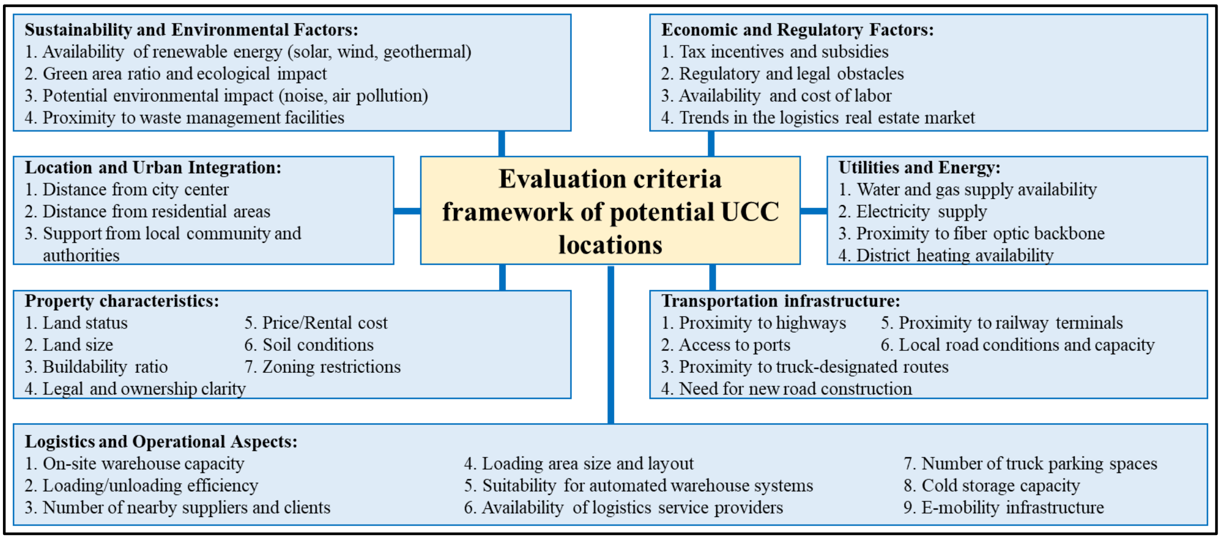

Figure 1: Proposed evaluation criteria framework of potential UCC locations

Closely related to this is transportation infrastructure, which plays a fundamental role in ensuring smooth logistics operations. The site's distance from highways, railway terminals, and ports significantly affects the movement of goods. Local road conditions and capacity need to be evaluated for congestion risks, and proximity to truck-designated routes helps optimize freight movement. If new road construction is required, it may lead to increased costs and delays, making it a critical factor in site selection.

Another crucial consideration is utilities and energy availability, which supports uninterrupted UCC operations. A stable water supply is necessary for facility maintenance and employee welfare, while gas and electricity availability ensures continuous warehouse operations, including heating, lighting, and machinery. In today's digital world, the proximity to a fiber optic backbone is essential for logistics solutions and real-time tracking systems. District heating availability can further contribute to energy efficiency and sustainability.

Beyond infrastructure and utilities, sustainability and environmental factors are increasingly influencing logistics site selection. The availability of renewable energy sources, such as solar, wind, and geothermal, helps reduce operational costs and carbon emissions. The ecological impact must also be assessed, considering factors such as green area ratio, potential environmental damage from noise and air pollution, and the site's proximity to waste management facilities, which can support sustainable waste disposal practices.

For an UCC to function effectively, logistics and operational aspects must also be taken into account. The on-site warehouse capacity, size and layout of loading areas, and the number of truck parking spaces directly influence efficiency. Loading and unloading processes need to be optimized to reduce delays, while cold storage capacity is essential for handling perishable goods. Additionally, suitability for automated warehouse systems can improve operational efficiency. The presence of nearby suppliers and clients, along with logistics service

providers, can lower transportation costs and increase service reliability. Furthermore, modern logistics infrastructure increasingly depends on e-mobility, making the availability of electric truck charging stations a growing priority.
Equally significant is the location and urban integration of the UCC. The distance from the city center affects last-mile delivery speed and efficiency, while proximity to residential areas can create challenges related to traffic congestion and noise pollution. Support from local communities and authorities plays a vital role in determining project feasibility, influencing zoning regulations and the potential for financial incentives.
Finally, economic and regulatory factors must also be evaluated. Tax incentives and subsidies can make a location more attractive by reducing operational costs. However, regulatory and legal obstacles, such as zoning restrictions and environmental regulations, may present compliance challenges. The availability and cost of labor are critical for day-to-day operations, while trends in the logistics real estate market can impact long-term investment decisions and property values.
By considering all these factors carefully, we can make informed decisions about the optimal location for an UCC. A well selected site ensures efficient logistics operations, cost savings, and sustainable growth while minimizing regulatory and environmental challenges. In an ever-evolving urban landscape, strategic site selection will remain a key factor in optimizing supply chain performance and meeting the increasing demands of modern logistics.

2.3. Numerical results with conventional voting methods

In this chapter, the above-described voting methods are analyzed through a numerical study to demonstrate their applicability in the preliminary assessment of potential UCC locations. Furthermore, the purpose of this numerical study is to provide reference values for the comparison with the results of our novel integrative evaluation approach, which integrates the advantages of the individual existing methodologies. In the case study, the evaluation of five potential UCC locations (A to E) is demonstrated based on the criteria framework shown in Figure 1, using the following methods: Date, Dodgson, Condorcet, Plurality, Weighting, and Copeland method.
To ensure that the computational results are clearly illustrated, we do not demonstrate the individual analysis based on all 37 criteria for each method. Instead, we determine the normalized values of the 37 criteria for each evaluation criterion group as shown in Table 2 and Table 3.

Table 2: Evaluation criteria values and the normalized values of evaluation criterion groups, part I.

Criterion	Notation	Potential locations				
		A	B	C	D	E
Property characteristics						
Land status (rentable/purchasable 0/1)	P_1	1.00	0.00	0.00	0.00	1.00
Price/Rental cost (*HUF/m²*)	P_2	2000	1800	1300	0	1000
Land size and expandability	P_3	0.73	0.65	0.92	0.38	0.19
Soil conditions (stability, load capacity)	P_4	0.80	0.36	0.60	0.79	0.68
Buildability ratio and zoning restrictions	P_5	0.34	0.97	0.81	0.03	0.48
Legal and ownership clarity	P_6	0.64	0.83	0.66	0.24	0.90
Normalized values	P_n	1.00	0.82	0.82	0.35	0.83
Transportation infrastructure						
Proximity to highways (*km*)	T_1	5	10	3	7	9
Proximity to railway terminals (*km*)	T_2	1	4	7	9	11
Access to ports/river transport	T_3	0.18	0.60	0.66	0.11	0.69
Local road conditions and capacity	T_4	0.81	0.07	0.89	0.44	0.05
Proximity to truck-designated routes	T_5	0.05	0.81	0.24	0.70	0.53
Need for new road construction	T_6	0.05	0.12	0.67	0.49	0.43
Normalized values	T_n	0.45	0.82	0.99	0.89	1.00
Utilities and energy						
Water supply availability	U_1	0.56	0.41	0.27	0.05	0.80
Gas supply availability	U_2	0.62	0.46	0.82	0.20	0.73
Electricity supply	U_3	0.55	0.95	0.09	0.06	0.86
Proximity to fiber optic backbone	U_4	0.57	0.24	0.99	0.14	0.44
District heating availability	U_5	0.85	0.27	0.44	0.01	0.36
Normalized values	U_n	0.98	0.72	0.80	0.14	1.00
Sustainability and environment						
Availability of renewable energy	S_1	0.73	0.01	0.08	0.80	0.16

Green area ratio and ecological impact	S_2	0.41	0.60	0.30	0.83	0.23
Potential environmental impact	S_3	0.77	0.27	0.87	0.33	0.54
Proximity to waste management facilities	S_4	1	3	4	5	2
Normalized values	S_n	0.74	0.49	0.67	1.00	0.44

Table 3: Evaluation criteria values and the normalized values of evaluation criterion groups, part II

Criterion	Notation	Potential locations				
		A	B	C	D	E
Logistics and operation						
On-site warehouse capacity	L_1	0.35	0.83	0.59	0.02	0.42
Loading area size and layout	L_2	0.51	0.80	0.91	0.46	0.09
Number of truck parking spaces	L_3	0.99	0.44	0.32	0.64	0.74
Loading/unloading efficiency	L_4	0.60	0.73	0.56	0.43	0.16
Cold storage capacity	L_5	0.91	0.26	0.64	0.71	0.24
Suitability for automated warehousing	L_6	0.06	0.95	0.64	0.11	0.82
Number of nearby suppliers and clients	L_7	0.40	0.18	0.56	0.79	0.09
Availability of logistics service providers	L_8	0.95	0.70	0.29	0.25	0.27
E-mobility infrastructure	L_9	0.80	0.46	0.61	0.06	0.50
Normalized values	L_n	1.00	0.96	0.93	0.63	0.58
Location and urban integration						
Distance from city center	Z_1	10	5	7	9	13
Distance from residential areas	Z_2	8	10	6	17	5
Support from community and authorities	Z_3	0.01	0.14	0.33	0.37	0.64
Normalized values	Z_n	0.55	0.52	0.61	0.99	1.00
Economy and regulatory factors						
Tax incentives and subsidies	E_1	0.36	0.20	0.40	0.94	0.71
Regulatory and legal obstacles	E_2	0.12	0.16	0.58	0.32	0.23
Availability and cost of labor	E_3	0.40	0.18	0.68	0.85	0.67
Trends in the logistics real estate market	E_4	0.08	0.65	0.64	0.18	0.82
Normalized values	E_n	0.39	0.50	1.00	0.92	0.98

We can normalize the values in four phases. In the first phase, we convert all values of the evaluation criteria into a "higher is better" form. If the evaluation criterion has a "lower is better" value (for example in the case of proximity to highways, railway terminals, or waste management facilities), then it must be converted into a higher is better criterion:

$$\forall i,j,k: \alpha_{ijk}^{*} = \max_{k} \alpha_{ijk} - \alpha_{ijk}, \quad (1)$$

where α_{ijk} is the evaluation criterion j of potential UCC location k in the evaluation criteria group i, and α_{ijk}^{*} is the normalized evaluation criterion. The next phase is to normalize the converted evaluation criteria values as follows:

$$\forall i,j,k: \alpha_{ijk}^{N*} = \alpha_{ijk}^{*} / \max_{k} \alpha_{ijk}^{*}, \quad (2)$$

where α_{ijk}^{N*} is the normalized value of the converted evaluation criterion. The next phase is to summarize the normalized converted evaluation criteria values:

$$\forall i,k: \beta_{ik} = \sum_{j=1}^{j_{max}} \alpha_{ijk}^{N*}, \quad (3)$$

where β_{ik} is the sum of the normalized converted evaluation criteria. In the final phase, we normalize the total value of the normalized converted evaluation criteria values as follows:

$$\forall i,k: \beta_{ik}^{N} = \beta_{ik} / \max_{k} \beta_{ik}, \quad (4)$$

where β_{ik}^{N} is the normalized evaluation criterion value for the potential UCC location k in the evaluation criterion group i.

2.3.1. Numerical analysis based on the Date method

Table 4 shows the numerical results of the evaluation using the Date method. In our case, the second location was chosen as the reference, and the other four locations were compared to it.

Table 4: Numerical results using the Date method for the seven criterion groups (CG)

CG	Locations				
	A	B	C	D	E
P	1	X	-1	-1	1
T	-1	X	1	1	1
U	1	X	1	-1	1
S	1	X	1	1	-1
L	1	X	-1	-1	-1
Z	1	X	1	1	1
E	-1	X	1	1	1
SUM	3	X	3	1	3
RANK	1	X	1	4	1

Using the Date method, the best locations of the UCC are location A, C and D. The calculation led to tie.

2.3.2. Numerical analysis with the Dodgson method

Table 5 shows the numerical results of the evaluation using the Dodgson method focusing on the number of wins in the pairwise comparison, their sum and the resulted ranks.

Table 5: Numerical results using the Dodgson method for the seven criterion groups (CG)

CG	Locations				
	A	B	C	D	E
P	0	3	5	7	1
T	8	7	3	5	1
U	2	5	3	7	1
S	2	5	3	1	7
L	0	1	3	5	7
Z	6	7	5	3	1
E	8	7	1	5	3
SUM	26	35	23	33	21
RANK	3	5	2	4	1

The best location of the UCC is location E.

2.3.3. Numerical analysis with the Condorcet method

Table 6 shows the numerical results of the evaluation using the Condorcet method.

Table 6: Numerical results using the Condorcet method for the seven criterion groups (CG)

	Criterion group (CG)						
	P	T	U	S	L	Z	E
A vs. B	A	B	A	A	A	A	B
A vs. C	A	C	A	A	A	C	C
A vs. D	A	D	A	D	A	D	D
A vs. E	A	E	E	A	A	E	E
B vs. C	B	C	C	C	B	C	C
B vs. D	B	D	B	D	B	D	D
B vs. E	E	E	E	B	B	E	E
C vs. D	C	C	C	C	C	C	C
C vs. E	E	E	E	C	C	E	C
D vs. E	E	E	E	D	D	E	E

Using the Condorcet method, the best location of the UCC is locations C and E, because the total number of winners in Table 6 are the followings: UCC location A: 15 wins; UCC location B: 9 wins; UCC location C: 18 wins; UCC location D: 10 wins; and UCC location E: 18 wins.

2.3.4. Numerical analysis with the Plurality method

Table 7 shows the numerical results of the evaluation using the Plurality method.

Table 7: Numerical results using the Plurality method for the seven criterion groups (CG)

CG	Locations				
	A	B	C	D	E
P	1	0	0	0	0
T	0	0	0	0	1
U	0	0	0	0	1
S	0	0	0	1	0
L	1	0	0	0	0
Z	0	0	0	0	1
E	0	0	1	0	0
SUM	2	0	1	1	3
RANK	2	5	3	3	1

Using the Plurality method, the best location of the UCC is locations E.

2.3.5. Numerical analysis with the Weighting method

In the case of the Weighting method the first task is to define the weighting factors for each evaluation criterion group. We have chosen the following weighting factors: property characteristics 10%, transportation infrastructure 20%, utilities and energy 15%, sustainability and environment 30%, logistics and operation 5%, location and urban integration 10%, economy and regulatory factors 10%. These factors can significantly influence the results of the evaluation, therefore it is important to find the best weighting factors, depending the expected result of evaluation. A sensitivity analysis can support to choose the best weighting factors. Table 8 demonstrates the numerical results of the evaluation using the Weighting method. In Table 8, wX is for the weighted value of evaluation criterion value of UCC location X, where $X \in \{A, B, C, D, E\}$.

Table 8: Numerical results using the Weighting method for the seven criterion groups (CG)

CG	Locations				
	wA	wB	wC	wD	wE
P	0.10	0.08	0.08	0.04	0.08
T	0.09	0.16	0.20	0.18	0.20
U	0.15	0.11	0.12	0.02	0.15
S	0.22	0.15	0.20	0.30	0.13
L	0.05	0.05	0.05	0.03	0.03
Z	0.05	0.05	0.06	0.10	0.10
E	0.04	0.05	0.10	0.09	0.10
SUM	0.70	0.65	0.81	0.76	0.79
RANK	4	5	1	3	2

Using the Weighting method, the best location of the UCC is locations C.

2.3.6. Numerical analysis with the Copeland method

Table 9 shows the numerical results of the evaluation using the Copeland method.

Table 9: Numerical results using the Copeland method for the seven criterion groups (CG)

CG	Locations				
	A	B	C	D	E
P	1	3	4	5	2
T	5	4	2	3	1
U	2	4	3	5	1
S	2	4	3	1	5
L	1	2	3	4	5
Z	4	5	3	2	1
E	5	4	1	3	2
SUM	20	26	19	23	17
RANK	2	5	3	3	1

Using the Copeland method, the best location of the UCC is location E, because the potential UCC location won the most evaluation in the case of the seven evaluation criterion groups (three times).
As the above-discussed numerical studies show, in the case of the six voting methodologies, the resulting best solutions were different; therefore, the results of the case study cannot be considered consistent. In order to resolve this issue, the following chapter introduces a new integrative method that aims to provide reliable results for determining the optimal location of the UCC by combining the advantageous properties of the previously discussed methods.

3. Results and Discussion

This chapter describes our novel approach, which, through methodological integration, analyzes alternative locations of UCCs based on multiple criteria while considering the methodological approaches of well-known methods from the literature. It then recommends the best solution. The chapter includes both a formal description of the integrative approach (see Chapter 3.1.) and a numerical study that demonstrates its applicability (see Chapter 3.2.).

3.1. Formal description

Our novel method includes three different approaches to choose the optimal alternative: the first approach focuses on the pairwise comparison of potential locations of UCCs across predefined criteria (see Chapter 3.1.1.); the second part takes into consideration predefined weighting factors (see Chapter 3.1.2.), while in the case of the third approach a reference value for each criteria is taken into consideration and the alternatives are evaluated by comparing them with the reference values of the criteria (see Chapter 3.1.3.). The method that enables the integration of these three evaluation approaches and allows the selection of the optimal alternative using these three different evaluation approaches is presented in Chapter 3.1.4.

3.1.1. Pairwise comparison

The input parameters of the pairwise comparison across criteria with ranking system are the followings:

- $A = \{a_1, \dots a_i, \dots a_m\}$ is the set of m alternative, potential locations of UCCs,
- $C = \{c_1, \dots c_j, \dots c_n\}$ is the set of c evaluation criteria.

Based on a pairwise comparison, we can calculate the preference score for each potential alternative location, for each evaluation criteria:

$$PS(a_i, c_j) = \sum_{i=1}^{m} \sum_{k=1,k\neq i}^{m} P(a_i, a_k, c_j), \quad (5)$$

where $P(a_i, a_k, c_j) = 1$ if a_i is preferred over a_k in evaluation criteria c_j, $P(a_i, a_k, c_j) = -1$ if a_k is preferred over a_i in evaluation criteria c_j, and $P(a_i, a_k, c_j) = 0$ if a_i and a_k are tied in evaluation criteria c_j.
Based on the preference scores, we can determine the rank of each alternative location for each evaluation criteria as follows:

$$r(a_i, c_j) = m - \sum_{k=1}^{m} \mathbb{I}\,(PS(a_i, c_j), PS(a_k, c_j)), \quad (6)$$

where $\mathbb{I}$ is an indicator function, which returns 1, if $PS(a_i, c_j) > PS(a_k, c_j)$ condition is true, otherwise 0.

The winner of the pairwise comparison across criteria can be determined as follows:

$$a^* = \min_i \sum_{j=1}^{n} r(a_i, c_j). \quad (7)$$

3.1.2. Weighting method

The input parameters of the weighting-based approach are the followings:

- $A = \{a_1, \dots a_i, \dots a_m\}$ is the set of m alternative, potential locations of UCCs,

- $C = \{c_1, \ldots c_j, \ldots c_n\}$ is the set of c evaluation criteria,
- $W = \{w_1, \ldots w_j, \ldots w_n\}$ is the set of w weighting factor of c evaluation criterion.

In the case of this approach, the weighting factors must be normalized:

$$\sum_{j=1}^{n} w_j = 1. \quad (8)$$

The first phase of this method is the evaluation of the m alternative, potential solutions from the evaluation criteria point of view, using a 1 to 5 scale. This evaluation value can be given as a $EV = \{ev_{11}, \ldots ev_{ij}, \ldots ev_{mn}\}$ set for the m alternative and c evaluation criteria. Formally, for the EV set we can define, that all elements of the set are distinct (there are no repetitions) in the case of the same alternative solution. It means, that the values of the EV set in the case of the same alternative solution are the permutations of the set $\{1, \ldots i \ldots m\}$, where $i \in \mathbb{Z}$:

$$\forall i: ev_{ij} \neq ev_{ik} \wedge ev_{ij} \in \{1, \ldots i \ldots m\}. \quad (9)$$

Based on the evaluation values and the predefined weighting factors, we can calculate the weighted value for each alternative and we can choose the optimal alternative:

$$a^* = \max_i \sum_{j=1}^{n} ev(a_i, c_j) \cdot w_j. \quad (10)$$

3.1.3. Reference-based method

The input parameters of the reference-based approach are the followings:

- $A = \{a_1, \ldots a_i, \ldots a_m\}$ is the set of m alternative, potential locations of UCCs,
- $C = \{c_1, \ldots c_j, \ldots c_n\}$ is the set of c evaluation criteria,
- $R = \{r_1, \ldots r_j, \ldots r_n\}$ is the set of r reference values for each criterion.

Based on a pairwise comparison of alternative and reference, we can calculate a reference-related score for each alternative, potential location:

$$RRS(a_i) = \sum_{i=1}^{m} P(a_i, r_j, c_j), \quad (11)$$

where $P(a_i, r_j, c_j) = 1$ if a_i is preferred over r_i in evaluation criterion c_j, $P(a_i, r_j, c_j) = -1$ if r_i is preferred over a_i in evaluation criteria c_j, and $P(a_i, r_j, c_j) = 0$ if a_i and r_i are tied in evaluation criterion c_j.

The winner of the pairwise comparison across criteria can be determined as follows:

$$a^* = \max_i RRS(a_i). \quad (12)$$

3.1.4. Integrative method

If the individual methods provide quantitative results, we can apply Multi-Criteria Decision Making (MCDM) techniques such as:

- TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution): Compares alternatives based on their proximity to an ideal and an anti-ideal solution (Majid et al., 2012).
- ELECTRE (Elimination and Choice Expressing Reality): Performs pairwise comparisons between alternatives (Kannan & Brandt, 2016).
- AHP (Analytic Hierarchy Process): Makes decisions based on a weighted criteria system (William & Xin, 2018).

As an integrative method, we have chosen TOPSIS, because it simultaneously considers both the best and worst solutions, ensuring a balanced evaluation of alternatives. It is easy to apply, works well with quantitative data, and provides a clear ranking of options. Additionally, it effectively handles multiple conflicting criteria, making it a robust method for decision-making in complex scenarios (Majid et al., 2012).

We have five alternatives, potential locations evaluated using three different evaluation methods (pairwise comparison, weighting, and reference-based). Each approach assigns a final score or rank to each alternative. Let us define these scores in the case of the pairwise comparison method based on Equation 2 as follows:

$$s_{\alpha 1} = 1 + \max_{\alpha} \sum_{j=1}^{n} r(a_i, c_j) - \sum_{j=1}^{n} r(a_i, c_j). \quad (13)$$

These scores in the case of the weighting method based on Equation 6 can be defined as:

$$s_{\alpha 2} = \sum_{j=1}^{n} ev(a_i, c_j) \cdot w_j. \quad (14)$$

These scores in the case of the reference-based method can be defined as:

$$s_{\alpha 3} = \sum_{i=1}^{m} P(a_i, r_i, c_j) + \left| \min_{\alpha} \sum_{i=1}^{m} P(a_i, r_i, c_j) \right|. \quad (15)$$

The first phase of the TOPSIS is to normalize the decision matrix containing the scores:

$$s_{\alpha j}^* = s_{\alpha j} \Big/ \sqrt{\sum_{\alpha=1}^{m} s_{\alpha j}^2}, \quad (16)$$

where $s_{\alpha j}^*$ is the normalized decision matrix, α_{max} is the number of alternatives.

The next phase is to calculate the weighted normalized matrix:

$$s_{\alpha j}^{*W} = s_{\alpha j}^* \cdot w_j^T, \quad (17)$$

where $s_{\alpha j}^{*W}$ is the weighted normalized matrix, and w_j^T is the weighting factor of used approaches in the TOPSIS.

The third phase is to identify the best and the worst solution. The best solution is obtained by selecting the maximum value for each alternative:

$$A_j^B = \max_{\alpha} s_{\alpha j}^{*W}, \quad (18)$$

The worst solution is obtained by selecting the minimum value for each alternative:

$$A_j^W = \min_{\alpha} s_{\alpha j}^{*W}, \quad (19)$$

Thus, the best and the worst solutions can be represented as:

$$A^B = (\max_{\alpha} s_{\alpha 1}^{*W}, \max_{\alpha} s_{\alpha 2}^{*W}, \dots, \max_{\alpha} s_{\alpha j_{max}}^{*W}), \quad (20)$$

$$A^W = (\min_{\alpha} s_{\alpha 1}^{*W}, \min_{\alpha} s_{\alpha 2}^{*W}, \dots, \min_{\alpha} s_{\alpha j_{max}}^{*W}), \quad (21)$$

where j_{max} is the number of applied evaluation methodologies (in our study $j_{max} = 3$, because we have used three approaches to analyze the alternatives (pairwise comparison, weighting, and reference-based evaluation)).

The fourth phase of the TOPSIS-based integrative method is to calculate the Euclidean distances from the best and from the worst solution for each alternative location:

$$ED_\alpha^B = \sqrt{\sum_{j=1}^{j_{max}} \left(s_{\alpha j}^{*W} - A_j^B\right)^2}, \quad (22)$$

$$ED_\alpha^W = \sqrt{\sum_{j=1}^{j_{max}} \left(s_{\alpha j}^{*W} - A_j^W\right)^2}, \quad (23)$$

The fifth phase of the integrative step is to define the relative closeness to the best solution:

$$RC_\alpha = ED_\alpha^W / (ED_\alpha^B + ED_\alpha^W), \quad (24)$$

The alternative solution with the best relative closeness value is the best solution.

3.2. Numerical results

In this numerical analysis, we demonstrate the application of our proposed novel integrative method, which uses both pairwise comparison, weighting method and a reference-based evaluation and the results of these approaches are integrated by TOPSIS.

Based on Equations 5-15 we can calculate the final scores/ranks for all five potential UCC locations, the numerical results are shown in Table 10.

Table 10: Final scores/ranks based on pairwise comparison (PC), weighting (W) and reference-based evaluation (RBE)

Met-hod	Locations				
	A	B	C	D	E
PC	10	1	13	3	15
W	0.70	0.65	0.81	0.76	0.79
RBE	3	1	7	3	5

Based on Equation 16, we can normalize the finals scores/ranks, as Table 11 shows.

Table 11: Normalized scores/ranks based on pairwise comparison (PC), weighting (W) and reference-based evaluation (RBE)

Met-hod	Locations				
	A	B	C	D	E
PC	**0.45**	**0.04**	**0.58**	**0.13**	**0.67**
W	**0.42**	**0.39**	**0.49**	**0.45**	**0.48**
RBE	**0.31**	**0.10**	**0.73**	**0.31**	**0.52**

We have chosen the following weighting factors within the TOPSIS for the three evaluation approach:

- for the pairwise comparison: 0.4,
- for the weighting method: 0.3,
- for the reference-based approach: 0.3.

Based on Equation 17, we can calculate the weighted, normalized matrix of the finals scores/ranks, as Table 12 shows.

Table 12: Weighted and normalized matrix of the final scores/ranks based on pairwise comparison (PC), weighting (W) and reference-based evaluation (RBE)

Met-hod	Locations				
	A	B	C	D	E
PC	**0.18**	**0.02**	**0.23**	**0.05**	**0.27**
W	**0.13**	**0.12**	**0.15**	**0.14**	**0.14**
RBE	**0.09**	**0.03**	**0.22**	**0.09**	**0.16**

Based on Equations 18-21 we can identify and calculate the best and the worst solution:

$$A^B = (0.27, 0.15, 0.22), \quad (25)$$

$$A^W = (0.02, 0.12, 0.03), \quad (26)$$

and based on these best and worst solutions we can calculate the Euclidean distances from the best and from the worst solution for each alternative location and we can calculate the relative closeness to the best solution, as Table 13 shows.

Table 13: Euclidean distances from the best and from the worst solution for each alternative location and the relative closeness

Loca-tions	Locations				
	A	B	C	D	E
ED_{α}^{B}	**0.15**	**0.31**	**0.04**	**0.25**	**0.06**
ED_{α}^{W}	**0.17**	**0.00**	**0.29**	**0.07**	**0.28**
RC_{α}	**0.53**	**0.00**	**0.89**	**0.23**	**0.82**

The alternative solution with the best relative closeness value is the best solution; it means that our novel integrative approach resulted location C as the optimal location of the UCC. In the case of the conventional methods, the location E was the winner four times, while the location C was the winner three times. The winners are shown in Table 14 for each existing methods.

Table 14: Winners of the various conventional methodologies

Method	Locations				
	A	B	C	D	E
Date	**X**		**X**	**X**	
Dodgson					**X**
Condorcet			**X**		**X**
Plurality					**X**
Weighting			**X**		
Copeland					**X**

It is important to analyze the impact of weighting factors in the TOPSIS method, as the selection of these factors can significantly influence the accuracy of the results. In the case study presented, we performed a sensitivity analysis on the weighting factor of the pairwise comparison method. Although the relative closeness values changed, the optimal solution consistently remained at location C. However, under different weighting factor ratios, the significance of selecting appropriate weighting factors became more important. As illustrated in Figure 3, changing the weighting factor of the pairwise comparison method between 0 and 0.6 not only influenced the relative closeness values but also affected the optimal location for the UCC. Specifically, at a value of 0.25, the previously optimal location C was replaced by location E as the most favorable solution. For location B, the relative closeness value is always 0 because the potential UCC site at B ranked last in all three approaches based on the evaluation criteria.

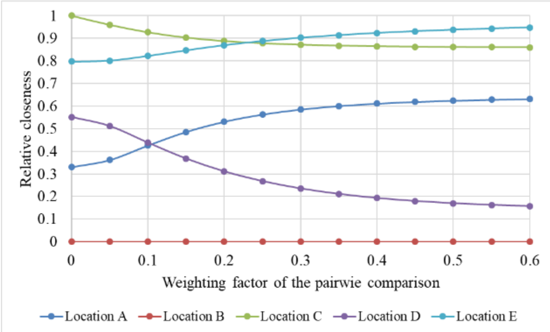

Figure 2: Impact of weighting factor of pairwise comparison method on relative closeness and optimal location of UCC

As the above-described case study shows, the proposed integrative method is suitable for selecting the optimal location for a UCC from among potential sites by considering a complex evaluation framework. The case study and its sensitivity analysis, conducted for validation purposes, confirmed that the developed novel method can provide reliable results when appropriate parameters (weighting factors) are selected. However, it is essential to assess the impact of these parameters on the results for each specific problem individually.

The literature discusses a wide range of studies focusing on the selection of the optimal location for UCCs; however, these methods are based on optimization algorithms, especially on heuristics and metaheuristics. In contrast, the objective of the present approach is to determine the most suitable location through an integrative analysis of potential sites before applying optimization techniques. Additionally, this approach allows for the exclusion of the least favorable locations from the optimization process, significantly reducing the number of variables. By narrowing down the search space, it decreases the dimensions of the multidimensional search space in heuristic optimization, enabling more precise results with lower computational effort. The limitation with regard to the application are the followings:

- The parameters of the evaluation approach, especially in the case of the weighting factors used in the integrative TOPSIS methods, can significantly influence the results.
- Obtaining the necessary data for the evaluation criterion framework can be time-consuming.
- The reliability of the data assigned to the evaluation criteria significantly impacts the effectiveness of the method. Therefore, ensuring accurate and reliable input parameters is essential.

The most significant advantage of the proposed method and its application is that, by utilizing the suggested evaluation framework, the assessment of potential UCC locations can be conducted efficiently and within a short timeframe. This, in turn, can greatly contribute to accelerating the establishment process of UCCs.

4. Limitations and Conclusion

The research identifies key strengths and weaknesses of existing voting methodologies for Urban Consolidation Center (UCC) locations, including the Condorcet, Copeland, Date, Dodgson, Plurality, and Weighting methods. A case study demonstrates the potentials of existing voting methodologies. Based on these findings, a new evaluation approach is proposed to overcome limitations of existing methods, offering a more robust and sophisticated decision-making framework. This contribution enhances both theoretical understanding and practical applications in facility location planning for UCCs.

4.1. Results of the research

As a result of the research, a new method has been developed that integrates the advantages of existing voting methodologies to provide a comprehensive comparison of potential UCC locations. This outcome is based on three key findings:

- A review and case study analysis of existing voting methodologies (Condorcet, Copeland, Date, Dodgson, Plurality, and Weighting methodologies), highlighting their strengths and weaknesses, revealed that while these methods are useful for evaluating UCC locations, their results vary significantly depending on the chosen approach.
- A hierarchical evaluation criterion framework was developed, taking the following main factors into consideration: property characteristics, transportation infrastructure, utilities and energy, sustainability, logistics, urban integration, economy, and regulations
- A new integrated evaluation approach was developed, combining pairwise comparison, weighting method, and reference-based comparison within this framework. By integrating the benefits of existing methods with TOPSIS, the proposed approach ensures more reliable and consistent evaluation results.

4.2. Future research directions

Our short-term research direction is to test the Analytic Hierarchy Process (AHP) instead of TOPSIS within the novel developed integrative method. Other short-term research direction is a detailed sensitivity analysis to show the impact of weighting factors and evaluation criteria on the results. In the long-term, we aim to develop new methods and tools for the logistics-oriented planning of UCCs, including facility location, routing, inventory, etc. Other potential research direction is to use other alternatives such as TOPSIS, AHP, or VIKOR as an integrator of conventional voting methodologies.

4.3. Limitations and open challenges

During this research, we faced several challenges, the most significant being the ability to work with real-world data. Since we could not find an active project within the research timeframe to test our method with real-world data, we performed numerical studies using sample datasets. Despite this, our results provide valuable insights, and in future research, we plan to validate the proposed approach with real-case applications.

The lack of detail about decision-maker participation and weighting rationale could weakens the robustness of the numerical results. In the current study, the weighting of criteria was based on our own experiences, reflecting commonly accepted priorities in the context of UCC site selection. However, we recognize that the theoretical robustness could be enhanced by a more transparent documentation of the decision-makers' roles and the rationale behind the assigned weights. Therefore, in future work, we plan to incorporate participatory approaches, such as structured expert elicitation or stakeholder-driven weighting techniques, to ensure greater transparency, reproducibility, and contextual relevance of the decision-making framework.

4.4. Exploitation perspective

In our opinion, one of the most practical forms of exploitation could be a service. Since the evaluation criteria framework can be adjusted and modified flexibly, the method can be easily adapted to other planning tasks that require decision support.

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Towards a Resilience Management System in Value Chains: A Methodological Approach for SMEs

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Abstract

Small and medium-sized enterprises (SMEs) face significant challenges managing disruptions in global supply chains (SC) due to limited resources and restricted strategic options. Traditional approaches from risk management and supply chain management (SCM) are typically used independently, making it challenging for SMEs to effectively select and apply resilience-enhancing strategies. This paper presents a conceptual framework that integrates existing methods from both risk management and SCM into a modular toolbox based on morphological analysis. The toolbox is designed to support SMEs by providing a structured and practical approach to systematically identify and implement tailored resilience measures.

1. Introduction

The increasing vulnerability of global SC to geopolitical, environmental, and technological risks presents considerable challenges and opportunities, especially for SMEs in production and logistics (Klementzki et. al, 2023). Due to their limited resources and low diversification options, SMEs require specialized methods to increase SC resilience (Gebhardt et. al, 2022). This paper addresses the issue that current risk management and SCM methods are often applied separately (Fan & Stevenson, 2018). The objective is to develop an integrated methodological toolbox based on a morphological analysis, enabling SMEs to systematically and cost-efficiently select appropriate measures. Particular emphasis is placed on integrating methods from risk management and SCM to reduce the probability of disruptions and overall susceptibility to disturbances.

Against this backdrop, the concept of resilience becomes increasingly important for SMEs. In this context, resilience describes the ability of a company or a SC to effectively respond to unexpected and negative events and to emerge stronger from them (Wieland & Durach, 2021).

Although Supply Chain methods are important for all companies, comparatively few scientific studies examine its implementation in SMEs, especially regarding the development of specific tools and methods (Biedermann, 2018; Schröder, 2019). SMEs primarily rely on creating additional capacities or inventories to mitigate potential risks in the SC. In contrast to large enterprises, SMEs tend to act reactively by resorting to redundancies. Furthermore, they often lack the capability described in SCM literature to rapidly recover after disruptions, as they typically have lower liquidity and fewer capital reserves compared to larger companies. (Ljungberg & Lindgren, 2024)

Against this background, the following research question arises:

How can SMEs integrate methods from risk management and supply chain management into a morphological analysis-based resilience toolbox, and how can the effectiveness of this toolbox be evaluated in terms of improved supply chain resilience?

The aim of this paper is to analyze existing methodological approaches from risk management and SCM, and to develop an approach for their combinatorial development using a morphological analysis. Based on this morphological analysis, SMEs should then be enabled to select suitable methods for enhancing resilience individually, systematically, and cost-effectively. The paper begins with a theoretical foundation, describing typical risks and characteristics of SMEs in production and logistics. Subsequently, established methods from risk management and SCM will be presented and analyzed. Following that, the integrative methodological approach based on the morphological analysis will be introduced and explained. Finally, the potentials and limitations of this approach will be critically discussed, and an outlook on future research and application potentials will be provided, briefly touching upon the possible role of AI-based (Artificial Intelligence) support.

2. State of Research

SMEs constitute the majority of economic actors in Europe and play vital roles in production as well as logistics. They are defined by having fewer than 250 employees and an annual turnover not exceeding 50 million euros (Bak et. al, 2023). In production and logistics, SMEs typically exhibit high specialization, limited resources, and low flexibility regarding strategic alternatives. These characteristics make SMEs especially vulnerable to disruptions within the SC (Johnson, 2025).

A SC generally refers to all stakeholders involved in the extraction of raw materials, the manufacturing and delivery processes, through to the disposal of a product (Wehking, 2020; Klementzki et. al, 2023). Thus, the SC encompasses all activities necessary to provide a demanded product (Hohmann, 2022; Klementzki et. al, 2023). The supply chain includes not only the physical flow of materials but also the resulting flow of information between the companies involved, thus forming a procurement chain that contributes to the creation of products (Bichler et. al, 2017). The supply chain is seen as a network of different companies, which simultaneously defines the structural arrangement (Ostertag, 2008).

Especially during global crises, such as the COVID-19 pandemic, the blockade of the Suez Canal, or the Russian invasion of Ukraine etc., it becomes clear how quickly such international networks can collapse (cf. Ivanov, 2023; Klementzki et. al, 2023). Consequently, supplier management should specifically foster resilient supply structures that enable companies to respond proactively and flexibly to global disruptions and opportunities, thereby becoming more resilient (cf. Voß, 2023).

This vulnerability to opportunities and risks is particularly critical for SMEs, as they often lack the financial and organizational capacities required for rapid response (cf. Johnson, 2025).

2.1. Concept of Resilience

Entrepreneurial resilience generally refers to a company's ability to remain stable despite external stresses caused by strikes, internal crises like breakdowns of machines etc., while simultaneously adapting flexibly to altered conditions (Günther, 2018; Klementzki et. al, 2023). Organizational resilience specifically implies that companies can withstand occurring disruptions, adapt to them, and restore their original performance levels after successfully managing such disturbances (Biedermann, 2018; Klementzki et. al, 2023). This resilience must be deliberately established within companies to make processes resilient in advance and to define agile measures for seizing opportunities and responding to disruptions (Voß, 2023; Klementzki et. al, 2023). The challenge for companies is to implement targeted measures to increase resilience to seize opportunities and eliminate disruptions (Voß, 2023).

Increasing resilience is particularly beneficial for SMEs, as they often lack the capacity to absorb the consequences of disruptions financially or operationally in the long term (Johnson, 2025). Resilience principles are regarded as guidelines for resilient value creation systems. These include early detection, the creation of redundancy, networking, asynchrony, modularity, isolation, bricolage, reversibility, and ductility (Buß et. al, 2021; Klementzki et. al, 2023). In this context, the concept of the supply chain must also consider the specific demand that has been placed. A customer within a supply chain can request a new demand, requiring the upstream members of the supply chain to adapt to seize this new opportunity. (Klementzki et. al, 2023)

Resilience involves a focus on flexibility to provide adaptable areas within the company when an opportunity arises (Buß et. al, 2021; Klementzki et. al, 2023). Flexibility refers to the capacity to absorb shocks by holding extra inventory or maintaining backup suppliers (creating buffers at the cost of higher fixed costs) (Klementzki et. al, 2023).

Agility forms an essential foundation for innovative solution approaches, as it essentially describes an organization's ability to realign business and organizational models as well as the structure and process design of the supply chain. Moreover, this flexibility enables the organization to develop into a fundamentally different and potentially more advantageous state (Klementzki et. al, 2023; Zitzmann, 2018; Kleemann & Frühbeis, 2021). The goal of resilience management is to enable an organization to apply predefined solution strategies in the event of disruptive incidents and to use the resulting developments as opportunities for optimization (Meissner et. al, 2023; Buß et. al, 2021; Klementzki et. al, 2023).

2.2. SCM Approach

Due to their complex structures, SC require targeted management and coordination (Hohmann, 2022). This task is addressed by SCM, a process-oriented management approach encompassing all flows of products, finances, and information, as well as contractual and social relationships from raw

material procurement to the final consumer. Its objective is to integrate all value-adding processes and enhance the competitiveness of all stakeholders involved. (Wehking, 2022)
Initially, SCM focuses on integrating material and information flows for each member of the SC and fostering sustainable collaboration among participating companies. Additionally, establishing shared objectives within the SC aims to achieve better overall outcomes and create a standardized process structure for all actors involved. (Biedermann, 2018) Supply chain management is a field that emphasizes the coordination of factories, suppliers, warehouses, distribution hubs, and retail stores to ensure products are manufactured and delivered to customers at the correct place, time, and price. This process aims to reduce costs while ensuring a defined service level is maintained. (Göpfert, 2019) The goal is to optimize performance potential and service quality in relation to the effort involved (Voigt et. al, 2018).

2.3. Understanding of Risk Management

An appropriate and strategic approach to handling risks and opportunities is essential for companies to secure their long-term existence (Huth & Romeike, 2016). Since companies make numerous daily decisions aimed at increasing their value creation, risks and opportunities inevitably become part of their everyday business. Therefore, it is crucial to develop suitable strategies for dealing with these risks. (Huth & Romeike, 2016) Risk management, therefore, refers to the systematic examination of opportunities and potential threats arising during entrepreneurial activities (Romeike, 2018). This typically involves a prior risk analysis, where expected profits are evaluated and weighed against potential risks. Establishing risk awareness among all employees is also crucial. (Gleißner, 2019) The risk management cycle begins with identifying potential risks and opportunities, followed by assessing them. Subsequently, appropriate control measures are implemented, accompanied by ongoing risk monitoring. (Hager & Romeike, 2020)

3. Analysis of Methodological Approaches

For the systematic development of a specific method in resilience management, an analysis of existing approaches from risk management and SCM is necessary. The objective of this chapter is to present existing methods and to highlight their practical applicability for SMEs.

3.1. SCM Methodology

Figure 1 below illustrates the fundamental business areas on which SCM is based, including procurement, marketing, logistics, as well as quantitative methods for managing the SC (Ostertag, 2008).

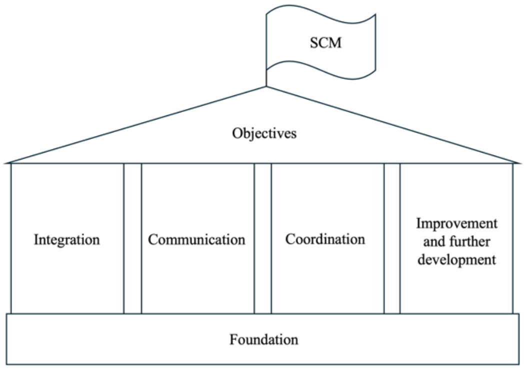

Figure 4: The House of SCM (adapted from Ostertag, 2008)

SCM can be divided into three core areas of responsibility: integration, communication, and coordination. The integration area includes the selection of suitable partners within the network, the design of collaboration throughout the entire SC, and its strategic leadership. (Ostertag, 2008)
The communication area primarily involves the use of standardized IT systems that ensure a shared process orientation and provide tools for transparent planning within the SC (Ostertag, 2008). The implementation of standardized processes and shared IT systems enables seamless data exchange between partners across the SC (Werner, 2017).
In the coordination area, SCM aims to improve data transfer, reduce error rates, and save time through shared IT solutions. Processes along the entire SC are analyzed and, if necessary, comprehensively optimized to fulfill customer orders in the best possible way. Advanced Planning Systems are also used to support collaboration between different departments of the SC partners during the planning process. (Ostertag, 2008)
Through close collaboration within the supply chain, continuous improvement and sustainable development of goal achievement for all participating partners are promoted. A consistent focus on process- and flow-oriented procedures will also establish a unified structure that enables more efficient process design, systematic identification of potential, and targeted enhancement of the overall performance of the value chain. (Biedermann, 2018)
Supplier evaluation is an SCM method that can contribute to securing and improving SC stability. Based on relevant factors such as sustainability, cost structure, delivery reliability, and product quality, it allows for an objective and structured assessment of supplier performance. (Schuh, 2014) Through this analytical approach, suitable business partners can be selected, and potential production-related risks can be identified and reduced at an early stage. The findings from this evaluation help maintain product standards, manage costs, and ensure reliable delivery processes. (Schuh, 2014) As such, this method serves as a tool to enhance SC stability and secure the company's long-term competitiveness (Schmieder et. al, 2018; Schuh, 2014).

The potential analysis serves to assess the potential of possible new suppliers and their process capabilities before collaboration begins, and to verify their suitability for regular operations within the supply chain. This analysis considers the supplier's experience and capabilities in developing and delivering the requested scope of services, as well as their ability to implement customer-specific requirements in planning and process execution. (Verband der Automobilindustrie, 2024)
The objectives are the nomination of new suppliers, the forecast of potential service quality, and risk minimization. Preparation for the analysis involves gathering information through supplier self-assessments and research activities. (Verband der Automobilindustrie, 2024)
The evaluation is based on key questions (referred to as "star questions") regarding process elements such as corporate strategy, capacity planning, development capabilities, reorder systems, potential transportation methods, smart packaging, warehouse digitalization, and the ability to communicate within the supply chain. The results of the potential analysis are derived from the evaluation of these star questions. Scoring is carried out using a point system assigned to the process elements and corresponding star questions. Points are awarded as follows, depending on the degree of fulfillment: 10, 8, 6, 4, or 0. The highest score of 10 indicates full compliance with the requirements, while 0 indicates non-fulfillment. (Verband der Automobilindustrie, 2024)

$$E_{PA}[\%] = \frac{\text{Sum of points achieved from all evaluated starred questions}}{\text{Sum of possible points from these starred questions}}$$

The overall percentage fulfillment rate is calculated as the ratio of the sum of points achieved across all evaluated star questions to the sum of the maximum possible points for these questions. (Verband der Automobilindustrie, 2024)
The result is categorized using a traffic light system. Green means the evaluated supplier has a fulfillment level of at least 90% and is therefore approved as a supplier. Yellow indicates a fulfillment level between 80% and 90%, meaning the supplier can be used under controlled conditions. Red applies to a fulfillment level below 80%, indicating that the supplier is blocked. (Verband der Automobilindustrie, 2024)
Due to ongoing digital transformation, supplier evaluation processes can increasingly be automated and accelerated, though human expertise remains essential for interpreting the results. Transparent and comprehensible evaluation methods increase suppliers' willingness to cooperate and support the development of strategic and sustainable business relationships. (Schmieder et. al, 2018; Schuh, 2014)
The advantages of supplier evaluation lie in its ease of application, low methodological effort, and timely results.
Disadvantages include partial subjectivity in qualitative assessment methods and the complexity of quantitative methods, which can be too resource-intensive for SMEs.

3.2. Methodological Approach to Risk Management

One risk management method used to optimize the decision-making process is scenario analysis (Romeike, 2018). This proactive approach aims to gain insights into future issues and to present the associated possible options (Hager & Romeike, 2020).
Starting from the current situation, various scenarios are developed using trends or potential developments. These scenarios are intended to cover as many future possibilities as possible in order to derive valuable insights. (Huth & Romeike, 2016)
Figure 2 below illustrates the basic process of scenario analysis.

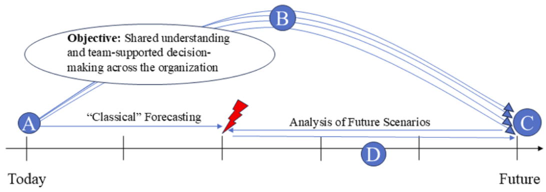

Figure 5: The Process of Scenario Analysis (adapted from Romeike, 2018)

The starting point is determined through an analysis of the current state and a retrospective review (Step A). This allows for the identification of important trends and potential changes (Step B). Subsequently, potential future scenarios are derived and evaluated (Step C). By analyzing future developments and scenarios, valuable insights can be gained to learn from a possible future (Step D). (Romeike, 2018)
The further the possible scenarios lie in the future, the greater the uncertainty involved (Hager & Romeike, 2020). The core approach is to outline an alternative situation and derive conclusions for the issue under analysis (Huth & Romeike, 2016) In most cases, the insights gained serve as a basis for formulating targeted recommendations for action (Hager & Romeike, 2020).
In scenario analyses, potential future developments of the SC are simulated in order to proactively derive appropriate measures. Although scenario analyses offer strong explanatory power, SMEs often struggle with the complex requirements of data collection and processing. (Kgakatsi et. al, 2024)
For SMEs, the advantages include forward-looking risk assessments and realistic risk evaluations.
However, disadvantages include high methodological and personnel requirements, as well as a limited internal database. (Kgakatsi et. al, 2024)
Although all of the aforementioned methods are well-established and partially applied in SMEs, a critical review reveals that their isolated use has certain shortcomings. Risk management methods often focus heavily on preventive and theoretical aspects, whereas SCM methods tend to be more

operational and short-term oriented. (Fan & Stevenson, 2018)

This presents SMEs with the challenge of selecting suitable methods from a wide range of available options ones that match their specific requirements such as cost, complexity, resource needs, and practical benefit (Buganová et. al, 2023). At present, there is a lack of clear methodological guidance for this selection process.

By combining methodologies from risk management and SCM, an integrated approach tailored to SMEs is proposed. This approach aims to develop a method for integrating existing tools using a morphological box in the form of a modular building block system. This enables SMEs not only to select measures based on their specific needs, but also to account for various constraints and requirements.

4. Development of a Modular Building Block System

The importance of resilience and its targeted strengthening is becoming increasingly relevant for companies, as it plays a crucial role in preparing for unexpected events.

One of the key challenges for businesses is identifying the right approaches and reducing uncertainty regarding the implementation of resilience measures. (Voß, 2023)

A central aspect of resilience management is the development of predefined strategies that can be applied immediately in the event of severe disruptions (Meissner et. al, 2023)

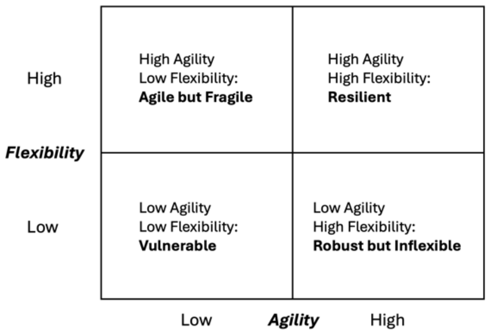

Figure 3: Resilience portfolio (adapted from Fan & Stevenson, 2018)

Figure 3 presents a 2x2 portfolio used to classify companies in terms of resilience. This classification can be based on flexibility indicators such as inventory reserves or buffer production capacities. For agility, the availability of real-time data can serve as an indicator, for example.

By examining methods from risk management and SCM with a focus on SMEs, an attempt is made to describe an integrative methodological approach that takes the specific needs of SMEs into account. The core element of this approach is the further development of a morphological box.

Table 4: Example Representation of a Morphological Box (adapted from Arnet et. al, 2024)

Parameter	Characteristic 1	Characteristic 2	Characteristic 3	…
Procurement Strategy	Single Sourcing	Multiple Sourcing	Local Sourcing	…
Inventory Management	Just-in-Time (JIT)	Safety Stock	Strategic Stockpile	…
Production Network	Centralized Production	Regionalized Production	Decentralized Production	…
Distribution	Single Warehouse	Multiple Warehouses	Flexible Routing	…
…	…	…	..	

Table 1 presents an exemplary morphological box and illustrates a systematic problem-solving tool that breaks down complex issues into manageable elements, thereby enabling a targeted and practice-oriented selection of solutions. It clearly contrasts various characteristics of a problem with corresponding solution options. (cf. Rakov, 2020)

In the context of SC resilience, the further development of the morphological box can be used to systematically identify measures that strengthen resistance to disruptions. By organizing problem aspects and potential solutions in a matrix format, the morphological box allows SMEs to explore a wide range of combinations and develop innovative resilience strategies tailored to their specific needs. (cf. Arnet et. al, 2024; Mittelstand-Digital Zentrum Hamburg)

Table 2: Example Representation of a Morphological Box (adapted from Arnet et. al, 2024)

Parameter	Characteristic 1	Characteristic 2	Characteristic 3	…
Procurement Strategy	Single Sourcing	Multiple Sourcing	Local Sourcing	…
Inventory Management	Just-in-Time (JIT)	Safety Stock	Strategic Stockpile	…
Production Network	Centralized Production	Regionalized Production	Decentralized Production	…
Distribution	Single Warehouse	Multiple Warehouses	Flexible Routing	…
…	…	…	..	

Table 2 shows a morphological box, where the selection of the characteristic manifestations took place.

The proposed integrative approach offers SMEs a systematic method to specifically address their individual challenges in optimizing resilience within the SC. The modular building block system currently under development enables clear structuring and individual adaptability, designed with the needs of SMEs in mind. (Rakov, 2020) It is easy to understand and requires no extensive methodological knowledge, which is particularly beneficial for SMEs with limited human resources (Feng et. al, 2020)

For the validation of the approach, the morphological box can initially be presented to representatives from the logistics and production sectors of SMEs, risk managers, and SCM specialists. Subsequently, a comparative analysis of the listed methods and measures can be carried out. In the final step, the process will lead to the identification of common consensus and possible divergences in the evaluation of the morphological box. (Ritchey, 1998)

Through the targeted use of the modular system to enhance resilience, SMEs can benefit from a resource-efficient selection of optimal methods (Rakov, 2020). A morphological box offers a systematic approach to make a complex problem more understandable. Due to this characteristic, it enables the creation of a comprehensive overview of possible solution options. This allows for the identification of the best possible problem solution, even when resources are limited. (Tsutsumi et. al, 2023)

This is particularly valuable for SMEs, which often must operate with limited resources and require a clear structure to identify and implement resilience measures. The modular system under development allows SMEs to select suitable methods depending on their changing circumstances.

To demonstrate increased resilience, metrics such as entropy or recovery time can be used (Wieland & Durach, 2021; Ivanov, 2023).

However, the final decision on method combinations ultimately relies on the subjective judgment of the user. This could lead particularly risk-averse SMEs to choose too many measures, potentially resulting in unnecessarily high costs.

Up to now, the further development of the morphological box has only been considered theoretically. Empirical validation and thus practical evidence of effectiveness is still pending. As a result, no conclusive statements can yet be made regarding its practical applicability.

While the approach aims to be applicable across industries in both production and logistics, it may not sufficiently reflect the specific challenges of individual sectors, which could limit its generalizability.

5. Outlook

The developed approach on a morphological box has the potential to reduce the increasing vulnerability of SC for SMEs. It has been demonstrated that SMEs, due to limited resources, dependency on suppliers, and restricted diversification options, are particularly exposed to external shocks and internal disruptions. The combination of systematic methods from risk management and SCM forms the methodological concept of the modular building block system.

This approach offers SMEs the opportunity to use their scarce resources more effectively by allowing the selection of individually suitable measures. The result will be the creation of a methodological toolbox that enables SMEs to optimize their own resilience.

Another promising future direction could be the use of AI methods. Although the use of AI was not the focus of this paper, SMEs could benefit significantly from AI-based systems that enable real-time monitoring of SC, early risk identification, or automated method selection. AI technologies could help reduce the effort and complexity of method application such the potential analysis while improving the accuracy and effectiveness of resilience management. A deeper examination of these options holds considerable potential for future research.

Future research activities will focus on the development of the methodology, empirical testing, and the practical and methodological refinement of the approach.

In conclusion, this project description lays the foundation for a methodological yet practice-oriented approach to resilience management for SMEs, offering great potential for further research and real-world application.

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Study of Industry 4.0 with a perspective of implementation in Cuba

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Abstract

This study addresses Industry 4.0 through a literature review of the new technologies used such as: the artificial intelligence (AI), the Internet of Things (IoT), 3D printing, among others; in addition, its feasibility of implementation in Cuba, with emphasis on the metal mechanical sector, showing how the adoption of these technologies face great political, economic and social challenges can achieve to be the engine that drives the economic recovery of the country.

The work underlines the need for a comprehensive strategy that combines technological investment, human capital formation and public policies to achieve a sustainable transition to Industry 4.0 in Cuba.

1. Introduction

With the global advance of Industry 4.0, characterized by the integration of disruptive technologies, it is necessary for Cuban companies to employ measures to modernize their production processes seeking international compatibility. The central problem lies in the technological gap between Cuban industries and international standards. Although there are studies on the implementation of Industry 4.0 in developed contexts, there is still a gap in research on how to adapt these technologies to environments with limited resources and specific socioeconomic realities, such as the Cuban case.

This study aims to address this gap through a methodology based on an updated bibliographic review and synthesis of Industry 4.0 in developed countries, contrasting them with local conditions, with the objective of identifying viable strategies for the partial or progressive implementation of 4.0 solutions in Cuban metalworking companies, prioritizing low-cost and high-impact solutions.

The results derived from this study are aimed at proposing a framework for action that will allow Cuba's most developed industries to optimize their production processes, reduce costs and improve their integration with global value chains, without ignoring the need for public policies that promote human capital training, international cooperation and access to critical technologies. In this way, it not only contributes to the academic discussion on Industry 4.0 in emerging contexts, but also offers practical tools to promote sustainable and resilient industrial development in Cuba.

2. The Technological Revolution

2.1. The First Industrial Revolution

It was born in Great Britain at the end of the 18th century and then spread throughout the rest of Europe. This occurred when there was a change in the economy, which was no longer based on agriculture and craftsmanship, but on industry.

This was a moment that brought with it technological, cultural and socioeconomic changes that affected the entire structure of society at that time (Kiss, 2024):

- Technological changes came given with new materials such as iron, steel and coal; the appearance of the steam engine, considered as the initial engine of the Industrial Revolution, spinning and weaving machines. All this allowed an improvement and increase in production with little labor and promoted the division of labor. With this came the development of transportation with trains and ships, increasing the role of industry and the economy.
- The cultural changes are given by the new knowledge reflected in all branches, both scientific and technical and health.
- The social change is reflected in the growth of cities due to the migration of rural population, the high birth rate and a decrease in mortality due to health advances with the creation of vaccines, as well as the emergence of a new social class, the industrial proletariat.

2.2. The Second Industrial Revolution

It took place in some countries, especially in Europe, between 1850 and 1914, coinciding with the beginning of the First World War, according to most historians.

This phenomenon can be considered the second phase of the first Industrial Revolution that took place in the United Kingdom. In this case, the countries in which industrial advances expanded were France, Germany, Belgium, Japan and the United States. Subsequently, industrialization would spread to Spain, Russia and Italy and later to the rest of Western countries.

For Selva Belén (2016) at that time, technological and scientific advances began to take on a more complex appearance. This was due to the access to different natural resources, unavailable or not very useful until then (metals such as steel, zinc, aluminum, nickel or copper, among others), in addition, with the advance of the chemical industry, chemical products such as soda, artificial colorants, explosive materials or fertilizers began to be used, at the same time, different forms of available energy appeared, such as: Watt's machine, turbines or the gas industry, in the same way, new ways of obtaining energy, such as electricity or oil, were obtained.

In this way, transportation was modernized with the appearance of the first automobile propelled by gasoline and the airplane, the railway industry experienced a strong growth, especially in Great Britain, the arrival of the electric tramway was highlighted, as for maritime transportation, steel became the main material for the manufacture of ships, which became propelled by steam turbines. However, the Second Industrial Revolution was not limited to the development of transportation; the increasing importance of electrical energy in industrial processes led to the invention of the light bulb, the creation of the telephone and the radio. Other areas of science also experienced great advances, such as pasteurization to preserve food, which was of great importance in research related to vaccines and antibiotics, the development of chemistry led to the invention of dynamite, as well as the appearance of fertilizers that increased agricultural productivity.

2.3. The Third Industrial Revolution

It is a process of change where new transportation, communication and energy technologies converge. It differs from its predecessor by replacing old forms of energy that pollute the environment (such as oil or coal) with renewable energy sources (such as solar, wind and hydraulic energy) and the use of digital technologies such as the Internet, fiber optics, fiberglass or advances in nanotechnology.

According to López (2016), the potential for change due to the convergence of new technologies in communication and energy has generated significant repercussions. In his paper, Lastra Lastra (2017) points out that the five pillars of the Third Industrial Revolution are the internet, green energy and technologies such as 3D printers. He states that the five pillars of this Revolution are:

- The transformation of renewable energy.
- Use the buildings of every continent in micro power plants to generate renewable energy.
- Expand hydrogen and other storage technologies in every building, as well as in the entire infrastructure for storing energy.
- Use the Internet to transform the global power grid into an energy network that acts as the connection to the Internet.
- Transitioning from fossil to electric vehicles allows clean energy to be bought and sold through a smart, continental, interactive grid.

2.4. The Fourth Industrial Revolution

It is a process of technological and industrial development that is linked to the organization of processes and means of production. This topic started to gain relevance since 2011. Industry 4.0 is aimed at smart factories which allows to raise their efficiency by focusing on digital transformation, driven by technologies (cyber-physical systems) such as automation, robotics, internet of things (IoT), artificial intelligence (AI), connection between devices and cooperative coordination of production units in the economy, which generates both opportunities and challenges.

2.4.1. Emergence

The Fourth Industrial Revolution arises from these disruptive technologies that in the future most professionals will handle in one way or another; here are some examples (García Ortega, 2021):

- Internet of Things (IoT): The Internet of Things allows objects in our daily lives to connect to the Internet to facilitate real-time tracking, problem-stopping and valuable data collection. Growing trend that we are integrating into our daily lives such as in cars and home, etc.
- Artificial Intelligence (AI): Artificial Intelligence allows simulating human behavior

and thinking in the machine. This technology is applied in automated industrial processes to optimize production and prevent workers from performing tasks that involve risks, another example of its use is with cobots, collaborative robots designed to interact with humans in work environments.

- Big Data: In Industry 4.0, the interpretation and combination of amounts of data facilitate decision making by companies, so the application of Big Data improves production and storage processes, shows predictions about demand and helps define business strategies, that is, large volumes of data are collected from various sources to identify patterns, trends and opportunities for improvement.
- Cloud Computing: Cloud services are environments that store, manage and process databases, servers and networks, facilitating real-time access to information from anywhere and reducing the need for local infrastructure.
- Virtual Reality: thanks to technological advances and the application of the Internet in devices, we will be able to live an immersive and multisensory experience with the arrival of Mark Zuckerberg's 'Metaverse'. This is a shared virtual space where we will be able to interact socially and economically as avatars.
- Robotics: Robots are understood as any type of machine capable of performing a given task or one programmed by a person, including autonomous vehicles and drones.
- 3D printing: 3D printing applied to manufacturing processes makes it possible to speed up and significantly improve all phases of product design, development and creation.
- Modern ways to use of computerized numerical control: CNC drilling and milling are fast and accurate subtractive machining processes that require minimal operator intervention, controlled by computers that automate the entire process, running by a programmed code to dictate the drilling operation. With this process, the desired shape and size of parts can be achieved with great precision.

2.4.2. Impact

The implementation of Industry 4.0 reveals a complex and multifaceted economic, social and environmental impact that are interrelated, presenting both benefits and biases.

- The economic impact depends on several factors, including the industrial sector, the size of the company, the adaptability of the workforce and government policies that allow generating significant economic growth, but its success depends on strategic planning, adequate public policies and responsible adaptation by companies and workers.
- Social impact generates changes in daily life, both positive and negative, that with a proactive and strategic approach can create a more equitable, just and sustainable society for all.
- The impact on the environment is presented as an opportunity for sustainability or as a risk of further environmental damage that depends on the regulation when adopting and implementing 4.0 technologies taken by the political or business bodies of a country.

2.4.3. Opportunities and challenges

Table 1: Opportunities and Challenges of Industry4.0 Application

Opportunities		*Challenges*
• Increased productivity and efficiency. • Creation of new products and markets. • Improved supply chain management. • Development of new skills and jobs. • Improved quality of life. • Increased customization and flexibility.	**Economic And Social**	• Unemployment and labor displacement. • Initial investment costs. • Digital divide. • Technological dependence. • Increased concentration of wealth. • Need for regulation. • Ethical concerns. • Impact on mental health.
• Increased energy efficiency. • Waste reduction. • Predictive maintenance. • Use of renewable energies. • Circular economy.	**Ambiental**	• Increased resource consumption. • Generation of electronic waste. • Increased transportation. • Dependence on raw materials. • Impact on biodiversity.

2.4.4. Industry 4.0 in Cuban metal-mechanical companies

To recapitulate, Industry 4.0, characterized by the integration of advanced technologies such as artificial intelligence, the internet of things, robotics and big data, is transforming production processes globally, however, in Cuba's metal-mechanic sector, its implementation faces a dual scenario: while globally these technologies revolutionize efficiency and connectivity, in Cuba their adoption is limited by multifaceted factors.

In the Cuban context, metal-mechanical companies have shown interest in adopting Industry 4.0

technologies, but their progress has been slow and uneven. Limitations in the technological infrastructure where the obsolescence of machinery and the lack of access to IoT systems hinder the integration of digital solutions, the scarcity of resources and the restrictions imposed by the economic blockade limit the import of components necessary for the development of this sector and the licenses for the use of specialized software having to be obtained from third countries, collaborations or donations, which makes modernization projects more expensive, reducing the capacity to invest in disruptive technologies and prioritizing basic maintenance needs. Despite this, there are specific initiatives that seek to incorporate 4.0 solutions to improve the efficiency and quality of production processes.

One of the main obstacles is connectivity due to limited access to high-speed internet, which hinders the implementation of IoT systems, real-time communication and the use of cloud platforms; in addition, staff training in digital skills is required due to the migration of talent to more lucrative sectors, such as MIPYMES, tourism and self-employment; as well as migration abroad, that exacerbates the lack of specialists, which translates into investments in training and skills development.

Despite these challenges, some companies have begun to explore the automation of some processes and the use of specialized software for production management. In the case of the Universidad Central "Marta Abreu" de las Villas, collaborative projects with foreign academic institutions and research centers have allowed the introduction of technologies such as 3D printing, computer numerical control (CNC) and small-scale laser cutting machines for the creation of a Digital Fabrication Workshop for personal use (Fab Lab).

Companies such as CYCLOS MINERVA, with reference in the production of palletized racks, have assimilated solutions 4. 0 solutions, which allows them to achieve greater productivity in their manufacturing and reach a higher quality than the current one due to the reorganization of the work area and the obtaining of a new production line from China that presents in a consecutive way the activities of stamping the holes that will assimilate the folded tabs and the safety pins, the shaping of the profile by lamination and the cutting at the end of the line; In comparison, with the one used in 2008 with which these products have been manufactured, with its own technology, where equipment of general use in the metal-mechanic industry and others adapted to this production have been used.

In conclusion, while Industry 4.0 is advancing by leaps and bounds in other parts of the world, in Cuba its adoption in the metal-mechanical sector is still at an incipient stage. A comprehensive strategy that includes investment in infrastructure, human capital formation and international cooperation is required to overcome current barriers and take advantage of the opportunities offered by this industrial revolution.

3. Conclusions

Although significant challenges exist, Industry 4.0 offers a unique opportunity to modernize the metal-mechanical sector in Cuba. Its adoption requires a strategic approach that combines investment in technology, personnel training and supportive public policies. The integration of these technologies would not only improve the competitiveness of Cuban companies, but also lay the groundwork for more sustainable industrial development in the future so research, development and collaboration between academia, business and government must be encouraged to accelerate the transition to it.

In conclusion, while Industry 4.0 is advancing by leaps and bounds in other parts of the world, in Cuba its adoption in the metal-mechanical sector is still at an incipient stage. A comprehensive strategy that includes investment in infrastructure, human capital formation and international cooperation is required to overcome current barriers and take advantage of the opportunities offered by this industrial revolution.

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Logistics 4.0 in the Mechanical Industry in Cuba. Actuality and Future Perspectives

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Abstract

Logistics 4.0 represents a revolution in supply chain management, driven by advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data and blockchain. These tools make it possible to optimize processes, reduce costs and improve efficiency in industrial sectors, including the mechanical industry. In Cuba, and specifically in the province of Villa Clara, the mechanical industry faces significant logistical challenges, such as lack of technological infrastructure, obsolete manual processes and limited integration of intelligent systems. These problems negatively impact the competitiveness and sustainability of the sector objective of this article is to present a compilation of the current state of the mechanical industry in Villa Clara, identifying the technological and operational gaps that limit its logistic performance.

1. Introduction

In the era of the Fourth Industrial Revolution, known as Industry 4.0, logistics has undergone a radical transformation driven by advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data, blockchain and cyber-physical systems. This new paradigm, dubbed: **Logistics 4.0**, is characterized by the integration of intelligent systems that enable automation, real-time optimization and data-driven decision making. These innovations not only improve the efficiency of supply chains, but also reduce costs, minimize errors and promote sustainability in industrial processes.

However, while developed countries and some emerging economies have successfully adopted these technologies, many developing regions, such as Cuba, face significant challenges in implementing Logistics 4.0 solutions. In particular, the **mechanical industry in Villa Clara**, a key province in Cuba's industrial sector, is at a crossroads. Despite its strategic importance for the local economy, this industry faces critical logistics problems, such as a lack of technological infrastructure, obsolete manual processes and limited capacity to integrate intelligent systems. These challenges not only affect the competitiveness of companies, but also limit their ability to respond to the demands of the global market.

In this context, the need arises to investigate and propose innovative solutions to modernize the logistics processes of the mechanical industry in Villa Clara. The implementation of a model based on the principles of Logistics 4.0 could represent a unique opportunity to optimize the supply chain, improve operational efficiency and promote sustainability in the sector. This approach could serve as a case study for other regions of Cuba and countries with similar contexts.

This study addresses the following research question: How can Logistics 4.0 technologies be strategically adapted to overcome infrastructural and economic constraints in Cuba's mechanical industry, specifically in Villa Clara, to enhance supply chain resilience and competitiveness?

1.1. Literature Gap and Contextual Relevance

While Logistics 4.0 frameworks are well-documented in industrialized nations (Zhou et al., 2023), their applicability to resource-constrained environments remains understudied. Recent works in Latin America (e.g., Plaza, 2024) highlight adaptive solutions for SMEs (Small and Medium Enterprises)., but Cuba's unique socio-economic conditions such as trade embargoes and limited IoT infrastructure require tailored approaches. This study bridges this gap by combining global technological trends with local empirical data.

2. Methodology

2.1. Data Collection

Fieldwork: 3-month observational study in 3 Villa Clara factories (2024), documenting workflow inefficiencies.
Interviews: Semi-structured consultations with professionals (engineers, logistics managers).

2.2. Analytical Framework

Triangulation
Cross-validation of field notes, interview transcripts, and academic literature.
SWOT Analysis: Applied to evaluate technological adoption feasibility (see Table 1).

Table 1: SWOT Analysis for Logistics 4.0 Adoption in Villa Clara

Factor	Internal	External
Strengths	Skilled workforce	Inter-national academic collabora-tion
Weaknesses	Obsolete digital infra-structure	Economic sanctions
Opportunities	University pilot projects	Development agency funding
Threats	Cultural resistance to change	Cyberattacks on critical systems

3. Key concepts

3.1. Logistics 4.0

Logistics 4.0 is a natural evolution of logistics management, driven by the Fourth Industrial Revolution (Industry 4.0). It is based on the integration of advanced technologies to create intelligent, autonomous and highly efficient logistics systems. Unlike traditional approaches, which rely on manual processes and reactive decisions, Logistics 4.0 uses real-time data and predictive algorithms to optimize each stage of the supply chain.

3.2. Enabling Technologies

Internet of Things (IoT)
Allows connection and communication between physical devices, such as sensors and vehicles, to monitor and control logistics processes in real time. For example, sensors in warehouses can automatically track inventories.
Artificial Intelligence **(AI) and Machine Learning**: These technologies analyze large volumes of data to predict demand, optimize transportation routes and proactively manage inventories.
Big Data: Facilitates the analysis of large data sets to identify patterns and trends, improving decision making.
Blockchain: Provides transparency and security in the supply chain, enabling product traceability and transaction verification.
Digital Twins: Virtual replicas of physical systems that allow to simulate and optimize processes before their implementation in the real world.

3.3. Differences between Traditional Logistics and Logistics 4.0

Table 2: Differences between Traditional Logistics and Logistics 4.0.

Points of comparison	Traditional Logistics	Logistics 4.0
Efficiency	Responds to problems after they occur (Reactive approach).	Anticipates and prevents failures through predictive analytics (Proactive approach)
Costs	Limited automation, with extensive human intervention	Maximized automation, reducing human intervention in repetitive tasks
Decision making	Data are isolated	Data flows between systems in an integrated manner, enabling a holistic view of the supply chain.

3.4. Application in the Mechanical Industry

- Supply Chain Optimization:

Logistics 4.0 enables more efficient management of material and component flows in the mechanical industry. For example, the use of IoT and Big Data Logistics plays an essential role in the development of SMEs in the mechanical processing sector. It covers

different activities, such as: purchasing, transformation, planning, storage, material handling, distribution and transport, internal and external procedures. These activities, due to the characteristics of the SMEs in the sector, are a clear impediment to the development of the field, which is made up of many companies, most of them with reduced assets and a lack of human resources. The high costs of logistics management and the need to carry out very detailed checks make it practically impossible to compete on price in international markets. That is why the main objective of this project is to place this sector at the forefront of the fourth industrial revolution, and at the same time to improve, based on the concepts of logistics 4.0, its systems and working methods.
can optimize production planning and reduce delivery times.

- Intelligent Inventory Management:
  Automated AI-based systems can predict the demand for parts and components, avoiding inventory overages or shortages. This is especially useful in the manufacturing of industrial machinery and equipment.
- Predictive Maintenance:
  Using IoT sensors and data analytics, it is possible to monitor the condition of machines in real time and predict failures before they occur. This reduces downtime and repair costs.
- Warehouse Automation:
  Robots and autonomous systems can handle tasks such as warehousing, sorting and transporting materials, increasing efficiency and reducing human error.
- Traceability and Security:
  The blockchain makes it possible to trace the origin and path of materials, guaranteeing the authenticity and quality of the components used in manufacturing.

One of the main problems in the mechanical processing sector is the disconnection between operations and warehouse management decisions. A fundamental tool to deal with this situation is the use of logistics information systems, used in the field of information technology. It is necessary to provide the operator with.

3.4.1. Impact

Logistics plays an essential role in the development of SMEs in the mechanical processing sector. It covers different activities, such as: purchasing, transformation, planning, storage, material handling, distribution and transport, internal and external procedures. These activities, due to the characteristics of the SMEs in the sector, are a clear impediment to the development of the field, which is made up of a large number of companies, most of them with reduced assets and a lack of human resources. The high costs of logistics management and the need to carry out very detailed checks make it practically impossible to compete on price in international markets. That is why the main objective of this project is to place this sector at the forefront of the fourth industrial revolution, and at the same time to improve, based on the concepts of logistics 4.0, its systems and working methods.

One of the main problems in the mechanical processing sector is the disconnection between operations and warehouse management decisions. A fundamental tool to address this situation is the use of logistics information systems, used in the field of information technology. It is necessary to provide the operator with answers and resources that facilitate decision-making, i.e., the logistics 4.0 solution cannot be developed without the vision of an operator 4.0. Considering that the key factors of a 4.0 logistics solution in mechanical processing companies must include: sensors, big data, cloud, automatic planning, modular and collaborative robotics, cyber-physical systems, augmented reality and microprocesses, we must have a transversal training in all the technical and efficiency aspects that this industry requires.

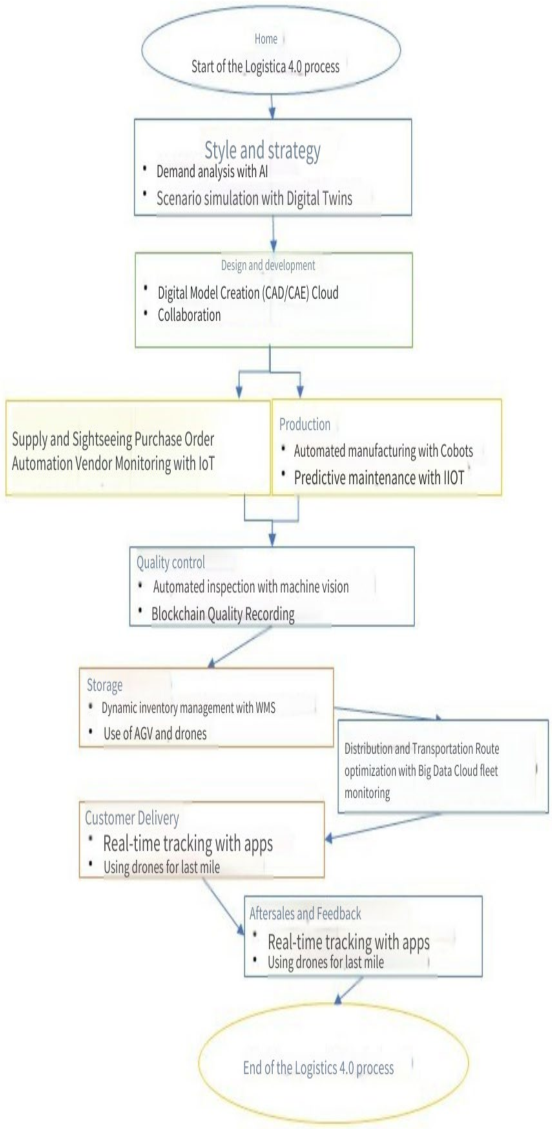

Figure 1: Flowchart of Logistics 4.0

4. Conclusions

The implementation of Logistics 4.0 in the mechanical industry in Cuba, specifically in the province of Villa Clara, represents a significant challenge but also a unique opportunity to modernize and optimize logistics processes. Through this article, it has been evidenced that the adoption of advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data, blockchain and cyber-physical systems can radically transform supply chain management, improving efficiency, reducing costs and promoting sustainability.

However, the current reality of the mechanical industry in Villa Clara shows a considerable technological and operational gap. The lack of technological infrastructure, the dependence on obsolete manual processes and the limited integration of intelligent systems are obstacles that hinder the sector's competitiveness in the global market. These challenges not only affect operational efficiency, but also limit the ability of companies to respond to market demands and take advantage of the opportunities offered by the Fourth Industrial Revolution.

To overcome these limitations, it is essential that companies and government institutions work together to encourage investment in enabling technologies and promote the training of human resources skilled in Logistics 4.0. The creation of a technological ecosystem that integrates all actors in the supply chain, from suppliers to customers, is essential to achieve a successful transition to smart logistics.

In addition, the implementation of solutions such as warehouse automation, predictive maintenance and traceability through blockchain will not only improve operational efficiency, but also increase transparency and security in logistics processes. These innovations can serve as a model for other regions of Cuba and countries with similar contexts, demonstrating that Logistics 4.0 is not exclusive to developed economies.

Field data revealed that 72% of maintenance delays in Villa Clara factories (n=3) stem from manual inventory tracking. Implementing RFID tags (as piloted by Company BMW) could reduce these delays by 40%, based on similar cases in Colombia (SENA, 2023). However, Cuba's limited internet bandwidth (avg. 4.2 Mbps vs. Latin America's 18.5 Mbps) necessitates offline-capable solutions like blockchain edge computing (IBM, 2021)

In conclusion, Logistics 4.0 offers a promising path for the modernization of the mechanical industry in Villa Clara. However, its success will depend on the ability of companies and institutions to overcome current challenges and adopt a proactive approach to technological innovation. Collaboration between academia, industry and government will be key to driving this transformation and ensuring a more competitive and sustainable future for the mechanical industry in Cuba.

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Characterization and preliminary evaluation of liquid waste from vanadium catalytic residue processing

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Abstract

Vanadium catalysts are used in the production of sulfuric acid, but once spent, they constitute polluting residues. These residues can be processed by leaching with sulfuric acid and subsequent precipitation, generating a liquid residue consisting mainly of sodium sulfate, which could be used in the manufacture of construction materials. In this work, the chemical composition and density of the residue were determined, and its behavior was evaluated in the formulation of grinding wheels, composed of Portland cement 35, abrasive, and residue. It was found that the residue contains 5.5% sulfate and less than 0.30 mg/L of vanadium and lead. Regarding the behavior of the grinding wheels, it was observed that the residue contributed to improving the mechanical properties and performance of the wheels. The results obtained indicate the possibility of using the residue in the formulation of grinding wheels, thus avoiding its discharge into the environment.

1. Introduction

The generation of polluting industrial waste is a problem of special interest, especially when it is not properly managed, which can cause health and environmental risks.

In Cuba, environmental protection has always been of paramount importance. An example of this is the approval of Law 150 of the Natural Resources and Environmental System, which states in Article 4 that the State protects the environment and the country's natural resources. The objective of this law is to regulate the actions of the State, citizens and society in general to guarantee the implementation and operation of the Natural Resources and Environment System in Cuba (Ley 150/2022 "Del Sistema de los Recursos Naturales y el Medio Ambiente", 2023).

In addition, Article 75 of the Constitution of the Republic of Cuba states that "all persons have the right to enjoy a healthy and balanced environment. The State protects the environment and the country's natural resources. It recognizes their close linkage with the sustainable development of the economy and society to make human life more rational and ensure the survival, well-being and security of present and future generations" (Constitución de la República de Cuba, 2019).

The National Environmental Strategy constitutes the basis of Cuban environmental policy and the expression of environmental policy, identifying the main environmental problems and establishing priorities and lines of action (Constitución de la República de Cuba, 2019; Miranda Cuéllar, 2023). This strategy pointed out the insufficient level of waste utilization in most productive entities, and proposed that the Hazardous Waste Confinement Facility at the Juraguá Nuclear Power Plant (CEN) be set up for the confinement of the country's

hazardous waste, with vanadium-containing waste, spent catalysts from the manufacture of sulfuric acid and ashes from oil combustion, being among the first streams to be confined (Estrategia Ambiental, 2016). Based on the problems detected, efforts are being made to find processing alternatives for these industrial wastes, in order to avoid their confinement in the National Confinement of Hazardous Wastes.
At the Central University "Marta Abreu" of Las Villas, studies are being carried out for the processing of spent catalysts from the manufacture of sulfuric acid, with the research going through several stages, which are represented in the following mental map.

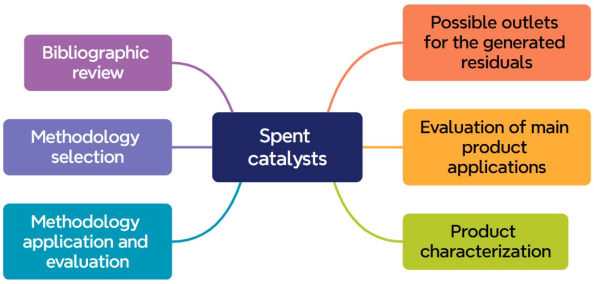

Figure 1: Mind map of the research.

The methodology selected for the processing of catalytic residues, which has been evaluated in previous studies, consists mainly of acid leaching and subsequent precipitation, which makes it possible to recover a product consisting mainly of vanadium, which can be used in the manufacture of welding consumables (Perdomo Gómez et al., 2022).
However, hydrometallurgical processing of the catalysts generates new residuals, a solid residual that is generated during leaching and consists of 98 % silica, and a liquid residual that is generated during precipitation, consisting mainly of sodium sulfate, but can be contaminated with metallic elements, such as V, Zn, Ni, Mg, Fe, and Cr (Perdomo Gómez et al., 2024; Perdomo Gómez, 2024).
The generation of liquid waste must be managed under technical and environmental criteria to minimize its impact, being necessary the characterization of the same for which physical, chemical and biological parameters such as COD, BOD_5, suspended solids, heavy metals, pH, temperature, etc. are determined. Taking into account the characteristics of the catalytic waste, it is essential to determine the content of heavy metals in the liquid waste generated, being possible the presence of the elements V and Pb, given their presence in the spent catalyst.
Based on the results of the characterization of the liquid waste, the strategy for its discharge is drawn up, and there are norms that establish the maximum permissible values. In Cuba, one of these standards is NC 27/2012: Discharge of wastewater to land water and sewage, however, this standard does not include vanadium, being necessary to be governed by international standards (Oficina Nacional de Normalización, 2012).
In order to avoid the dumping of these new wastes, the possibility of using them in the manufacture of construction materials is being evaluated, which should allow their immobilization.
The possibility of using these new residuals in the construction industry leads to the application of the principles of circular economy. The concept of circular economy is based on the fundamentals of the environmentalist school, and proposes a change to the "reduce, reuse and recycle" paradigm for a deeper and more lasting transformation, which will reduce the impact caused by human activities on the environment (Lett, 2014). Under this approach, the waste becomes the "food" raw material of natural cycles or is transformed to become part of new technological products, with a minimum energy cost (Lett, 2014).
Therefore, the objective of the work is to analyze the chemical composition of the liquid waste generated during the processing of catalysts and the possibility of using it in construction materials.
The research is important because it offers a possible application for this liquid waste, which contributes to the preservation of the environment by avoiding the dumping of new waste.

2. Procedure, methods and experimental part

2.1. Raw material and reagents

The analysis sample studied consists of the liquid residue generated during the chemical processing of spent catalysts from the manufacture of sulfuric acid, precipitating with Na_2CO_3 (RL). The spent catalysts that were processed come from the Patricio Lumumba Plant, in Pinar del Río, which is currently not working.

2.2. Catalyst processing

The general scheme describing the chemical processing of spent catalysts is shown in Figure 2.

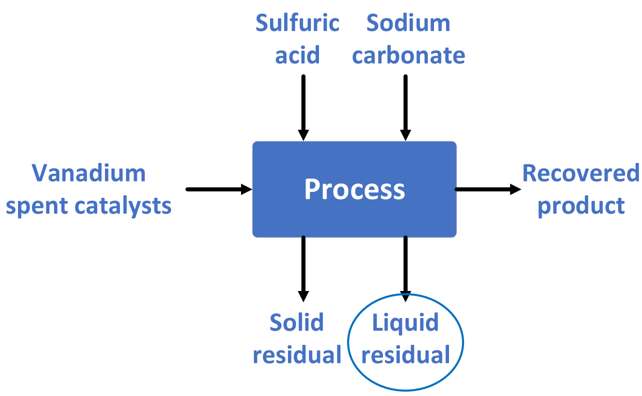

Figure 2: General processing scheme

The proposed processing consists of a first leaching stage, in which the catalyst is mixed with a diluted H_2SO_4 solution (leaching agent) in order to separate the elements capable of dissolving (leachable) from

the rest of the compounds that make up the residual, which remain as insoluble residues. Once the leaching time is over, the sample is filtered, separating the liquid phase that is used for the next stage of processing. In addition, it is separated a solid residual containing the elements that were not able to dissolve in the sulfuric acid solution (Perdomo Gómez et al., 2024; Perdomo Gómez et al., 2021).
The next stage is precipitation, in which an insoluble solid, called a precipitate, is formed from a chemical reaction between two solutions. This reaction results in the formation of solid particles that separate from the liquid medium. It is the final operation in the processing of the vanadium residue and can be performed in several ways. Proper pH control is key to vanadium separation and recovery. Selective precipitation can be used to remove unwanted impurities and metal separation (Perdomo Gómez et al., 2024; Nasimifar & Mehrabani, 2022). This stage results in a recovered solid containing the elements of interest and a liquid residual.
By using a sulfuric acid solution as a leaching agent and a sodium carbonate solution for precipitation, sodium sulfate is formed as part of the chemical reactions that occur in the process, which becomes part of the liquid waste that is generated. This process can be represented by the following chemical reaction (Perdomo Gómez et al., 2024):

$$M_2(SO_4)_x + Na_2CO_3 \rightarrow M_2O_x + CO_2 + Na_2SO_4 \quad (1)$$

Where:
M is the metal,
x is the formal oxidation state of the metal.

In addition, this liquid residue may contain metallic elements such as Zn, Ni, Mg, Fe, Cr, among others, depending on the residue and its composition.

2.2.1. Generation of liquid waste

The generation of the liquid residual takes place during the precipitation reactions, and can be represented by the flow diagram in Figure 3, where it can be seen that it is separated after filtration (Perdomo Gómez, 2024).

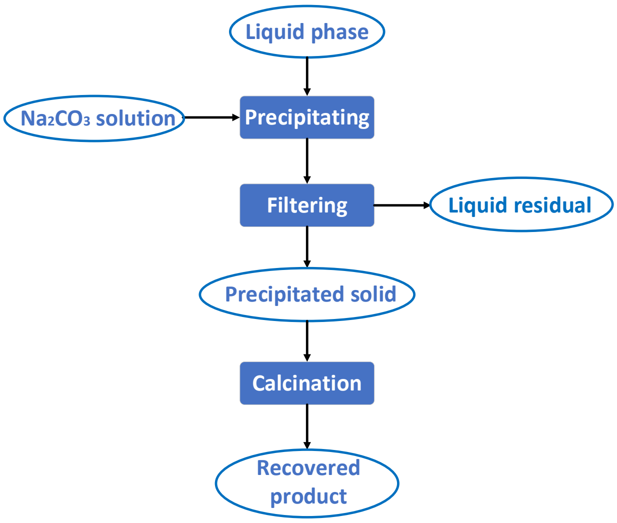

Figure 3: Generation of the liquid residual.

2.3. Determination of sulfate concentration in the liquid residue

For the determination of sulfate content, it was used the turbidimetry method, proposed by the Standard Methods (Eaton, 2005), for water and wastewater analysis.
Reagents (pure for analysis):

- Magnesium chloride ($MgCl_2 \cdot 6H_2O$)
- Sodium acetate ($CH_3COONa \cdot 3H_2O$)
- Potassium nitrate (KNO_3)
- Acetic acid (CH_3COOH)
- Barium chloride crystals ($BaCl_2$)

A buffer solution was prepared for which it was necessary to dissolve 30 g of magnesium chloride, 5 g of sodium acetate, 1.0 g of potassium nitrate, and 20 mL of acetic acid (99 %), in 500 mL of distilled water and it was made up to 1000 mL. A standard solution of sodium sulfate was prepared from which a calibration curve was prepared with the points 10, 20, 25, 30, 40 mg/L. For the determination of the sulfate content, 100 mL of sample was taken and added into a 250 mL erlenmeyer, 20 mL of buffer solution was added and mixed on shaker. While stirring, a tablespoon of $BaCl_2$ crystals was added and timing was started and stirring was maintained for 60 seconds. After stirring was completed, the solution was poured into an absorption cell of the spectrophotometer. Turbidity was measured at a wavelength of 420 nm. The described procedure is performed on the calibration curve and the test sample.

2.4. Determination of the density of the liquid residual

Among the analyses performed for the characterization of the liquid waste generated from the processing of the spent catalysts is the determination of its density, which will increase as the concentration of salts in the waste increases.
To determine the density of the liquid residual, a pycnometer is taken and weighed empty on the

analytical balance, then the liquid residual is added, rooted and then weighed (Atarés Huerta). The expression to determine the density of the liquid is shown in Equation 2.

$$\rho = \frac{m_{(p+l)} - m_p}{V} \quad (2)$$

Where:

m_{p+l}: mass of pycnometer and residual liquid.
m_p: mass of the empty pycnometer
V: volume of the pycnometer

2.5. Determination of the chemical composition of the liquid residue

The liquid residue used was characterized at the Research Center for the Metallurgical Industry (CIPIM). The characterization was carried out by inductively coupled plasma spectroscopy (ICP).

2.6. Preparation of grinding wheel samples

Among the possible uses that were evaluated for the liquid residue was its incorporation into the mixture during the manufacture of grinding wheels agglomerated with P-35 cement, in order to evaluate the effect that this residue could have on their behavior. For this purpose, two working conditions were studied, one where the grinding wheel specimens were manufactured in laboratory conditions, and the other where they were manufactured in workshop conditions, similar to those in which the grinding wheels are manufactured in the Construction Materials Company of Villa Clara, in order to see the influence of the preparation conditions.

For the manufacture of the grinding wheel prototypes, both in laboratory and workshop conditions, the same ratio between the components was maintained.

The formulation used in the preparation of the grinding wheel prototypes is shown in Table 1. In this case, it corresponds to the samples prepared under laboratory conditions.

Table 1: Shaping of grinding wheels with residual under laboratory conditions (in g)

Mixture	Water	Liquid residue	Abrasive	Cement
P_L	17,5	-	15	35
RL_LC	-	17,5	15	35
RL_LD	8,75	8,75	15	35

For the preparation of the grinding wheels, P-35 cement was used as a binder and abrasive powder with a grain size between 0.2 - 0.1 mm. The abrasive powder used is manufactured at the Dr. Sc. Rafael Quintana Puchol Abrasives Plant of the Unidad Empresarial de Base Combinado Hormigón Rolando Morales Sanabria of the Municipality of Cifuentes (Martin Delgado et al., 2023). The water/solid ratio evaluated was 0.5 and the amount of abrasive was kept constant.

All the components, once weighed, are mixed with a mechanical stirrer for two minutes at 1,600 rpm and placed in the oven for seven days at 30 °C in a closed mold. The P_L mixture corresponds to the test tube used as a standard under laboratory conditions. The concentrated residual (RL_LC) and the residual diluted by half (RL_LD) were used.

The manufactured grinding wheels were reproduced by modifying the preparation conditions, simulating shop conditions. The solid components were mixed for seven minutes in a porcelain rotary mixer, and once the components were removed from the mixer, the residual liquid was added, continuing the mixing manually, and then the mixture was poured into test tubes with dimensions of 4.2 cm in diameter and 3 cm wide, and allowed to stand for 21 days for further evaluation. The grinding wheels were immersed in water daily for a short period of time to maintain surface moisture and promote cement hydration (ACI Committee 308, 2016). The formulation used for the mixtures under workshop conditions was double the quantities used under laboratory conditions (see Table 1). The P_i sample corresponds to the standard sample under the above conditions. As in the previous analysis, the concentrated residue (RL_iC) and the residue diluted by half (RL_iD) were used.

A diagram of the grinding wheel preparation process is shown in Figure 4.

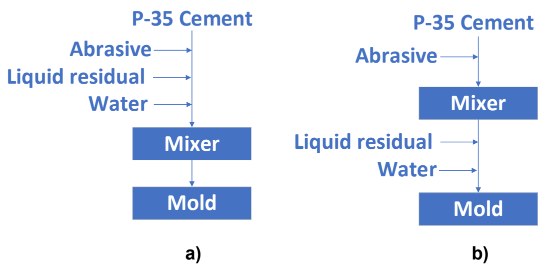

Figure 4: Grinding wheel preparation, a) laboratory scale, b) workshop scale

The grinding wheel samples manufactured were measured for compressive strength in a mechanical testing machine of the Center for Research and Development of Structures and Materials (CIDEM) of the Universidad Central "Marta Abreu" de Las Villas using the TestExpert.NET software. In the case of the samples manufactured under laboratory conditions, images of the surface were taken with an optical microscope.

3. Results and Discussion

3.1. Chemical composition of the liquid residual

The results of the determination of the chemical composition of the liquid residual by ICP spectroscopy are shown in Table 2.

Table 2: Composition of the liquid residual

Ca	121,56	mg/L
Mg	135,60	
Mn	10,54	
Cu	0,29	
Pb	0,22	
Fe	<0,5	
Ni	11,50	
Al	0,76	
Cr	<0,2	
V	0,30	
Na	13,627	g/L

From Table 2 it can be determined that the sodium sulfate content present in the liquid residual is equivalent to 42.06 g/L (4.2 %) of Na_2SO_4. This concentration of sulfate contained in the residual allows us to evaluate possible applications of this product in cementitious materials.

On the other hand, if we add the rest of the metallic elements, we can see that they represent 0.028 % of the metals present in the liquid waste, including the most dangerous chemical elements such as vanadium and lead, which represent 0.52 mg/L.

The maximum permissible limit of vanadium in wastewater varies according to the regulation and the specific country or region, and in many cases the regulations do not report specific values for this metal.

In Cuba, Cuban Standard NC 27/2012 does not include vanadium among the elements of interest (Oficina Nacional de Normalización, 2012). For this reason, it is taken as a reference for the analysis to be carried out what is stated in the Ecuadorian Environmental Regulations (Ribadeneira, 2001).

In the liquid waste analyzed, the vanadium content gave a value of 0.30 mg/L, which is below that established in the Environmental Regulations for Hydrocarbon Operations in Ecuador (Ribadeneira, 2001), which establishes a maximum permissible limit of vanadium <1 mg/L for effluent discharge, complying with the requirements of the standard.

Considering that the amount of liquid residual added to the test tubes is in the range of 17.5 to 35 mL, it is obtained that between 0.005 and 0.01 mg of V are added to the mixture, which represents between 3.9×10^{-6} and 7.8×10^{-6} % in the total mass of the formulated mixture, so the concentration in the mixture is between 0.039 and 0.078 mg/L, relatively low contents.

As for lead, it can be observed in Table 2, that the residual contains 0.22 mg/L, complying with the requirements established by Cuban Standard NC 27:2012 (Oficina Nacional de Normalización, 2012), which establishes 1 mg/L as the maximum allowable limit of lead in wastewater. This concentration value indicates that part of the lead present in the catalytic residual passed to the leached phase and subsequently under the precipitation conditions developed did not precipitate all the lead present, remaining in the liquid residual.

Regardless of the levels of vanadium and lead contained in the residue, work is being done to inertize it in a cementitious matrix, which further reduces the possible polluting effects.

3.2. Sulfate content in the residual liquid

To determine the sulfate concentration in the liquid residual sample, the method described in section 2.3 was developed, obtaining the calibration curve shown in Figure 5.

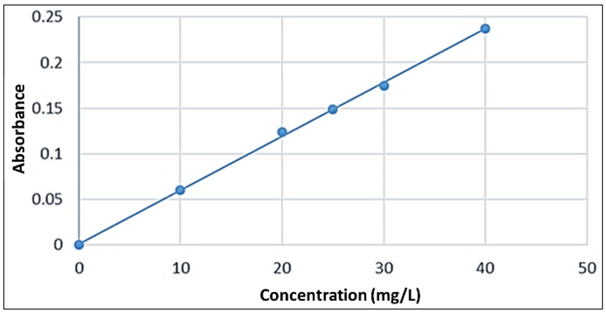

Figure 5: Calibration curve for sulfate determination.

The model describing the calibration curve is as follows:

$$A = 0,0059\ c + 0,0015 \quad (3)$$

Where:

A is the absorbance
c is the concentration

As a result of the analysis performed, the sulfate concentration in the liquid residual sample was 5.49 %, which was analyzed by triplicates.

Table 3: Results of sulfate determination in liquid residue

Sample	Concentration SO_4^{2-} (mg/L)	Concentration SO_4^{2-} (%)	σ
RL	54915,25	5,49	0,0479

σ: Standard deviation

As can be seen in Table 3, the sulfate concentration presents in the liquid waste analyzed is 5.5 %, which is higher than the sulfate content required by the sodium determined in Table 2. This means that the rest of the sulfate present in the waste is forming sulfates with the other metallic elements contained in the waste, such as: Ca, Mg, Al, Mn, Cu, Pb, Ni, etc.

The sulfate content determined can be considered high, so it is feasible to evaluate alternative uses for this waste. In this case, it was carried out an evaluation of the influence that this residual can have in the manufacture of materials for construction, where Na_2SO_4 is frequently used as an alkaline activator.

3.3. Density of liquid residual

To determine the density of the liquid residual, the technique described in section 2.4 was used, obtaining the results shown in Table 4.

Table 4: Results of residual density determination

Residual	Density (g/cm^3)
$\bar{x}$	1,053
σ	0,003

As can be seen in Table 4, the density of the liquid residual is 1.053 g/cm^3, which confirms that it is a liquid with a significant concentration of dissolved solids.

3.4. Possibilities of using liquid residue on grinding wheels

Among the uses that have been studied in recent years for sodium sulfate is as an alkaline activator in the production of geopolymers.

Compared to other alkaline activators, sodium sulfate is generally less expensive and less harmful.

Alkaline activators are the second essential component in the development of alkaline cements. These activators are usually included in the mixture as a solution, although they can also be incorporated in a solid state, well mixed with the slag and ash (Torres-Carrasco & Puertas, 2017).

The activators have the function of accelerating the solubilization of the aluminosilicate source, favoring the formation of stable hydrates of low solubility and promoting the formation of a compact structure with these hydrates (Rodríguez Martínez, 2009).

Taking into account these criteria, it is evaluated as a possible outlet for this residual for use in grinding wheels agglomerated with Portland 35 (P-35) cement.

As a result, were obtained the grinding wheels shown in Figure 6, produced under laboratory conditions. The image shows that the grinding wheels have a high degree of compaction and do not show porosity or defects to the naked eye, the latter mainly due to the mixing conditions and the quality of the processing mold, in addition, the samples show considerable hardness, being able to scratch glass and other metal surfaces.

Figure 6: Grinding wheels under laboratory conditions

Figure 7 shows images of the surface of the specimens obtained, which were taken with an optical microscope.

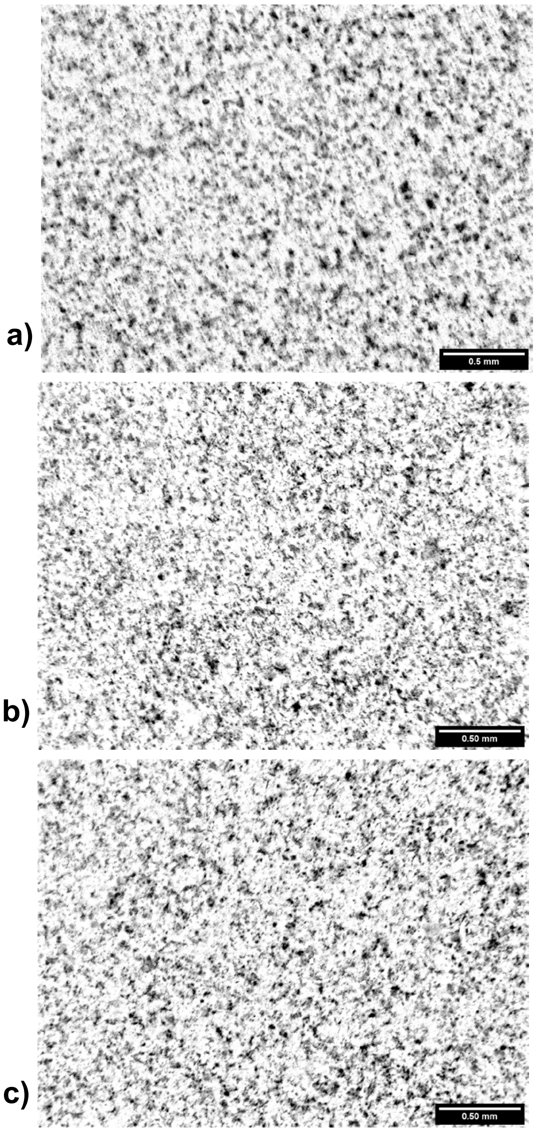

Figure 7: Image of the surface of grinding wheels. a) P, b) RL_LC, c) RL_LD

Figure 7 reveals a homogeneous distribution of the components of the mixture regardless of its composition, which is important because it shows that the abrasive was distributed uniformly throughout the specimen (grinding wheel), ensuring a stable behavior of the grinding wheel during the grinding or polishing process of the surfaces.

To evaluate the performance of the grinding wheels, it was carried out a compressive strength test. Table 5 shows the mechanical compressive strength data obtained with the prepared samples. This study was carried out 30 days after the grinding wheel samples were made.

Table 5: Compressive strength of grinding wheels (in MPa)

Grinding wheels	Resistance (MPa)
P	18
RL_LC	28
RL_LD	20

Table 5 shows that the addition of 1.109 g of sulfate as part of the liquid residual to the mixture slightly increases the mechanical compressive strength of the RL_LD sample, with the greatest effect being observed with the addition of the concentrated solution (2.218 g of sulfate) in the RL_LC sample, which increases the strength by 55 % with respect to the original mixture.
On the other hand, as described in section 2.6, grinding wheels were manufactured in workshop conditions, obtaining the prototypes shown in Figure 8.

Figure 8: Grinding wheels in workshop conditions.

The new samples were tested for compressive strength to evaluate their mechanical properties, obtaining the results shown in Table 6.

Table 6: Compressive strength test (in MPa)

Grinding wheels	Resistance (MPa)
P	24,0
RL_iC	30,1
RL_iD	25,5

It can be observed in Table 6 that the highest resistance corresponds to the sample with concentrated residual (RL_iC), showing an increase in resistance of 25%; however, the sample prepared with the diluted liquid residual showed an increase in resistance of only 6%. The trend observed in the behavior of these grinding wheels is similar to that shown by the samples manufactured under laboratory conditions, where the incorporation of the concentrated liquid residual showed the best results, confirming its role as an effective alkaline activator.
According to the data obtained for compressive strength, shown in Tables 5 and 6, higher values can be observed for the grinding wheels manufactured under workshop conditions, in relation to those manufactured under laboratory conditions.
These results may be associated to a longer curing time for the grinding wheels manufactured in workshop conditions, which was 21 days, as opposed to the grinding wheels prepared in laboratory conditions, which was 7 days, which allowed a more complete hydration of the P-35 cement, increasing its resistance.
On the other hand, in the case of the grinding wheels prepared in workshop conditions, the natural environmental humidity could have acted as an uncontrolled moist curing, benefiting the hydration of the cement, since they were immersed in water daily, unlike those in the laboratory, which were in a closed container.

Taking into account the results obtained in the characterization of the residue and its preliminary evaluation in the manufacture of grinding wheels, Figure 9 shows the working scheme to be applied with the liquid residue generated.
Once the liquid residue is generated, if the vanadium concentration is less than 1 mg/L (Ribadeneira, 2001)), then the residue is used in the manufacture of grinding wheels. On the other hand, if the vanadium content is higher than this value, sulfuric acid can be added to the residue, acidify the solution and then reuse the liquid in the preparation of the initial leaching solution, so that the residue is not discharged into the environment.

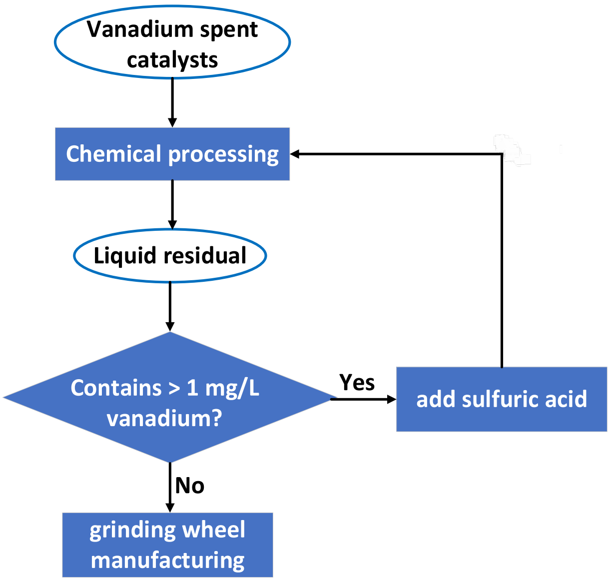

Figure 9: Sequence of work for the liquid residue.

4. Conclusion

- The liquid residue generated from the chemical processing of the spent catalysts is constituted by 13.6 g/L of sodium, 0.22 mg/L of lead and 0.30 mg/L of vanadium as fundamental contaminating elements, a density of 1.053 g/cm^3 and 5.5 % sulfate, which allows it to be considered for use as an alkaline activator.
- The use of the liquid residual, generated during the processing of the catalysts, in the substitution of 50 % and 100 % of the water used in the formulation of grinding wheels bonded with P35 cement, increased the compressive strength of the formulated specimens, the effect being greater in the case Reaccion puzolanica mas completa of total substitution.
- The possibility of using the liquid residue generated from the processing of spent catalysts in the development of new materials allows improving the properties of the new product obtained and avoids its discharge into the environment.

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Meat export supply chain management from Kyrgyzstan

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Abstract

This article examines the prerequisites for organizing supply chains for the export of halal products, specifically meat from Kyrgyzstan. Export of halal meat from Kyrgyzstan would significantly increase the country's export potential. Export of halal products opens up new opportunities for local producers to process meat according to halal standards, as a product with high added value. For this purpose, the country lacks a multifunctional logistics center for processing and organizing the initial link in the supply chain of halal products for export - the so-called "Meat Products Park". The article analyzes the existing positive factors for organizing a specialized logistics center - the presence of ecological pastures, clean water, labor resources. And for the construction of a meat products park (MPP), the primary task is to justify the choice of a place for its construction. For this purpose, the most meat-producing regions of the country are proposed and the most preferable location of the MPP is proposed using the spatial optimization method, taking into account the infrastructural conditions of the existing transport network.

1. Introduction

Kyrgyzstan's meat industry as a whole does not produce enough meat to meet domestic demand, so it imports some types of meat, such as poultry, into the country. At the same time, exports of domestic meat to other countries are insufficient. Pilot deliveries of Kyrgyz meat (beef and lamb), butchered according to halal standards, have shown significant interest in the Middle East, Malaysia and other countries. To meet this demand, Kyrgyzstan lacks the infrastructure, equipment and technical equipment to meet the volume, standardized meat quality and regulatory requirements of willing international buyers.

At the same time, Kyrgyzstan has the necessary legislative basis for the development of the halal industry. An important step forward was the adoption in 2024 of the "Law on the Halal Industry" in the Kyrgyz Republic, which provides clear legal guidelines for the production of certified Halal goods. The paper based on the literature (Abdul Rahman et al., 2022; Islam et al., 2020; National Statistical Committee of the Kyrgyz Republic; Reuters, 2023) according to study, trends, report and an example. The market for halal products in Kyrgyzstan is growing rapidly, driven by the growing demand for high-quality certified products such as meat, dairy products and confectionery. Efforts to improve certification processes have increased consumer confidence, while exporting halal products opens up new opportunities for local producers. Educational and information campaigns, as well as the growth of halal tourism, are also contributing to the development of the industry.

Kyrgyzstan's underdeveloped meat processing industry makes it difficult to exploit its enormous potential in the global meat trade.

The key characteristics of Kyrgyz meat are centered around quality, which is determined by its environment and free-range nature. Based on the information gathered, meat in Kyrgyzstan is obtained from free-range pastures and fed by organic feedlots. This, combined with a clean environment and glacial water, provides the market with high-quality meat for consumption.

At the same time, the development of the agricultural sector is crucial for improving the well-being of the population. The livestock sector supports the local economy and is an inherent part of the traditional lifestyle of most people. This sector employs 30% of the total workforce in the agricultural sector.

Exporting top-quality meat and high-value products from ancillary industries (such as processed meat and beef-based products) will create a sustainable and highly skilled business ecosystem that strengthens the country's capabilities and potential.

The idea of creating a Halal Meat Processing Park is to create a multifunctional enterprise in the region that can help local farmers and entrepreneurs expand their market sector and product range to meet the needs of the market.

2. Procedure, methods or experimental part

2.1. The study of the basic prerequisites for the organization of the export supply chain of agricultural products

- Infrastructural conditions

Transport network: Kyrgyzstan has a railway network of about 420 km, more than 95% of freight traffic is carried out by road, and temperature-controlled rolling stock (for example, refrigerated trucks for perishable products) is available.

- Storage: availability of places for harvesting, processing and storage that meet Halal standards.
- Standardization and certification

Compliance with international standards:
ESMA (UAE), JAKIM (Malaysia), HALAL Food Authority (Europe), etc.

- Logistical optimization

Timing management: Using IoT sensors to monitor temperature and humidity in real time.
Customs clearance:
Automation of document management (for example, electronic phytosanitary certificates).

- Market analysis

Target markets:

Table 1: Sales markets (2025)

Region	Import volume (thousand tons/year)	Trends
The Middle East	2,500	Demand for camel meat (+15% since 2023)
Southeast ASIA	1,800	Growth of halal semi-finished products (+22%)
eu	900	Organic Halal (+30% in Germany, France)
USA/Canada	600	Niche brands for millennials

Price competitiveness: Kyrgyzstan's domestic market: medium high
price = 5.7 USD per kg; China-Muslim population: 28.1 million, average meat price: 12.63 USD per kg; Persian Gulf-population: 54 million, average meat price: 10.59 USD per kg

- **Financial mechanisms**

Risk insurance:
Covering currency fluctuations (for example, forward contracts) and force majeure.

- **Legal support**

Contractual terms:
Clear Incoterms-2025 parameters (e.g. FOB for grain, CIF for fruit).
Permissive documentation:
Phytosanitary certificates, declarations of conformity TR CU 021/2011.

- **Sustainability and ESG factors**

Environmental friendliness:
Reducing the carbon footprint (for example, switching to bio-packaging for the EU).
Social responsibility:
Confirmation of the absence of child labor (SMETA standards).

2.2. Analysis of the current state of the meat industry in Kyrgyzstan

Total number of cattle = 1.7 million
The total amount
of meat produced per year is 428 thousand tons.
Meat exports per year = 224 thousand tons
Average meat price is relatively cheap,
about 5.7 USD per kg. It's cheap and has a big impact on farmers' living standards.

Advantage of Kyrgyzstan:
53.3% (10,606 thousand hectares) of Kyrgyzstan's territory are agricultural lands, of which 85% are natural mountain pastures, allowing for natural and high-altitude organic fattening. This unique fattening complex, as well as a large area of catchment rivers that provide livestock with natural water without processing, contribute to the high quality of Kyrgyz meat. The practice of animal husbandry in Kyrgyzstan is unique to their traditions, i.e. nomadic farming, and the skills inherent in animal husbandry ensure animal husbandry in accordance with the principles of healthy and environmentally friendly farming. Combined with the fact that 18.2% of Kyrgyzstan's 2,595,400 rural residents are agricultural workers, Kyrgyzstan has an active agricultural sector and large human capital.
The growth of Kyrgyzstan's agricultural sector is also facilitated by the unique landscape of the earth, where 90% of the territory is located at an altitude of 1,500 m above sea level. Of the huge 10,606,000 hectares of agricultural land, 85% are natural mountain pastures, which serve as a natural and organic feeding ground for livestock.
The key characteristics of Kyrgyz meat are centered around quality, which is determined by its environment and free-range nature. Based on the information gathered, meat in Kyrgyzstan is obtained from free-range pastures and fed by organic feedlots. This, combined with a clean environment and glacial water, provides the market with high-quality meat for consumption.
Preference is given to Kyrgyz beef due to the use of natural feed and the absence of chemicals in the feed. The positioning of meat as natural provides a temporary measure for authorities to prepare facilities and processes for not only Halal, but also organic certification. Once organic certification is obtained from an internationally recognized body, it will be able to position Kyrgyz meat as premium organic meat for export.
Almost 80% of livestock farmers work on free pastures.
One of the other potential sources of income for the meat industry may be the food industry sector, where cuts and other parts of meat can be used to produce food products such as sausages, burger patties, and barbecue patties. According to available data, there

are about 280 meat processing enterprises in Kyrgyzstan, and their potential needs to be improved.

The presence of PCM will significantly help build the capacity of these meat processing plants in terms of providing training, raw materials and infrastructure.

Kyrgyzstan has good opportunities to play in the semi-premium and premium zones.

2.3. Analysis of necessary infrastructure conditions

The main point of formation of halal meat products is the creation of a specialized logistics center, the Halal Meat Park, which will perform the following functions:

- Animal farm,
- Animal fattening operations,
- Slaughter of livestock,
- Meat processing,
- Eco-tourism.

The choice of a PCM location is very important from the point of view of the proximity of suppliers-farmers, favorable areas for raising animals, and a fodder base.

Free-range green pastures and a highly nutritious source of uncontaminated and untreated water are what contribute to the production of high-quality organic meat products in Kyrgyzstan.

The methods of zoning agricultural territories are based on the ideas of the 19th century, presented by Johann Heinrich von Thünen in his work "The Isolated State". The main thing is that the spatial organization of society largely depends on the distance and time required to overcome it, and the level of transport development. Rings, comparable to Thünen's zones, are the most common type of organization of any territory. Their configuration in real life depends on the characteristics of the territory. And in the center of the territory there is production and processing of raw materials. In our case, this is a meat park located in the center of the meat-producing region.

Modern studies widely apply the presented ideas of zoning territories, for example, in (Muhsin et al., 2017). This study also evaluates potential locations for industrial development using land suitability analysis (LSA) to emphasize both agricultural and industrial development in terms of sustainable growth. An integrated GIS-MCA model was used, which can serve as a policy and planning tool for determining the location of industrial economic zones, while preserving agricultural land and supporting environmental protection. To determine the optimal location of a logistics center in a commodity-producing region, the spatial optimization method is used - a method for determining the center of gravity (centroid) using the formula for calculating the center of mass to minimize total transportation costs:

$$X_c = \frac{\Sigma(Q_i \cdot x_i)}{\Sigma Q_i},\ Y_c = \frac{\Sigma(Q_i \cdot y_i)}{\Sigma Q_i} \qquad (1)$$

Where Q_i is the volume of production from the i-th section, (x_i, y_i) are its coordinates.

Practical stages of implementation

Collection of data on production volumes:

Total number of cattle = 1.7 million

Total amount of meat produced per year = 428 thousand tons.

Meat export per year = 224 thousand tons

Animal husbandry is concentrated in the mountainous regions of Naryn, Issyk-Kul and Osh regions and is mainly used for meat and milk production.

On the other hand, PCM can also be related to the labor aspect, where meat farming is usually carried out by small landowners and farmers, which leads to very strong community growth.

Preliminary selection of zones: exclusion of unsuitable areas (nature reserves, development zones).

Calculation of indicators: application of the selected centroid model

Let's analyze the location of the geographical centers of the 3 most productive meat-producing regions: Jalal-Abad, Issyk-Kul, and Naryn. To do this, we will first make a number of assumptions:

- We will assume that the feed base of animal husbandry approximately coincides with the territory of rural areas, with the exception of the area of large reservoirs and high-altitude lands above 4000 m,
- The areas of built-up settlements can be neglected in our approximate analysis;
- The yield of grasses and forages is the same in all regions.

Then, for our task, it will be enough to find the centers of gravity of the geographical contours of these regions, minus the areas of large reservoirs and high-altitude lands above 4000 m.

GIS programs (QGIS, ArcGIS) with data were used for accurate calculation:

- Administrative boundaries from the State Register of the Kyrgyz Republic
- ALOS PALSAR altitude data using the exclusion algorithm. The DeepSeek R1 AI was used for the calculation (Monica - ChatGPT AI Assistant Chrome Extension, 2025)

As a result, the required centers were obtained in 3 regions of Kyrgyzstan, shown in Fig. 1.

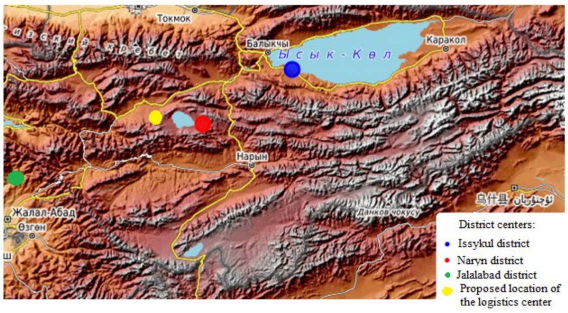

Figure 1: Centers of gravity of the territories of the regions of the Kyrgyz Republic

Coordinates of centroids in table 2.

Table 2: coordinates of regions centers

№	Region	Region Production Beef + Lamb (tons)	Coordinates of the center	Color of the point on the map
1	Jalalabad	33,700	41.4°N,72.5 °E	Green
2	Naryn	36,000	41.6°N,75.2 °E	Red
3	Issyk-Kul	52,000	42.3°N,77.1 °E	Blue
4	Recommended location of the MPP		41.9°N,74.7 °E	Yellow

To determine the location of the PCM, we calculate the average point for three regional centers, taking into account their weight in meat production. It is also necessary to take into account logistical factors - transport accessibility and main roads available in these regions.

2.4. Logistic conditions

In our case, the key main road connecting these regions is the new Balykchy-Jalalabad highway. It is also connected to other highways - North-South: M41 (Bishkek - Osh), A365 (Naryn - Kochkor) East-West: A372 (Karakol - Balykchy), A367 (Jalal-Abad - Uzgen) International: Torugart (to China), Irkeshtam (to China), Dostuk (to Kazakhstan) Development prospects:

The China-Kyrgyzstan-Uzbekistan railway under construction will shift its center to the Issyk-Kul region by 2030.

Based on the above considerations, we select the midpoint (highlighted in yellow), which is located in the Jumgal district of the Naryn region with coordinates 41.9°N,74.7°E.

Halal products can be transported via a multimodal chain, by land - cargo must travel long distances, for example, by road through Uzbekistan, Turkmenistan and Iran, and then by sea through the Persian Gulf to the United Arab Emirates, Qatar or Saudi Arabia.

The most valuable product is not frozen, but chilled meat, so the chain involves delivery by refrigerated truck to the airport and then air delivery. Currently, Kyrgyzstan has direct air links with the countries of the Persian Gulf.

3. Results and Discussion

As a result of the conducted research, it can be concluded that the organization of a halal meat park is a key link in the meat supply chain for export and may have the following consequences:

- The total production of halal meat should be 5-10% of the total number of cattle;
- Increase up to 3 times the total meat production in 10 years;
- Strengthen the positioning of Kyrgyz meat as premium organic meat for export;
- Achieve self-sufficiency in consumption;
- Ensuring the export of meat to the market with high added value, which will allow a local farmer to receive more than 30% profit increase;
- Increasing the food industry sector, where cuts and other parts of meat can be used for food production.

4. Limitations and Conclusion

Limitations: data collection from the National Statistical Committee reports is based on old values (1-2 years) and is sufficient only for initial estimates. However, the operational work of the PCM should be based on real figures obtained from concluded contracts, reports, etc.

Other supply chain issues have not been considered beyond the scope of this study and are awaiting further investigation:

- Halal meat cultivation;
- Logistics management in the supply chain;
- Project financing, sustainability, etc.

The most important conclusion:

- The choice of the location of the halal meat park in the Zhumgal district is relevant and justified;
- The next step should be the provision of a specific site by local governments, the development and approval of the project, construction and implementation within the framework of a public-private partnership.
- The prospect of using the research results is to use the experience of substantiation and technology for other Halal and organic products and services.

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Agriculture and Supply Chain: insights from recent studies for the period of 2020-2025

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Abstract

Research focusing on agriculture food and supply chain has become a prominent area of study within the academic community. This paper presents a comprehensive review aimed at understanding the research trends in these areas. Specifically, it analyzes scientific production and published articles on agriculture food, supply Chain from 2020 to 2025. Utilizing the Web of Science database, we collected, reviewed, and analyzed 163 publications that met our selection criteria. Our bibliometric analysis covered various aspects, including publication language, yearly distribution of papers, document types, the most cited papers, leading journals and affiliations by country. Additionally, co-authorship and the co-occurrence of keywords were examined to explore the knowledge components and structure of this research domain, identifying clusters of the most common keywords in the literature. The analysis underscores the need for international research on agriculture food, supply chain to expand scientific exchange on these topics. Furthermore, it highlights the importance of long-term, continuous research and the integration of Sustainable Supply Chain concepts for future intellectual development.

1. Introduction

The food supply chain (FSC) plays a critical role in the world economy (Sufiyan et al., 2019) and has been one of the crucial pillars of human civilization throughout history (Aqeel-ur-Rehman et al., 2014). The United Nations predicts that the world's population will reach 10 billion people within the next 100 years, with the majority of this increase occurring in urban areas. This mass migration from rural to urban areas can be seen as a significant concern (Mohtar and Lawford, 2016). In 2030, 59% of the world's population would be living in urban areas (Desa UN, 2011). Logistics function of supply chain management proves itself as a backbone (Esper et al., 2007) to provide the product by ensuring the all seven R's (Right Product, Right Customer, Right Price, Right Quantity, Right Quality, Right Time, Right Place) to the end customer (Hosseinzadeh Lotfi et al., 2023).

Industry 4.0, also known as the Internet of Things, is expected to significantly impact supply chains, business models, processes, productivity, and lead times (Abdirad and Krishnan, 2021). Kayikci in (2018) reported the transformation of industry 4.0 for organizations in Turkey, enhancing production and logistics. He also explained that sustainability requires vertical and horizontal integration, particularly in FMCG companies and transport service providers. Nowadays, organizations are in transformation phase and trying to implement smart logistics to improve the efficiency of supply chain management and to gain the competitive advantage (Kolasińska-Morawska et al., 2022).

Bibliometric analysis identifies cognitive structures and intellectual relationships by analyzing the performance of documents, authors, countries, journals, and institutions (Maassen, 2016). It is the purpose of this study to provide systematic methods for the acquisition of transparent bibliographic information related to a specific field of study (Sawassi and Khadra, 2021). It also learns topics that the scientific community considers relevant to social, economic, and environmental sustainability (Durán-Sánchez et al., 2020). Furthermore, bibliometrics has contributed to various academic fields sciences engineering (Cancino et al., 2017), sustainability (Pizzi et al., 2020), industry (Mei et al.,

2020), Industry 4.0, Blockchain, Artificial Intelligence (Bodkhe et al., 2020b). In this bibliometric evaluation, the concept of agriculture, aimed at improving sustainability in supply chain management is described as a technology-oriented logistical process that enhances supply chain efficiency throughout both upstream and downstream operations.
While these metrics offer valuable insights into scholarly output and citation impact, this review aims to broaden the perspective on researcher evaluation by exploring a diverse array of alternative performance indicators (Hassan and Duarte, 2024).

2. Materials and Methods

This review involved the identification and analysis of relevant publications based on existing research.

The study utilized the Web of Science, one of the most widely used bibliographic databases, focusing on the period from 2020 to 2025. The keywords used for the search were 'agriculture food, supply chain, logistics'. The analysis was conducted in March 2025. A total of 163 publications were selected for further examination of issues related to agriculture, food, supply chain, and logistics. The data analysis was carried out using a combination of tools including CSV files, Microsoft Excel 2021, RIS format, VOSviewer, MapChart, and RAWGraphs 2.0.

2.1. Article review and study eligibility criteria

A dataset was compiled using the keyword 'agriculture food, supply chain, logistics' with filters applied for English-language articles, document type 'article', and publication years 2020–2025. The search spanned subject areas including Agriculture, Food Science, Technology, Environmental Sciences, Ecology, Business, Economics, Chemistry, Transportation, Computer Science, Automation & Control Systems, Urban Studies, Engineering, and Energy & Fuels. Data collection was completed by March 2025. Figure 1 presents the methodological workflow used in the study.

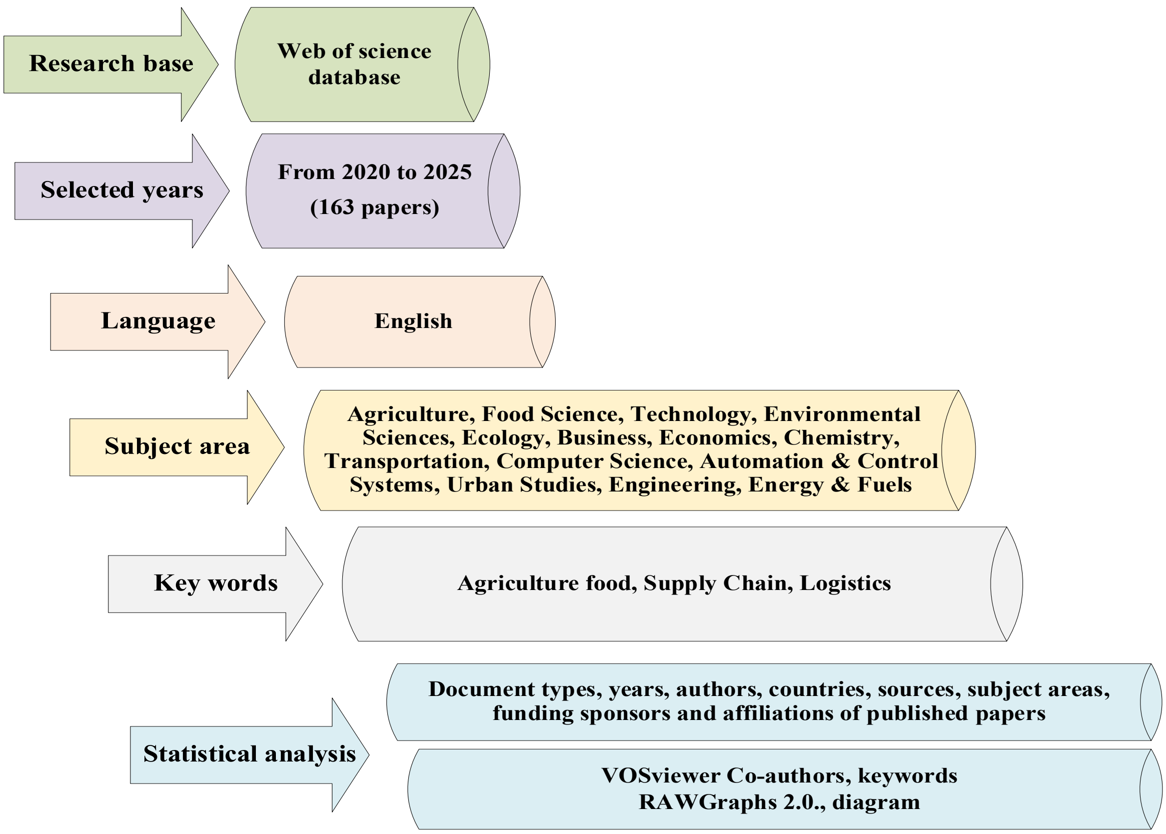

Figure 1: Methodology flowchart for the research

3. Results and Discussion

3.1. Trend of publications on agriculture food, supply chain, logistics

The relationship between agriculture food, supply chain, logistics has a wide range of scientific implications. Total of 163 papers published between 2020 and 2025 on issue (Fig.2).

This review makes an initial step towards shaping the role of agriculture food, supply chain, logistics in future and provides a summary of Agricultural Supply Chain (Bodkhe et al., 2020a), Smart Factory (Wu et al., 2018), Transportation, Logistics, Retail, Utilities (Talebkhah et al., 2023), transport infrastructure (Chandra Shit, 2020).

3.3. Top cited papers on agriculture food, supply chain, logistics

Given is in the Table 1 which presents data concerning ten the mostly cited papers on agriculture food, supply chain, logistics the world (Fig. 4., Fig 5.).

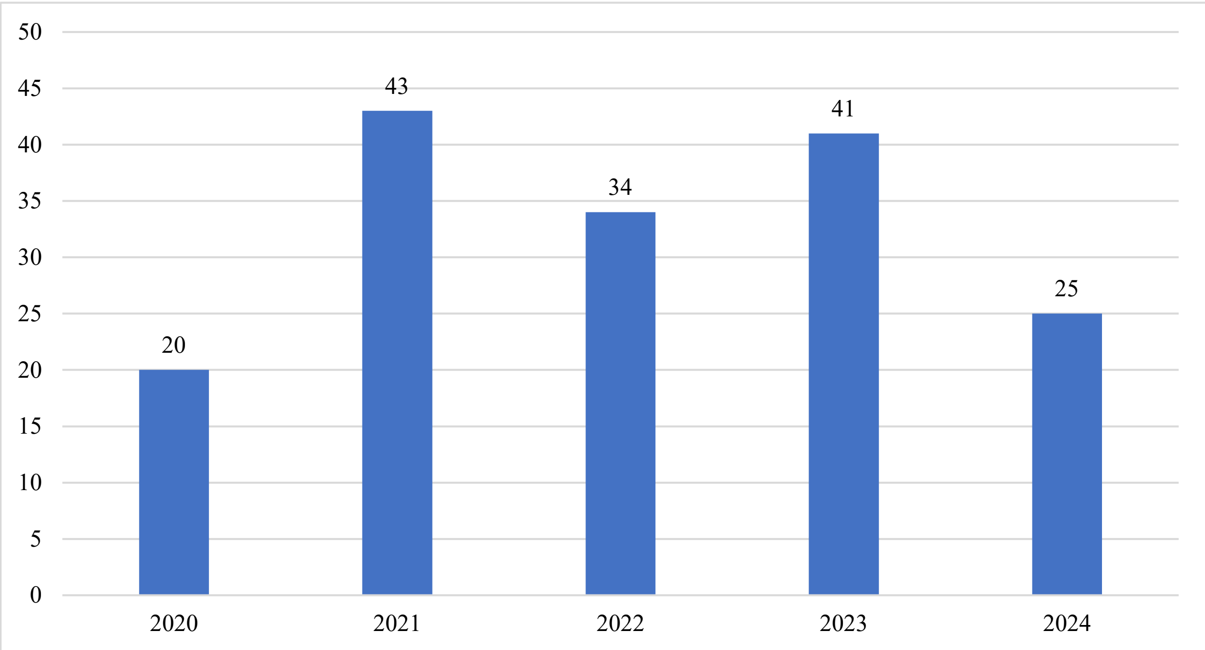

Figure 6: Annual production of articles on agriculture food, supply chain, logistics the period 2020-2025

3.2. Top countries on agriculture food, supply chain, logistics

Between 2020 and 2025, sixteen of the most productive countries contributed to research in the field of agriculture, food, supply chain, and logistics. Among them, Switzerland led with 70 publications, followed by the United Kingdom with 37, the Netherlands with 27, and the United States with 18. Other countries, including Italy (3), Germany (2), Argentina (2), Turkey (2), Indonesia (1), and Brazil (1), made more modest contributions to the field.

In conclusion, Switzerland demonstrated the highest research productivity during this period, significantly surpassing other countries in publication output. This highlights Switzerland's prominent role in shaping academic discourse in agriculture-related supply chain and logistics research, while other nations contributed at a relatively lower level.

3.4. Top authors/keywords on agriculture food, supply chain, logistics

Top publishers on agriculture food, supply chain, logistics it is widely considered due to the fact that of cited and impact of the articles analysis was carried out. We collected top authors in Fig. 4 which published the highest cited of papers.

Table 1: List of top cited publications on agriculture food, supply chain, logistics

No.	Title	Journal	Corresponding author	PY	Number of referencing 2020-2025	Doc.type
1	Food waste to bioenergy: current status and role in future circular economies in Indonesia	Energy ecology and environment	Suhartini S.	2022	307	Review
2	Digitalization in Food Supply Chains: A Bibliometric Review and Key-Route Main Path Analysis	Sustainability	Rejeb A.	2022	217	Article
3	Towards the sustainable conversion of corn stover into bioenergy and bioproducts through biochemical route: Technical, economic and strategic perspectives	Journal of cleaner production	Zabed HM.	2023	205	Article
4	After the COVID-19 pandemic: changes and continuities in the food supply chain	Food quality and safety	Yu CY.	2024	202	Article
5	A systematic literature review of the agro-food supply chain: Challenges, network design, and performance measurement perspectives	Sustainable production and consumption	Yadav VS.	2022	188	Review
6	Causal Impacts of Epidemics and Pandemics on Food Supply Chains: A Systematic Review	Sustainability	Cardoso B.	2021	188	Review
7	Logistics and Agri-Food: Digitization to Increase Competitive Advantage and Sustainability. Literature Review and the Case of Italy	Sustainability	Remondino M.	2022	185	Review
8	The logistics of the short food supply chain: A literature review	Sustainable production and consumption	Paciarotti C.	2021	175	Review
9	Blockchain-Based Traceability for Agricultural Products: A Systematic Literature Review	Agriculture-Basel	Lv GJ.	2023	175	Review
10	Implications of Green Logistics Management on Sustainable Business and Supply Chain Performance: Evidence from a Survey in the Greek Agri-Food Sector	Sustainability	Trivellas P.	2020	157	Article

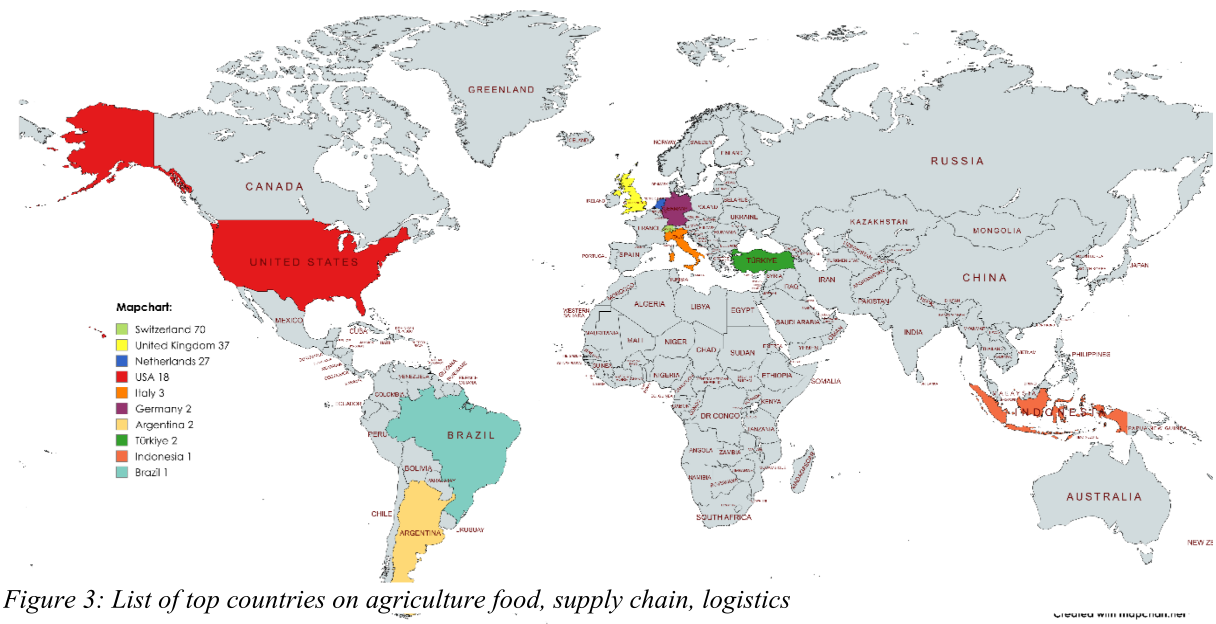

Figure 3: List of top countries on agriculture food, supply chain, logistics

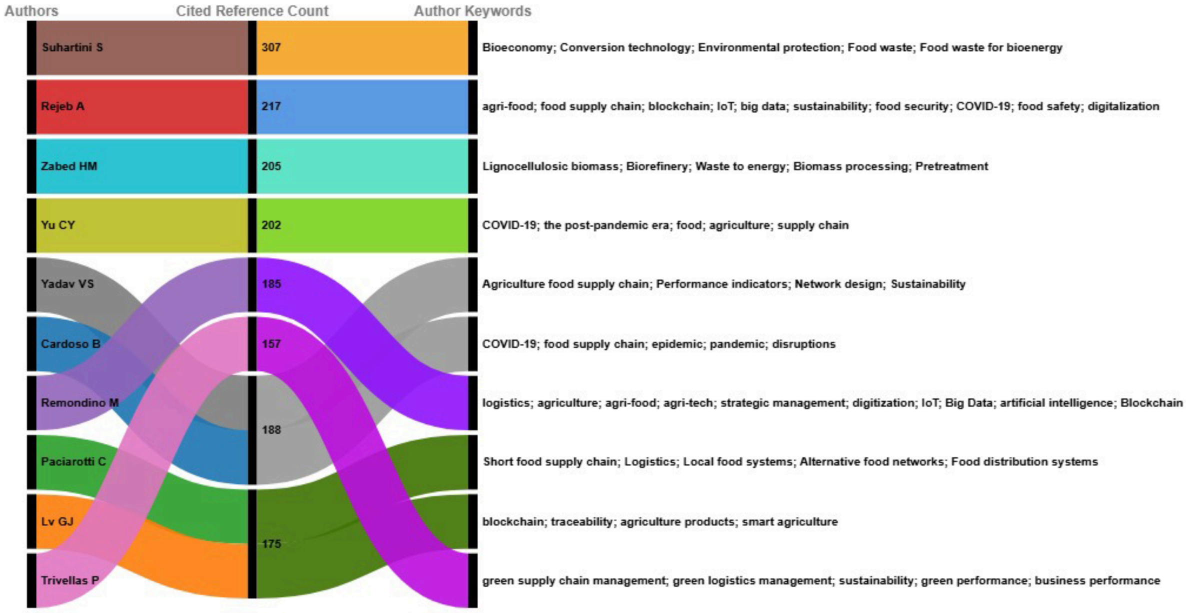

Figure 4: Top cited authors/keywords on agriculture food, supply chain, logistics

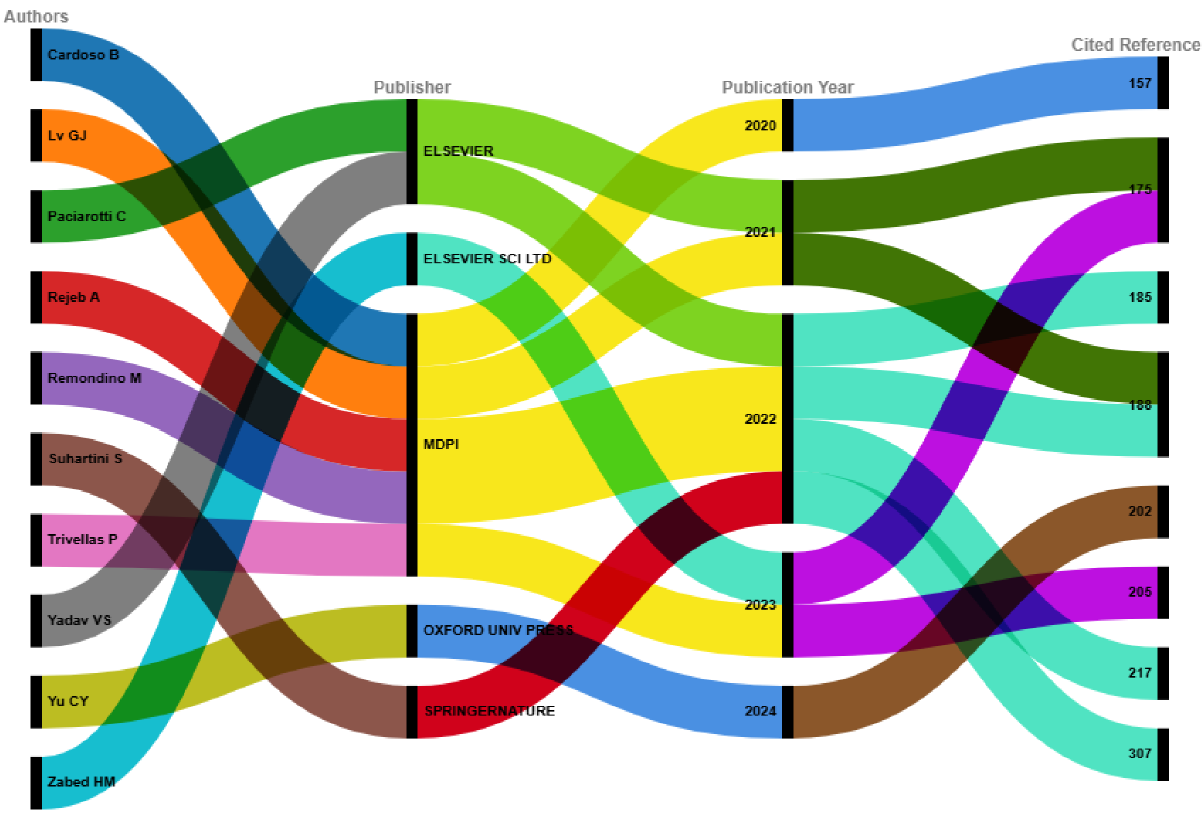

Figure 4.1: Top cited authors collaboration publishers on agriculture food, supply chain, logistics

Collaboration between top-cited authors and publishers in the fields of agriculture, food, supply chain, and logistics (shown in Fig. 4). To create this visual diagram, the authors used RAWGraphs 2.0. As shown in the figure 4.1, the top 10 authors collaborated with the following publishers: SPRINGERNATURE, MDPI, ELSEVIER, OXFORD UNIV PRESS.

3.5. Top co-authorships and keywords on agriculture food, supply chain, logistics

VOSviewer facilitates the visualization of scientific landscapes through the generation of co-authorship networks, keyword co-occurrence maps, citation patterns, bibliographic coupling, and co-citation analyses. It is compatible with various bibliographic data formats, including .txt, .ris, and .csv files, particularly those exported from databases such as Web of Science (Bhatt et al., 2022).

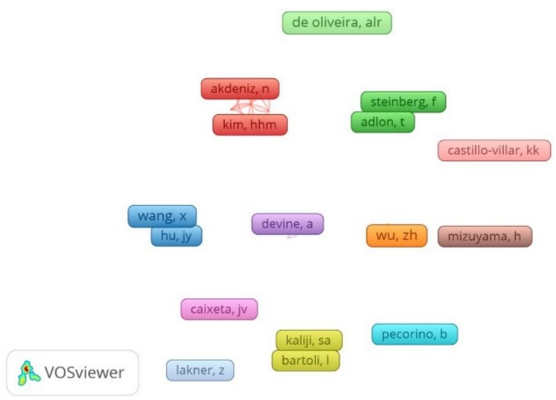

Figure 5: Network map of top co-authorships based on the total link strength

The raw data file was uploaded into VOSviewer, which was then used to generate a co-authorship and keyword co-occurrence map (see Fig. 5). The co-authorship analysis revealed a network comprising 736 authors. Figure 5 shows a co-authorship and keyword co-occurrence map of these authors, with elements represented in corresponding colors.

Only authors having a minimum of one publication on the topic of agriculture food, supply chain, logistics were included. There are 35 items distributed over 12 clusters: cluster 1 (6 items), cluster 2 (5 items) cluster 3 (5 items), cluster 4 (4 items), cluster 5 (3 items), cluster 6 (3 items), cluster 7 (3 items), cluster 8 (2 items), cluster 9 (1 items), cluster 10 (1 items), cluster 11 (1 items), cluster 12 (1 items). Total link strength (90) and links (51).
The analysis yielded 1074 keywords. After excluding the general keywords with a low relevance score and those with low occurrence (by default, a minimum of 10 occurrences of a keyword is selected, to strengthen the co-occurrence results), 22 items were finally identified. Based on the total link strength, each resulting keyword is sketched in a node, creating a network map of all keywords. Figure 6, shows the network map of the top 736 authors' keyword co-occurrence. The size of the node reflects the keyword's degree of importance. There are 22 items distributed over 3 clusters: cluster 1 (agriculture, consumption, covid-19, food, food security, logistics, resilience, supply chain, sustainability), cluster 2 (food supply chain, management, model, optimization, products, supply chains, waste), cluster 3 (blockchain, framework, impact, performants, quality). Total link strength (431) and links (176).

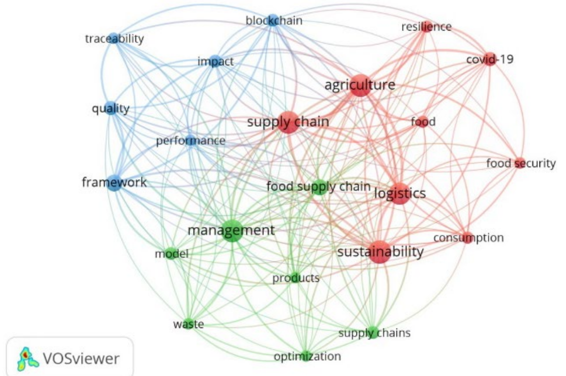

Figure 6: Network map of top keywords based on the total link strength

4. Discussion

The aim of this study was to examine the current knowledge on agriculture, food, supply chains, and logistics, and to identify through a systematic review the scientific articles and research areas that have had the most significant impact on these fields. The scientometric analysis revealed that articles published over the past five years yield the highest results in the areas of agriculture, food, supply chains, and logistics during this period. Switzerland ranks first with 70 (42.94%) articles. This can largely be attributed to the fact that Switzerland is traditionally considered one of the most developed countries in the world, with a significant presence of prestigious research centers and universities.
In general terms, the work aims to maintain with agriculture food, supply chain, logistics. From our analysis of the agriculture food, supply chain, logistics publications for countries over 5 years sorted out 163 of publications about agriculture food, supply chain, logistics. The publications published began from 2020 to 2025. In these articles, problem with Packaging System (Wang et al., 2022), Production of biofuels (Aboytes-Ojeda et al., 2020), Development of Bioeconomy (George et al., 2021), Delivery Operations (Issaoui et al., 2022), The Soybean Intermodal Transport (De Morais et al., 2023), Agri-Food Chain Sector from the Northern Region of Portugal (Madureira et al., 2024), African agri-entrepreneurship in the face of the COVID-19 pandemic (Kadzamira et al., 2023), Food supply

chain after the COVID-19 pandemic (Yu and Song, 2024), Agro-food chain distributive (Samoggia et al., 2023), Water resources in agriculture literature review (Mukanov et al., 2024b), Analysis of Competitiveness in Agri-Supply Chain Logistics Outsourcing: A B2B Contractual Framework (De and Singh, 2022), Groundwater in agriculture a bibliometric analysis (Kannazarova et al., 2024), Analysis of Logistics Cost on Smallholder and Middleman to Foster Tea Supply Chain (Tanuputri and Bai, 2022), Sustainable conversion of corn (Zabed et al., 2023), New trends in sustainable supply chains (Mukanov et al., 2024a) A literature review of the agro-food supply chain (Yadav et al., 2022), Logistics and Agri-Food: Digitization to Increase Competitive (Remondino and Zanin, 2022), Blockchain for Agricultural Products (Remondino and Zanin, 2022), Electrified Vehicles (Cheng et al., 2014), Autonomous Vehicle Intelligent System (Yu and Lam, 2018), Root harvester machine: a review of papers (Xaliqulov et al., 2023, pp. 1982–2022), Energy Management in Smart Cities (Zhang et al., 2023), Blockchain for Intelligent Transportation Systems (Das et al., 2023), Smart logistics (Issaoui et al., 2022). This is reflected in publications covering a wide range of topics, including supply chain and logistics, intelligent transportation systems and related transactions, transportation planning and technologies, various aspects of science and engineering, transportation business and management, mobile communication networks, vehicular communications, sustainable transportation, industrial applications, transportation engineering, traffic management, agriculture, environmental monitoring, ecology, distribution systems, resource management, supply processes, and optimization strategies.

Based on the above, it is evident that the issues of agriculture, food, supply chain, and logistics are closely linked to the challenges of Sustainable Supply Chains. Our analysis reveals that over a span of five years, 163 articles were categorized, with nearly 90% of these publications focusing on advanced technologies for Sustainable Supply Chains

5. Conclusion

This bibliometric analysis examines the research landscape within the fields of agriculture, food, supply chain, and logistics, focusing on identifying emerging research hotspots and potential future research directions from 2020 to 2025. The analysis is based on data extracted from the Web of Science database. A total of 163 publications were identified, reviewed, and analyzed. Of these, the majority were research articles (124 publications, accounting for 76.01%), followed by review articles (28 publications, 17.17%), conference proceedings (10 publications, 6.14%), and book chapters (1 publication, 0.62%). The analysis reveals that Switzerland was the top contributor to these publications, followed by the United Kingdom, Netherlands, United States, Italy, Germany, Argentina, Turkey, Indonesia, and Brazil. This distribution highlights key countries driving the current research in these areas.
As a result of this analysis, the following limitations were identified:

- Shortages of key resources and critical business-related price increases;
- The rising cost of order processing in e-commerce, driven by increased process complexity. Currently, sales channels in e-commerce are undergoing transformations, and although companies can cooperate with marketplaces, few understand how to work with them most effectively;
- Extended delivery time (lead time). The product delivery time depends on how demand is processed, product availability, and the actual delivery time;
- Possible solutions to reduce delivery time include: process automation, reducing order processing time, establishing long-term relationships with suppliers, flexible matrices for transaction, contract, and specification approval, and eliminating outdated approval cycles for various processes;
- Key reasons for this may include an inadequate data exchange system and the lack of international cooperation, resulting in a shortage of joint projects.

Key factors contributing to this issue may include an inefficient data exchange system and insufficient international collaboration, leading to a lack of joint projects.

Furthermore, international research in the fields of agriculture, food, supply chain, and logistics would greatly benefit from enhanced scientific exchange, particularly between emerging and developed countries, as well as between suppliers, buyers, stakeholders, and researchers.

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Prompt Engineering Enhances Gemma-3 Reasoning for SCM

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Abstract

The rising complexity alongside international container logistics uncertainty requires organizations to develop efficient decision support systems. This research assesses the effectiveness of Few-shot prompt engineering when adapting the base Large Language Model Gemma-3-27b-it to improve decision support performance in specialized domains while excluding Retrieval-Augmented Generation (RAG) and model fine-tuning. The research compared standard prompt generation to Few-shot prompting which added two semantically similar examples to the prompts. A specific dataset of 300 business cases based on East Asia-Northern Europe maritime corridor operations served as the evaluation foundation. For each case, reference solutions were generated by gemini-2.5-pro-exp-03-25 instructed to produce comprehensive plans. An independent LLM judge evaluated solution quality using Gemini 2.5 Pro to score solutions based on Logical Soundness, Explanatory Quality and Structure Clarity on a 10-point scale. The Few-shot prompting method delivered better results than baseline prompting because it achieved an average score of 8.43 in Explanatory Quality evaluation while the baseline scored 7.20. The overall average quality score reached 8.81 with Few-shot prompting while the baseline achieved 8.27 and the successfully resolved cases increased to 88.64% from 79.55% for achieving an average score of 8.0 or higher. The Few-shot prompting method generated better solutions when compared to the baseline approach in 68% of evaluation tests. Few-shot prompt engineering proves to be an effective method for enhancing base LLMs such as Gemma-3 in complex logistics reasoning tasks which enables the development of locally deployable AI assistants that provide better explanations.

1. Introduction

The field of international container logistics consists of many stakeholders who need to work within set rules and procedures which drive supply chain management effectiveness worldwide (Ambrosino & Sciomachen, 2021). The world economy relies heavily on efficient supply chain management within this sector. The sector operates most of the time in VUCA (Volatility, Uncertainty, Complexity, and Ambiguity) conditions because information visibility gaps, communication delays, and infrastructure bottlenecks decrease its efficiency and cost-effectiveness (Ouedraogo et al., 2023). Decision support systems (DSS) need to be robust to handle this complexity since there is not enough supply of highly skilled logistics professionals to fulfill the demand in global logistics operations management.

Large Language Models (LLMs) demonstrated remarkable effectiveness across multiple fields including natural language understanding and text generation together with complex problem resolution (Brown et al., 2020; OpenAI, 2023). The success of LLMs creates potential opportunities to improve decision-making and documentation automation and stakeholder communication in the logistics industry.

AI applications in supply chain management and logistics research includes studies about demand forecasting, route optimization and warehouse automation (Waller & Fawcett, 2013). Recent studies have started to explore the capabilities of LLMs for document analysis in logistics and exception handling and stakeholder interaction with decision support systems (Zhang et al., 2024). Certain approaches integrate LLMs with specialized Traffic Foundation Models (TFMs) to perform traffic analysis tasks and utilize LLMs to enhance relationship prediction in supply chain knowledge graphs for better visibility (Zheng & Brintrup, 2024). The implementation of simulation model generation through natural language descriptions represents one area of research (Jackson et al., 2024).

Most research applying LLMs depends on large models that consume high compute resources while implements Retrieval-Augmented Generation (RAG) and fine-tuning methods for adapting models to specific domains (Parthasarathy et al., 2024). These approaches show promise, but they lack adaptability for real-time local use because they require substantial resources or create data privacy and security concerns typical in logistics operations. The successful use of advanced prompt engineering methods to turn generalist models into specialists in medical domains (Nori et al., 2023) reveals an untapped potential for logistics which deserves further exploration. MedPrompt demonstrated that techniques such as dynamic few-shot selection and self-generated Chain-of-Thought (CoT) enabled GPT-4 to outperform fine-tuned medical models even without domain-specific instructions although new "reasoning-native" models might impact these techniques' performance (Nori et al., 2024).

A research gap exists because researchers have not studied the ability of smaller efficient locally deployable base LLMs such as those in the Gemma class (Gemma Team, 2024) for complex reasoning and decision support tasks in international multimodal container logistics using prompt engineering techniques alone. The current evaluation of advanced prompting techniques (few-shot learning) to boost the capabilities of these base models in this domain without using RAG or fine-tuning remains unexplored.

This research study investigates the following research inquiry: Advanced prompt engineering techniques utilizing few-shot learning with domain-specific examples selected qualitatively can enhance base LLM (Gemma-3-27b-it) response quality for international container logistics decision support tasks without Retrieval-Augmented Generation (RAG).

Multiple innovative aspects distinguish this research from existing work. This research investigates how Gemma-class models perform in deploying efficiently to international container logistics operations throughout the East Asia-Northern Europe corridor. We deliberately eliminate RAG and fine-tuning from evaluation to measure the direct effects of few-shot prompt engineering methods. A substantial amount of work went into building an advanced dataset containing authentic business scenarios and accurate solution answers for testing purposes. This research differs from past studies because it assesses prompt engineering's ability to transform a basic model suitable for local deployment into a sophisticated operational field for developing useful AI assistants in logistics.

The research follows this organization: Section 2 explains the methodology which includes the creation of the dataset along with the Gemma model prompting methods and the evaluation framework based on LLM. Section 3 presents and discusses the results of the evaluation, comparing the performance of the different prompting strategies. Section 4 outlines the limitations of the study and concludes with key findings, implications, and directions for future research.

2. Procedure, methods or experimental part

The research implemented a complete methodology to assess prompt engineering methods for adapting a base Large Language Model (LLM) to decision support tasks in international container logistics. The research included creating a specialized dataset and applying multiple prompting strategies to the target LLM followed by an LLM-as-a-Judge evaluation of the produced outputs. The research design implements an experimental method which evaluates various prompting conditions against a standard baseline.

2.1. Dataset Development

This study required the development of a domain-specific dataset consisting of 300 distinct business case-solution pairs. Each case described in detail typical problems that international container shipping operations encounter while shipping between East Asia (mainly China) and Northern Europe, focusing on major North Sea ports (Hamburg, Rotterdam, Antwerp-Bruges) and Baltic Sea ports (Riga).

These realistic case scenarios originated from a knowledge base structure which drew from real-world sources. An intermediate step involved in-depth analysis of relevant documentation and the extraction of atomic datapoints representing key facts, rules, procedures, or constraints in a standardized JSON format. The organized approach to data presentation enabled the creation of diverse and realistic business cases.

The documents from which datapoints originated together with case generation materials came from publicly accessible sources. Following resources served as the foundation for both datapoint extraction and case scenario generation:

- Official websites and regulatory documents of relevant port authorities (e.g., Port of Hamburg, Port of Rotterdam, Port of Antwerp-Bruges, Port of Riga, Port of Singapore, Port of Shanghai - Yangshan).
- Official websites and documentation from international bodies like the International Maritime Organization (IMO) (covering conventions such as SOLAS, MARPOL, FAL) and the United Nations Conference on Trade and Development (UNCTAD).
- Standardized trade terms documentation (e.g., INCOTERMS rules).
- The Union Customs Code (UCC) (European Parliament & Council of the European Union, 2013) as well as other normative documents and legislative acts.

Realistic synthetic scenarios were created using the information collected and extracted datapoints. Every case included detailed situational information, relevant context (e.g., cargo type, route, involved parties), and a specific problem which needed either a decision or solution. Senior (with large number of parameters and mature reasoning capabilities) gemini-2.5-pro-exp-03-25 model was directed to create reasoned and wide spectrum plans of action designed to minimize adverse outcomes and ensure prompt delivery of cargo basing on the actual principles of supply chain control and regulatory aspects.

A validation process was put in place to validate the dataset quality and realism and ensure data diversity. A checklist was implemented during development to check for scenario originality while preventing duplication and guaranteeing full logistical situation coverage. A specially instructed Reasoning Large Language Model (gemini-2.5-pro-exp-03-25) reviewed a whole set of the developed cases along with their ground truth solutions to evaluate their plausibility and complexity as well as their consistency with industry standards.

The final dataset contained 300 case-solution pairs that were split into two parts: training set (selecting examples for few-shot prompting) and test set (evaluating the model's performance).

2.2. Prompt Engineering Techniques

The author studied how various prompt engineering techniques affected the performance of Gemma-3-27b-it an instruction-tuned model from the Gemma family which is part of the LLM family known for its efficiency. The following configurations were tested:

- Baseline: The `Gemma-3-27b-it` model received the test case question (problem description) as the control condition without additional instructions, examples, or contextual framing. This experiment aimed to measure the unaided performance of the model in this field.
- Few-shot Prompting (In-Context Learning, ICL): Author adopted the few-shot prompting strategy based on Nori et al.'s (2023) positive findings about dynamic example selection in complex domains. For each test question, the model selected the two most relevant case-solution pairs from the training set. The relevance assessment depended on the cosine similarity calculation between the vector embedding of the test question and all the question embeddings in the training set. Embeddings were generated using the `text-embedding-004` model (Google, 2024). Two selected examples were added to the prompt which preceded the test question to demonstrate the proper reasoning process and output format for the model.

2.3. Evaluation Process

The quality of responses produced by 'Gemma-3-27b-it' in each prompting condition was assessed using another LLM, 'gemini-2.5-pro-exp-03-25' as an independent judge. This LLM-as-a-Judge approach is an attempt to bring a level of objectivity and consistency in evaluation (Zheng et al., 2023).

For each test case, the LLM judge was provided with:

1. The text of the question (problem) from the case (scenario_description).
2. The response generated by 'Gemma-3-27b-it' under one of the three prompting conditions (assistant_answer).
3. The LLM-generated ground truth solution (groundtruth_answer), which was created by gemini-2.5-pro-exp-03-25 during the dataset development phase (as described in Section 2.1), serving as the benchmark for an ideal response.

The LLM judge was asked to rate the `assistant_answer` in terms of reasoning quality in relation to the `scenario_description` and `groundtruth_answer`. The judge followed predetermined criteria to rate the `assistant_answer` on a 10-point scale (1 = Poor; 10 = Excellent) for three specific aspects:

- The reasoning quality in terms of the internal consistency and coherence of the model's arguments (reasoning logical soundness).
- The effectiveness of explaining the reasoning process and the conclusions reached (reasoning explanatory quality).
- The coherence of the model's response structure (reasoning structure clarity).

To compare the effectiveness of the prompting techniques quantitatively, we employed two metrics that were obtained from the LLM judge's scores:

- The percentage of solved cases: A case was considered solved if the average score for the three criteria of reasoning logical soundness, reasoning explanatory quality, and reasoning structure clarity was 7.0 or higher.
- The mean score of all test cases for each criterion and the mean score for each criterion and the overall mean score for each prompting condition.

2.4. Alternative Methodological Approaches Considered for the Research

In the design of the research methodology, other ways of adapting LLMs to this domain were explored but set aside or ruled out for the purpose of this specific study:

- Retrieval-Augmented Generation (RAG): RAG improves LLM responses by incorporating information retrieved from external knowledge sources. RAG can be useful for obtaining real time data or copious amounts of regulations; however, the effectiveness of RAG is highly dependent on the quality of document parsing, chunking, and retrieval process itself. Critical context or relationships between information fragments can be lost during the chunking process (Gao et al., 2023). Moreover, managing complex relations can sometimes need graph databases which is a lot of overhead. RAG was not used in this study to focus on the impact of the prompt engineering on the base model's ability to reason on its own.
- LLM-Agent Systems: The development of LLM-based agents that can function autonomously and make decisions without human input and use tools is a more complex model. As this is the general objective of the doctoral research being carried out, the present work focuses on the primary reasoning capabilities elicited through prompting in an assistant paradigm, rather than full agent autonomy.
- Fine-tuning: A possible approach could be to fine-tune the base LLM on a logistics dataset.

However, fine-tuning large models requires large amounts of computational power and large amounts of high-quality labelled data which may not always be readily available. And it is still a matter of debate as to whether fine-tuning on a relatively small and specialized dataset would result in better reasoning performance than effective prompt engineering applied to a capable base model (Parthasarathy et al., 2024). Our approach aims at examining the potential of light-weight adaptation techniques.

The choice of prompt engineering techniques for this study was based on the need to assess the adaptability of an efficient base LLM using flexible methods that do not require large computational resources or large-scale data curation during the adaptation phase itself, rather than relying on the model's ability to learn from large amounts of data using context and instructions.

3. Results and Discussion

This section presents and interprets the results obtained from evaluating the \`Gemma-3-27b-it\` model under the Baseline and Few-shot Prompting conditions, using the methodology described in Section 2. The evaluation focused on the quality of reasoning in generated solutions for international container logistics case studies, assessed by an LLM judge (\`gemini-2.5-pro-exp-03-25\`) across three criteria on a 10-point scale.

3.1. Presentation of Quantitative Results

The performance of the two prompting approaches is summarized by the average scores assigned by the LLM judge (Table 1), the percentage of cases deemed successfully solved (Table 2), and a head-to-head comparison indicating which approach produced a superior solution for each case (Figure 1).

A case was considered successfully solved if the average score across the three reasoning criteria was 8.0 or higher.

Table 1: Average LLM-Judge Scores (1-10 Scale) for Baseline vs. Few-shot Prompting

Metric	Baseline Score	ICL Score
Logical Soundness	8.30	8.45
Explanatory Quality	7.20	8.43
Structure Clarity	9.30	9.55
Overall Average Score	8.27	8.81

Table 2: Percentage of Successfully Solved Cases (Average Score >= 8.0)

Condition	Success Rate
Baseline	79.55%
Few-shot Prompting	88.64%

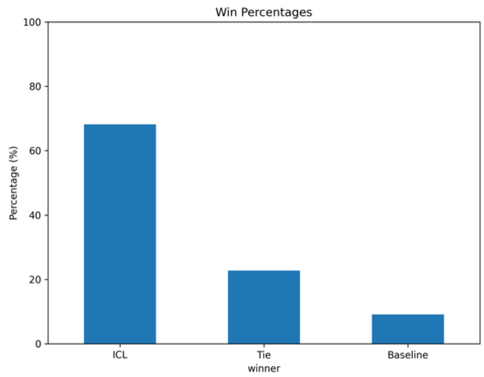

Figure 1: Head-to-Head Solution Superiority Comparison (N=44 Cases)

The results of direct comparisons between the solutions obtained by the Baseline and Few-shot Prompting (ICL) approaches for the same case studies are presented in Figure 1. It shows the percentage of cases where the Few-shot approach was rated better, where the Baseline was rated better, and where the solutions were considered equal (Tie).

3.2. Interpretation of Results

The results illustrated in Table 1 and Figure 1 clearly show that the Few-shot Prompting (ICL) significantly improves the quality of the solutions produced by ‘Gemma-3-27b-it’ for complex maritime container logistics case studies compared to the Baseline approach.

All the approaches were found to perform well in “Logical Soundness and “Structure Clarity” where the average scores were above 8.3 and 9.3 respectively. This means that the base \`Gemma-27b-it\` model has some built-in capabilities of producing logically consistent and well-organized responses when properly prompted for this type of task. The Few-shot approach enhanced these areas by +0.16 for Soundness and +0.25 for Clarity possibly through reinforcing consistent argumentation patterns and formatting seen in the examples.

However, the most notable difference was seen in “Explanatory Quality”. The Baseline approach scored comparatively low on this dimension (7.20), suggesting that the solutions produced were likely to be logically sound and structured, but not very clear in explaining the rationale behind the solution. On the other hand, the Few-shot Prompting approach yielded a significantly higher average score of 8.43 (+1.23 points, a 17.1% relative improvement). This therefore implies that giving relevant examples in the prompt can help the model to explain its reasoning process better and in a more convincing

manner, explaining the why of the conclusions made.
This improvement in explanatory quality was the major cause of the higher overall average score of the Few-shot approach (8.81 compared to 8.27). The head-to-head comparison (Figure 1) also lends credence to this result as it shows that the solution produced using Few-shot prompting was rated as better than the Baseline solution in more than two third of the cases (68.18%) compared to the Baseline being rated as better in less than 10% (9.09%) of the cases.

3.3. Discussion

Thus, the results of the research directly answer the research question and confirm that the advanced prompt engineering technique, Few-shot Prompting (ICL) with domain-specific examples selected dynamically, can enhance the quality of the responses from a base LLM like 'Gemma-3-27b-it' for decision support tasks in international container logistics, without resorting to RAG or fine-tuning. The increase observed, especially in explanatory quality, agrees with the results from other domains that indicate that in-context learning can influence LLM behavior to produce the desired output characteristics (Nori et al., 2023; Brown et al., 2020).
The practical implication of improved explanatory quality is crucial for Decision Support Systems (DSS). A logistics professional using an LLM assistant will be more likely to accept and make use of a recommendation if the rationale is well explained (Mersha et al., 2024). However, the base model showed good logical structuring, while the Few-shot approach enhances the output to be more practically useful by enhancing its interpretability and persuasiveness.
From a user-centered perspective, such an improvement in the explanatory quality has a promising capacity in actual world applicability. Service providers in logistics are usually faced with urgent, high-pressure decisions. AI assistant showing clearer, more detailed reasoning (supported by Few-shot approach) could possibly ease the cognitive load needed to comprehend the AI suggestions. This enhanced interpretability can increase the user's confidence in the outputs of the assistant thus hastening and eradicating doubt in decision-making. Besides, a system, which can produce well-explained solution, could be of great use as on-the-job training tool for the less experienced personnel, and could help them to learn effective strategies of solving problems in the complex logistics domain. Although direct user studies are needed to confirm (see Section 4.1) the superior explanatory performance observed, the Few-shot approach seems to produce outputs that are more aligned to the practical needs of end-users looking for meaningful and trustworthy decision support.
This study also points to the possibility of employing efficient, locally deployable models like Gemma-3 for solving complex domain specific problems through careful prompt engineering. This is especially important for the logistics industry as data privacy and the requirement for low latency and offline capabilities can be critical.
However, there are some limitations and issues regarding the generalizability of these findings that need to be considered. The assessment was made with a certain LLM ('Gemma-3-27b-it') and a certain judge ('gemini-2.5-pro-exp-03-25'); performance may change with other models. The dataset was developed to be typical for the East Asia-Northern Europe route; further research is required to establish the generalizability of the results to other shipping routes or logistics segments. The evaluation was done using an LLM judge; although this may provide consistency it may not capture all the nuances of human expert judgment (Zheng et al., 2023). Future research should also include user studies with logistics professionals to assess the actual usability and the quality of the solutions as perceived by the logistics professionals.
Nonetheless, the results show that there is a feasible way to develop LLM-based assistants for logistics decision support systems. The effectiveness of the Few-shot prompting approach indicates that the quality and relevance of examples are a key factor in the transfer of LLMs to domains like international container logistics. This approach can be used as a starting point for the development of tools that can aid logistics professionals in solving complex problems, generating well-grounded solution suggestions, and thus making better decisions.

4. Limitations and Conclusion

The study focused on examining the capability of Few-shot Prompting (In-Context Learning) to transform the `Gemma-3-27b-it` Large Language Model for solving complex decision support problems in international container logistics domain. The results show the potential of advanced prompt engineering with In-Context-Learning but also indicate directions for further research.

4.1. Limitations of the Study

There are some specific aspects which should be considered when analyzing the results of this research:

1. The study used a particular Large Language Model `Gemma-3-27b-it` and a specific Large Language Model judge `gemini-2.5-pro-exp-03-25`. The results and scores can be different if other language models or other assessment methods are used.
2. Another limitation is that the 'ground truth' solutions were used as benchmarks, which were produced by an LLM (gemini-2.5-pro-exp-03-25), and not humans – domain experts. Although this LLM was tasked to produce high-quality and thorough solutions, the benchmarks

reflect the interpretation of such solutions by an AI rather than the consensus of such by human experts or optimized by formal means. Thus, it is a main question of the study as to how well prompt engineering can facilitate Gemma-3-27b-it in conforming to the reasoning quality and style of a stronger LLM in terms of alignment, instead of alignment with human-expert-defined optimality. The assessment of the produced reference solutions by the same class of LLM opens the door to a possibility of correlated biases or views.

3. Although the dataset of 300 cases was selected with care, the dataset is relatively small and limited to the East Asia-Northern Europe trade corridor. This study does not attempt to explore the broader application of the results in other areas, transport modes, or logistics tasks.
4. Relying on an LLM-as-judge, while providing consistency, may not fully capture the subjective nuances and practical considerations that human logistics experts would apply when assessing solution quality (Zheng et al., 2023). Logistics professionals' real-world usability was not assessed in this study due to the lack of direct user studies.
5. The study was conducted without the use of Retrieval-Augmented Generation (RAG) and LLM fine-tuning to ensure that the impact of prompting could be determined. It fulfilled the research objective but left the evaluation of the synergistic effect of Few-shot prompting with other adaptation techniques undetermined.

4.2. Conclusion and Key Findings

Despite the limitations, this research yields significant findings. The most important result is the clear demonstration that Few-shot Prompting, using dynamically selected, domain-specific examples, substantially enhances the quality of responses generated by the `Gemma-3-27b-it` model for international container logistics case studies, compared to a baseline approach. The improvement was particularly pronounced in the "Explanatory Quality" of the reasoning (+17.1% relative improvement), leading to a higher overall average quality score (8.81 vs. 88.27 on a 10-point scale) and a significantly higher success rate (88.64% vs. 79.55% achieving an average score ≥ 8.0).

This study confirms that advanced prompt engineering is a potent technique for adapting efficient, instruction-tuned LLMs like Gemma-3 to specialized, complex domains such as logistics, without necessitating resource-intensive fine-tuning or external knowledge retrieval architectures like RAG. It highlights the capability of leveraging the model's inherent reasoning abilities through carefully crafted contextual examples.

4.3. Future Research Directions and Opportunities

The findings open several avenues for future research and represent opportunities to overcome current challenges:

- A crucial next step is progressing from the current assistant paradigm towards developing autonomous LLM-based agents for logistics. This involves equipping the LLM with capabilities for planning, tool use (e.g., accessing databases, APIs), and potentially interaction with simulation environments. Investigating how to grant agency reliably while maintaining control is a key challenge.
- Future work should explicitly evaluate the integration of tools, particularly RAG connected to curated regulatory and logistics knowledge bases, or web search capabilities, to potentially further enhance the accuracy and real-time relevance of the LLM assistant's responses, complementing the reasoning improvements gained from Few-shot prompting.
- A significant opportunity lies in evaluating the discovered Few-shot prompting approach on even smaller models within the Gemma 3 family, such as the 12B or 4B parameter variants. Success with these models could open possibilities for deploying capable logistics assistants directly on edge devices, like mobile phones (e.g., Pixel smartphones) or onboard vehicle systems, enabling offline access and enhancing data privacy.
- The developed approach to generate structured atomic datapoints from the diverse sources such as port regulations and IMO documents and dynamic retrieval of relevant examples proved to be effective. This methodology itself also requires separate investigation as a potentially promising technique for the knowledge representation and context provision for LLMs in other domains.

This study extends the model comparison to a wider set of LLMs (including both open-source and proprietary models) to have a better understanding of how the different model architectures and sizes perform when using the Few-shot prompting technique in this domain.

Creating a larger, more diverse dataset including additional trade routes, logistics scenarios (for example, incorporating disruptions, sustainability considerations), and data modalities (for example, including structured data or sensor readings) would enhance the robustness and generalizability of the evaluation.

It is essential to conduct user studies with experienced logistics professionals to validate the practical usability, trustworthiness, and decision-support value of the LLM assistant in real-world operational contexts.

Future iterations should focus on explicitly integrating and evaluating Explainable AI (XAI) techniques (Mersha et al., 2024) to further enhance the transparency and trustworthiness of the LLM assistant's recommendations for logistics professionals.

4.4. Exploitation Perspective

This research provides a tangible exploitation perspective for the logistics industry. The ability to significantly improve a relatively efficient LLM like Gemma-3 using prompt engineering opens a pathway toward developing practical, locally deployable AI assistants. Such tools can be used as valuable decision support systems components for logistics managers, assisting them in analyzing complex scenarios, understanding regulatory implications, and making well-reasoned action plans more efficiently. This directly addresses the industry's challenges related to complexity and the potential shortage of highly experienced personnel.

From a user-centered point of view, the evolution of such locally deployable assistants, especially those that are enhanced by Few-shot prompting to become more explicit, does not only provide some efficiency to the logistics professionals, but provides more. It offers a decision support advocate that can expose complicated situations, enabling consumers to be more discerning and self-assured with answers produced by AI. This may radically evolve in the way practitioners treat problem-solving, changing it from ordinary task automation to actual cognitive augmentation with the AI can be used to explain to the users why given solutions are proposed and thus increase practitioners' expertise and judgment. The emphasis on models that could execute on readily available hardware continues to democratize the access to this next level decision support making it an obtainable commodity for a larger group of the logistics operations and staff.

Such focus on models suitable for local or edge deployment offer significant advantages in terms of data privacy and security as sensitive operational data does not have to leave the enterprise environment to be processed by external APIs. Moreover, local deployment ensures lower latency and offline availability, which can be critical in fast-paced logistics operations. Further testing of the approach on smaller Gemma-3 models could further solidify the feasibility of deployment on readily available hardware, creating a tangible technological pathway for accessible AI support within the logistics sector. The structured datapoint methodology also presents potential for creating reusable knowledge assets for training and grounding AI systems within logistics enterprises.

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Partial Twin – Pragmatic Digital Twin Adoption for SMEs

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Abstract

With the help of digital twins, processes can be simulated and tested in a digital environment prior to conducting real-world tests, which often incur significant costs and use of resources. However, developing digital twins frequently entails complex, customized, and costly implementations, making it an impractical option for many small and medium-sized enterprises (SMEs). This paper proposes the idea for an affordable and easy-to-implement version of the digital twin, particularly tailored for manufacturing sectors, termed the "Partial Twin". The Partial Twin serves as a digital counterpart to a production site or its components, primarily based on numerical data. It aims to strike a balance between simplicity and necessary complexity, ensuring efficient representation and control options while lowering entry barriers. Designed for adaptability, it enables SMEs to incrementally implement digital capabilities, focusing on essential functionalities such as dynamic production planning and optimization. This paper validates the concept through a literature review, explores potential implementation strategies, and outlines the characteristics of the Partial Twin.

1. Introduction

Digital twins have become a widely discussed topic in research, particularly within the manufacturing sector. Jyeniskhan et al. (2024) highlight an exponential increase in publications and citations related to digital twins over the past decade. Furthermore, Alnowaiser and Ahmed (2023) report that from 2017 to 2021, 33% of digital twin research was dedicated to smart manufacturing. A more recent study by Dihan et al. (2024) reveals that 43% of digital twin research originates specifically from the manufacturing domain. Digital twins enable real-time monitoring to support data-driven decision-making, facilitate predictive maintenance to minimize downtime and costs, optimize production processes through simulations, and provide a virtual environment for testing new strategies and designs prior to their implementation (Botín-Sanabria et al., 2022; Dihan et al., 2024; Hakiri et al., 2024; Zhang, 2024, pp. 4–8). As a transformative technology, digital twins have gained significant attention for their promising potential. However, despite their long-term benefits, the comprehensive implementation of digital twin solutions remains challenging. Creating a complete digital twin for an entire production site presents a complex, resource-intensive, and costly undertaking. Key obstacles include the need for specialized expertise, potential investment in new sensors, and additional computational resources (Botín-Sanabria et al., 2022). Consequently, SMEs often hesitate to adopt digital twin solutions for managing their production processes (Hananto et al., 2024; Jyeniskhan et al., 2024; Uhlemann et al., 2017). Nevertheless, like larger enterprises, SMEs also require enhanced digitalization to improve production efficiency. In response to these challenges, several approaches have emerged to make digital twins more accessible to SMEs. For instance, some studies propose a business model for a "Lightweight Digital Twin as a Service" or platform-based solutions aimed at improving cost efficiency (Guo et al., 2023; Marra et al., 2024). Others have focused on making the integration of digital and physical assets easier (Yasin et al., 2021) or examined how a paid "Digital Twin as a Service" offering can reduce entry barriers for SMEs (Schmid et al., 2024). These approaches provide a foundation for developing digital twin models, particularly tailored for SMEs. However, they predominantly emphasize the creation of highly detailed digital twins, which can lead to complexities in implementation and a strong demand for granular data. Furthermore, existing models are typically structured within predefined pricing frameworks that contradict the necessity for cost-effective digital twin solutions for SMEs. To enhance the applicability of digital twins in SMEs, it is crucial to provide multiple development pathways, allowing for greater flexibility and adaptability to various operational needs. Consequently, there is a pressing need for accessible and swiftly deployable solutions to bridge the gap between current operational realities and the envisioned comprehensive digital twin.

Moreover, a recurring challenge highlighted in the literature is the lack of generalizable concepts and standardized interfaces in most digital twin research. This issue, already identified by Kritzinger et al. in 2018, remains unresolved (Alnowaiser & Ahmed, 2023; Botín-Sanabria et al., 2022; Hakiri et al., 2024; Hananto et al., 2024; Kritzinger et al., 2018; M. Liu et al., 2021; Yao et al., 2023; Zhang, 2024, p. 16). That is why, for example, Hananto et al. (2024) suggested introducing a clearer definition for better differentiation within the digital twin domain, e.g., "3D digital twin" for what is commonly referred to as a "digital twin".

This introduction is based on a forward-backward literature review approach. The keywords "Digital Twin" in the context of "Manufacturing Planning" and "Management" initiated the literature search. Targeted combinations of the term "Digital Twin" with keywords such as "application", "integration", "implementation", "development", "technologies" were examined to collect insights based on their practical applications. Additionally, the keyword combination "digital twin" and "SMEs" was used. The resulting research references were the starting point for this forward-backwards search.

According to the identified research gaps, we will follow these research questions (RQ):

- RQ1: How can the digital twin approach for manufacturing be modified and named to provide essential functionalities while ensuring a more accessible, expedited, and cost-efficient implementation for SMEs?
- RQ2: What functionalities should it possess, and what steps are necessary to implement these functionalities?

2. Methods

The literature review has revealed a significant gap between the capabilities of SMEs and the requirements for implementing digital twins in the manufacturing sector. The high initial costs and inherent complexity associated with digital twin adoption often render it impractical for SMEs. To address these challenges, we propose a framework designed to provide an overview of the production site's status while facilitating automated planning and control.

In Section 2.1 we will introduce the fundamental concepts underpinning digital twins. Section 2.2 will define the key properties of our proposed framework, elaborating on its design, functionality, and potential implementation. Furthermore, in Section 2.3, we will position our solution within the digital maturity model of digital twins as articulated by Liu et al. (2024). Finally, Section 2.4 presents potential use cases to enhance conceptual clarity.

2.1. Digital twin

The term "digital twin" can be defined in various ways. Its origins trace back to Dr. Michael Grieves, who first introduced the concept in 2002 (Grieves, 2016). Initially, it was defined within the context of product life cycle management as "a set of virtual information constructs that fully describes a potential or actual physical manufactured product" (Grieves, 2016, p. 2). Today, the digital twin paradigm extends to multiple domains, including supply chain management (Hong Lim et al., 2021), circular economy (Meng et al., 2023), smart cities (Adreani et al., 2023), vertical farming (Monteiro et al., 2018) and 3D-printing (Hananto et al., 2024). Consequently, definitions of digital twins vary significantly. For instance, Dihan et al. characterize it as "a digital copy or virtual representation of an object, process, service, or system in the real world" (Dihan et al., 2024, p. 2). In contrast, Hakiri et al. describe the digital twin as "a virtual replicate of the real-world system that receive data from the physical system and send decisions to perform closed-loop control" (Hakiri et al., 2024, p. 4). A "closed-loop system" allows for bi-directional data exchange between the digital counterpart and the physical entity it represents (Alnowaiser & Ahmed, 2023; Hakiri et al., 2024; Y. Liu et al., 2024). By creating these virtual replicas of physical assets, digital twins facilitate real-time monitoring and analysis of KPIs, enabling informed decision-making. This capability, for example, supports predictive maintenance, which reduces downtime and operational costs. Additionally, digital twins contribute to the optimization of production processes through simulations that identify inefficiencies and potential improvements. They allow organizations to test new strategies and designs in a risk-free virtual environment before implementing them in the physical world (Zhang, 2024, pp. 4–8).

Digital twins can manifest in various forms, such as augmented reality (AR) interfaces or three-dimensional visualizations that mirror their physical counterparts (Mishra et al., 2024, p. 2), and are often recognized as a detailed digital representation of machinery (Hananto et al., 2024). However, formal definitions suggest that a digital twin may encompass a broad array of concepts, including the digital representation of a physical object, a process, or a product (Dihan et al., 2024). Therefore, the notion of a digital twin is expansive, integrating multiple paradigms.

2.2. Partial Twin

To enhance applicability for SMEs, our approach presents a simplified and more targeted version of a digital twin tailored specifically to SMEs in the manufacturing sector. While the broader concept of the digital twin encompasses various industries and highly detailed models, our model focuses on practical, cost-effective solutions that address the challenges faced by smaller manufacturing enterprises. In the future, this approach could potentially be adapted for other domains.

Therefore, we would like to introduce the concept of the “Partial Twin”. This paper outlines an initial framework for this approach and proposes further steps toward its practical implementation. The Partial Twin serves as a streamlined, early-stage alternative to traditional digital twins, providing an accessible and affordable solution for SMEs. By doing so, this research contributes to the development of best practices for adopting digital twins in manufacturing environments of SMEs. The positioning of our approach is depicted in Figure 7.

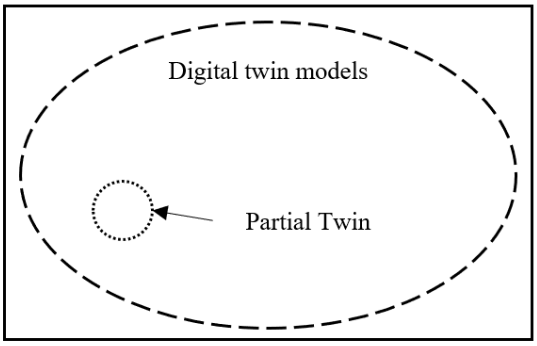

Figure 7: Positioning within the general digital twin approach

2.2.1. General properties

The proposed Partial Twin should be an affordable and easy-to-implement solution for the digital management of production sites. It is meant to provide a digital representation through, specifically KPIs or diagrams, including the ability to control the factory. Unlike most known digital twin models, which offer comprehensive real-time simulations and detailed object behavior often governed by physical laws, the Partial Twin focuses on integrating the data sources into a unified platform, to be used as a tool for automated planning and scheduling optimization. This information should be visible on a schematic overview of the factory by KPIs. Since it covers only a subset of the functionalities typically performed by a digital twin, it is called the “Partial Twin”.

A dashboard also provides detailed insights into the production site, but it lacks the capability to perform simulations or actively manage production processes. This paper makes use of dashboards for comparative purposes. Differentiation of key characteristics for dashboards, Partial Twin and digital twins can be observed in Figure 2 and Figure 3. Accordingly, Figure 2 illustrates the characteristics in a simplified form, while Figure 3 presents a morphological matrix to elucidate the principal attributes of the Partial Twin. The concept aims to combine the intuitive and simplified form of visualization that a traditional dashboard offers, with the advanced planning and management capabilities of a digital twin according to the needs of SMEs (Hananto et al., 2024). The new approach is envisioned as pre stage toward digital twin adoption, offering a practical transition solution for companies not yet ready for the full complexity of digital twins or companies for which a full digital twin would be too excessive. The Partial Twin is a specified version of the digital twin, intended to differentiate it from the broader digital twin concept. The representation should be less detailed as for the original digital twin but still facilitate bi-directional data exchange, thereby functioning as a closed-loop system in the easiest possible way. By providing a flexible platform approach, the framework encourages continuous improvement and allows for the gradual integration of new factory components, thereby enhancing adaptability. It should also serve as guidance for accessing relevant data sources that may already be collecting useful information for constructing the Partial Twin. Additionally, this framework aims to provide differentiation through a clear and new name, addressing the current ambiguity in naming various digital twin technologies (Hananto et al., 2024).

2.2.2. Implementation Ideas

In leading to possible implementation options, it is crucial to keep the perspective of the addressed companies in mind. They are SMEs constrained by limitations, in money, time and expertise regarding implementing a digital twin for factory control. The core idea is to develop a Python framework that defines the necessary interfaces for data access from existing systems, consolidating all important data and allow adaptability, such as adding production components later. The framework should also provide a user-friendly graphical user interface (GUI) that not only displays production metrics, but shows and explains the production plans. An agile approach can facilitate implementation, carefully

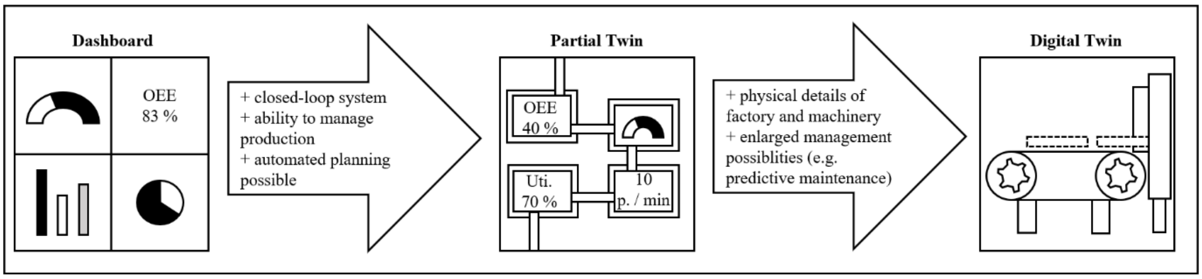

Figure 8: Simple morphology for Dashboard, Partial twin and Digital Twin

considering both associated cost and efforts involved (Beck et al., 2001).

Moreover, it is essential to consider an effective computer architecture to support this framework. Insights from Dihan et al. (2024) can offer further ideas regarding which methods to employ. For centralized data collection, employing a knowledge graph approach may provide a flexible and interconnected method for data storage, enhancing visibility and transparency. Potential downsides, particularly relating to large data volumes and implementation effort needed to set up a knowledge development to identify and address challenges that may arise during implementation.

2.2.3. Implementation phases

The implementation requires developing structured phases, allowing for the gradual integration of the framework. While there is no universally accepted process model for implementing a digital twin, the phases described in the literature exhibit a similar structure and share common steps. Sommer (2024) identified five key phases by analyzing various implementation approaches: "(1)

	Expressions		
Characteristics	1	2	3
Depiction of factory	No depiction of factory	Schematic overview of factory	Mirroring of the machinery / factory quite detailed
Detail of depiction	KPIs / numbers	Diagrams	All physical details of the machine
Detail of machinery shown	None	Machinery icons / sketch	Representation of most physical details and functionalities of machinery
Time reference	Historical view	As close to real-time as possible	Real-time
Closed-loop system / Bi-directional data exchange	No	Yes	
Data requirements	Historical data	Historical & real time data of medium detail	Detailed historical & real time data
Ability to control / manage factory	No	Yes	

Dashboard — Partial Twin — Digital Twin

Figure 9: Morphological matrix comparing Dashboard, Partial Twin and Digital Twin

graph or ontology should be carefully assessed (Dihan et al., 2024; Lippolis et al., 2025; Yang et al., 2025). Furthermore, the creation of an ontology could facilitate condition monitoring similar to models discussed by Cao et al. (2019), while also incorporating planning and control functionalities for production processes. Existing approaches aimed at democratizing digital twins for SMEs (Marra et al., 2024; Schmid et al., 2024; Yasin et al., 2021) should also be carefully examined for potential synergies. Additionally, simulation techniques can be employed for production scheduling to integrate crucial information for improved operational efficiency. By treating the Partial Twin as a dynamic software project, organizations can adopt an agile methodology that embraces iterative development and continuous improvement throughout the implementation journey (Beck et al., 2001). Ideally, example companies should be involved during

Definition/Initiation", "(2) Design/Development/Planning", "(3) Use/Scaling/Implementation", "(4) Controlling/Review/Validation", and "(5) Closing/Lessons Learned". In contrast, (Fett et al., 2023) proposed a more detailed framework consisting of seven "procedure steps" for digital twin modeling, emphasizing the creation process of the digital twin itself. Similarly, (Jin et al., 2024) presented a case study from the additive manufacturing industry, outlining a nine-step implementation process, which provides a more granular perspective compared to Sommer's five-phase approach (Fett et al., 2023; Jin et al., 2024; Sommer, 2024).

Based on these findings, the following five phases are suggested for implementing the Partial Twin:

1. Status quo
2. Design
3. Implementation
4. Operational use
5. Continuous improvement

Initially, the assessment of the **status quo** focuses on identifying existing data sources by examining what data is already collected and where it is obtained. It is essential to define the current landscape of company systems. This is followed by a **design** phase, in which it is defined what additional data should be collected in the future. During this phase, it is critical to identify relevant KPIs and establish how to respond to specific values (e.g., whether they are too high or too low) concerning the factory control system. The subsequent **implementation** phase involves the integration of this data into the model, including establishing connections via APIs and deploying the necessary infrastructure. After implementation, the **operational use** phase begins, during which the digital twin is actively employed to support decision-making processes and optimize workflows. The final phase, the **continuous improvement phase**, focuses on ongoing refinement of the system and the integration of new data sources to continuously enhance efficiency, accuracy and the overall impact of the system.

2.3. Maturity stage of the Partial Twin

To gain a clearer perspective on the capabilities of the Partial Twin, it should be positioned within the "Digital Twin Maturity Model" (DTMM) introduced by Liu et al. (2024). To create their maturity model, they consolidated different maturity models from the literature, based on the capabilities and definitions of different digital twin models. The DTMM defines maturity levels based on a model's capabilities. Here, "capability" encompasses the range of functions a digital representation of an object can perform. The authors categorized them on a **scale from low to high capability**, beginning with the classification "No Twin", which is equal to no capability. According to Lui et al. (2024), the subsequent capabilities on the scale are "Data Management", "Modeling", "Two-way Communication", "Simulation Activities", "Full Life Cycle Management", "Human Machine Interface", "Intelligent" and "Integration". Each level introduces more functions and complexity than the preceding one.

After classifying the models from the reviewed articles according to the capability scale, the authors inferred the following five levels for their DTMM:

- Level 0: Digital Model,
- Level 1: Digital Shadow,
- Level 2: Digital Twin,
- Level 3: Cognitive Digital Twin,
- Level 4: Federated Digital Twin.

A key distinction in this maturity model is that "Digital Model" and "Digital Shadow" feature one-directional data flow, whereas "Digital Twin" incorporates bi-directional data flow. In addition, the "Digital Twin" should cover monitoring and control of the physical counterpart, as opposed to the "Digital Model" and "Digital Shadow". The "Cognitive Digital Twin" and "Federated Digital Twin" level represent more advanced and intelligent versions of digital twins, incorporating greater autonomy, interactivity, and data-driven decision-making capabilities (Y. Liu et al., 2024).

The "Digital Twin" level typically requires the capabilities "Two-way Communication", "Simulation Activities", "Full Life Cycle Management" and "Human Machine Interface". The Partial Twin meets the first two criteria but lacks the latter two. Thus, it qualifies as a digital twin but represents a more specialized variant. This distinction underscores our framework's goal of refining the digital twin concept, aiming to provide a more applicable version for SMEs.

2.4. Example use cases for Partial Twin

The Partial Twin can serve a variety of purposes, including monitoring, analysis, and optimization. Another potential use case for the Partial Twin is the automated planning and optimization of production processes. By creating a Partial Twin of a production line, organizations can analyze real-time data to enhance efficiency, reduce waste, and improve resource allocation. This dynamic model allows for the simulation of different production scenarios, enabling proactive decision-making. In the next step, the prediction of both the current state and future conditions of the factory can be enhanced through the use of machine learning (ML) and artificial intelligence (AI). By leveraging historical and real-time data, ML algorithms can identify patterns and forecast future performance, allowing for timely interventions and minimizing downtime.

3. Results and Discussion

In response to RQ1, this paper presents the concept of a modified digital twin approach termed "Partial Twin". This approach aims to provide a specific digital twin application that enhances the accessibility, expedites implementation and improves cost-effectiveness of digital twin technology in the manufacturing for SMEs. The Partial Twin serves as a digital representation of the factory, incorporating KPIs within a closed-loop system.

To address RQ2, we identify several key attributes essential for the functionalities of our Partial Twin. It must effectively represent a factory digitally through a Python framework, offering a GUI to present an overview of factory and machinery's KPIs, along with a drill-down option for in-depth analysis. The system should be straightforward to implement, utilizing an agile approach. First, a thorough examination of the existing system landscape and the data currently being collected is crucial. This should be followed by a theoretical design of the Partial Twin, where critical KPIs are identified, and additional data requirements are established. Further considerations include configuring the system to determining which areas or components of the production process should be represented in the Partial Twin. After the design phase, the implementation and deployment of the system should commence, leading to its operational utilization and ongoing engagement in a continuous improvement process.

In summary, here is a list with all essential characteristics of the Partial Twin:

- New name for better differentiation: Partial Twin,
- Digital representation of a factory with less detail compared to a full digital twin,
- Closed-loop system facilitating bi-directional data exchange,
- Capable of managing and control the factory or parts of it,
- Python framework (incl. APIs & GUI for overview of the factory and machines)
- Designed for easy implementation by providing guides,
- Focused on continuous improvement with an agile approach.

In Section 2.3, our framework is positioned within a Digital Twin Maturity Model, demonstrating that it qualifies as a digital twin, by definition while also aiding in the differentiation of digital twin models based on their capabilities. Furthermore, Section 2.4 presents example use cases of the framework.

To validate the methodology and approach for developing the framework, existing frameworks, such as those examined by Hakiri et al. (2024), will be evaluated and utilized as foundational references. At this stage, the research remains theoretical and does not yet have direct practical applications. Future work will focus on prototypical implementation and testing within a company environment.

A critical aspect requiring further exploration is the precise definition of the tasks the Partial Twin should support, such as production planning. Additionally, during the setup and implementation phases, it will be essential to identify which data and data sources are crucial at different maturity stages of the Partial Twin. Enhanced differentiation in these stages could provide entry points for companies at varying levels of digitalization.

Moreover, considerations regarding the trustworthiness of digital twin models, as highlighted in recent studies (Hakiri et al., 2024; Kumar & Agrawal, 2024; Y. Liu et al., 2024), will play an integral role in our framework.

One notable limitation is the potential lack of internal access to company systems, which may complicate the frameworks development. However, this challenge also serves as motivation to maintain a generalized approach. It is essential to recognize that the successful adoption of digitalization in production heavily relies on the management's willingness to invest in these initiatives. While streamlining the implementation process is vital, a certain commitment will always be necessary. Nevertheless, the iterative approach should aim at achieve quick wins fostering ongoing engagement. Effective data pipelines are crucial; without some degree of prior digitalization of the factory, the proposed framework cannot function effectively. It also is important to note that cultural factors related to user acceptance, which are critical during the implementation of new software systems, have not been addressed in this study (Wallace & Sheetz, 2014). Conversely, the opportunities presented by this research include the facilitating a continuous improvement process that can enhance acceptance among users, as their familiarity with the software grows alongside its impact on their work. Additionally, the framework promotes easier access to advanced planning methods, promoting diversity within the organizational landscape and aiding smaller enterprises in catching up. Overall, these findings provide valuable insights for integrating the Partial Twin into manufacturing processes for SMEs and contribute to establishing competitive advantages in an increasingly digitized economy.

4. Limitations and Conclusion

In summary, the most significant outcome of this research is the introduction of the "Partial Twin" approach, designed to facilitate the adoption of digital twin technologies by SMEs. A primary distinguishing feature of the Partial Twin is its less intricate design compared to most established digital twin models. It emphasizes the display of essential KPIs of a factory while still progressing towards a closed-loop system. With its agile methodology, this approach provides a more accessible and straightforward alternative to traditional digital twin implementations, thereby enabling SMEs to engage with and adopt it successfully. Ultimately, it aims to enhance their competitiveness in an increasingly digitized marketplace.

One limitation of this work is that successful digitalization in production is heavily reliant on management's willingness to invest in such initiatives. While streamlining the implementation process is essential, some effort will always be required, necessitating an iterative approach focused on achieving quick wins to maintain engagement. This paper presents the theoretical idea for a framework and highlights the need for further research and future implementation.

Future research will focus on several critical next steps to advance and implement the Partial Twin framework. Initially, a prototype will be designed in collaboration with industrial partners to gather real-world experiences, which will subsequently be synthesized into guidelines and best practices that facilitate learning from past challenges. A fundamental aspect of this research will involve identifying criteria that delineate when a Partial Twin has reached sufficient maturity and when it should transition into a full digital twin, particularly as production sites or the complexity requiring management by the system increases. Additionally, the research may yield a generalizable framework if the prototype proves successful. From a practical perspective, this research holds promise for creating tangible use cases within companies to support SME manufacturing firms. Investigating effective methods to integrate AI into the Partial Twin, as highlighted by (Alexopoulos et al., 2020) will also be essential.

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Development of the logistics industry in the Kyrgyz Republic: prospects and challenges

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Abstract

The article is devoted to the state and development of the logistics industry in Kyrgyzstan in 2024, with an emphasis on the introduction of modern technologies and principles of sustainable development. Key technological trends such as artificial intelligence (AI), the Internet of Things (IoT), blockchain, as well as automation and digitalization of logistics processes are considered. Particular attention is paid to successful companies and initiatives that influence the increase of efficiency and sustainability of logistics operations. The article also analyzes the role of international exhibitions, such as KyrgyzTransLogistic 2024, in strengthening Kyrgyzstan's position in the global logistics arena and improving infrastructure. Challenges and opportunities for further development of logistics are considered, including maintaining environmental sustainability and deepening international logistics links.

1. Introduction

In the context of rapid technological progress and globalization, logistics has become a key sector of the global economy, including in countries like Kyrgyzstan. The efficient organization of logistics processes is becoming an important competitive advantage for both businesses and the state as a whole. In recent years, Kyrgyzstan has witnessed active development in the logistics industry, including the implementation of innovative solutions such as artificial intelligence (AI), process automation, the Internet of Things (IoT), and blockchain. These technologies contribute to increased efficiency, cost reduction, and improved service quality, which are critically important in a rapidly changing market environment.

This article places particular emphasis on the sustainable development of Kyrgyzstan's logistics sector. There is a growing interest each year in environmentally friendly solutions, such as the use of electric vehicles and supply chain optimization. It is important to note that logistics in Kyrgyzstan not only supports internal processes but is also actively integrating into international supply chains, which significantly impacts the country's overall economy. Logistics companies, striving for innovation, continue to expand their capabilities, implement digital solutions, and participate in international exhibitions and forums such as KyrgyzTransLogistic 2024. This underscores the importance of the sector for both business and national economic policy.

The main objective of this article is to analyze current trends in Kyrgyzstan's logistics industry, identify innovative solutions, and assess their impact on the development of the sector in 2024.

2. Current Trends in Kyrgyzstan's Freight Transport Market: Analysis and the Role of KyrgyzTrans-Logistics

Freight Transport Dynamics: Imports Rise, Exports Slow Down. According to the international freight exchange ATI.SU, the year 2024 has seen a significant increase in imports to Kyrgyzstan — the number of freight delivery requests from abroad grew by 37% compared to 2023, with a 105% increase recorded in the fourth quarter alone. The main import flows came from Russia, Belarus, Kazakhstan, as well as European countries such as Lithuania, Poland, and the Netherlands. This continues a trend that began in 2022, although the growth rate is starting to slow down.

At the same time, export shipments showed only a 6% increase over the year, which is a sharp contrast to the 67% growth observed the year before. The most notable decline occurred in the fourth quarter, with a 30% drop. Meanwhile, export freight rates rose by 36%, reflecting growing complexity in logistics operations. Among the destinations showing positive dynamics, Belarus stood out with a 115% increase, though the overall volumes remain low. Russia and Kazakhstan did not show any growth.

3. Domestic Market: Doubling in Groth and Transition to Digital Solutions

Domestic freight transportation in Kyrgyzstan doubled by the end of 2024. This growth is attributed to the low base effect and the increasing demand for transportation driven by the development of trade and industry. However, most local companies still rely on traditional communication methods — phone calls and messaging apps — although there is growing interest in digital platforms and the automation of logistics processes.

According to Emirlan Beyilbayev, Director of the ATI.SU office in Kyrgyzstan, the market is entering a phase of moderate growth following a sharp restructuring of logistics flows triggered by international sanctions in 2022. The slowdown in exports, particularly on the Russia–Kyrgyzstan route, is linked to the complications of payment operations under sanction pressure, despite the flexible stance of Kyrgyzstan’s banking system (economist.kg, 2025).

4. KyrgyzTransLogistic 2024: A Platform for the Future of Kyrgyzstan’s Logistics

The launch of the first international specialized exhibition, KyrgyzTransLogistic 2024, marked a significant milestone in the development of Kyrgyzstan’s transport and logistics sector. Given the country's strategic location at the crossroads of trade routes between Asia and Europe, logistics is becoming a key focus of national economic policy.

The event demonstrated strong interest from businesses, government authorities, and international partners. The exhibition served not only as a business platform but also as a tool for strengthening connections, exchanging expertise, and showcasing innovative solutions in transportation, logistics, and warehousing.

5. Significance for the Economy and Business

Participation in KyrgyzTransLogistic offers the opportunity to:

- Showcase the latest technologies and solutions in logistics to a wide audience,
- Attract investments and business partners,
- Stimulate exports and the development of the manufacturing sector,
- Create jobs and boost business activity.

The exhibition contributes to unlocking Kyrgyzstan’s logistics potential and strengthens the country's image as a reliable transit and trade partner (logisticexpo.kg, 2024).

6. The Role of the Government and Integration Efforts

Government bodies are actively supporting the development of logistics infrastructure. In recent years, large-scale projects have been implemented, including road construction, warehouse modernization, and the rehabilitation of international routes. These initiatives not only strengthen the economy but also enhance the country’s appeal as a transit hub.

Ministries involved in the sector emphasize the importance of the exhibition as a mechanism for shaping a sustainable financial and logistics environment. Infrastructure initiatives, export support, simplification of customs procedures, and improvements in tax policy are becoming key components in building a comprehensive logistics ecosystem.

7. The Contribution of the Capital and the Customs Service

Bishkek, as the logistics center of the country, is actively modernizing its transportation infrastructure. In 2024, extensive roadworks were carried out and new logistics hubs were established, enabling the capital to play a key role in the development of transport corridors.

The customs service, for its part, is actively engaging with the logistics sector, implementing more transparent and digital procedures. The discussion of new strategies during the exhibition was an important step toward creating a fast and efficient system for goods movement.

8. Blockchain in Logistics: Enhancing Transparency and Security

The blockchain technology market in supply chains continues to grow rapidly. According to a report by Market Research Future, the projected compound annual growth rate (CAGR) is 45.55% from 2023 to 2030, confirming the increasing interest in this innovation within the logistics sector. Blockchain is becoming a key element in enhancing the transparency and security of supply chains.

The main advantage of blockchain lies in its ability to assign a unique digital identity to every product. This allows for tracking the origin of goods, their history, production details, and certifications, significantly increasing the level of trust among supply chain participants. The use of blockchain enables real-time tracking of goods from the supplier to the end consumer, while also minimizing the risk of data manipulation.

Additionally, blockchain facilitates the automation and acceleration of processes through the use of smart contracts. These contracts execute predefined conditions automatically, without the need for manual intervention, which significantly reduces administrative costs and minimizes risks.

9. Blockchain Applications in Logistics

Many major companies have already begun implementing blockchain technologies to improve data visibility and transparency. For example, Maersk has partnered with IBM to create the blockchain platform TradeLens, which enables real-time tracking and data sharing about shipments, while also drastically reducing paperwork.

Another prominent example is Walmart's collaboration with IBM on the Food Trust system, which tracks the movement of food products from suppliers to stores. This significantly speeds up data processing and verification, and improves food safety — a particularly important factor in the retail industry.

Blockchain continues to gain popularity due to its ability to provide secure and transparent data exchange, which plays a crucial role in improving customer service and reducing costs for companies. In an era of expanding global supply chains and increasing data volumes, blockchain has a significant impact on enhancing the efficiency and security of logistics operations.

10. Kyrgyzstan Leads in Freight Market Growth Among EAEU and Central Asian Countries

In January–February 2024, freight turnover in Kyrgyzstan increased by 8.8%, significantly surpassing the average growth rate of 0.9% across EAEU countries. Passenger turnover also showed the highest growth in the union — 11.2%. Experts note a growing demand for international road transportation, particularly in the direction of Russia. In the first quarter of 2024, the number of freight delivery requests from Kyrgyzstan to other countries rose by 72%, while average prices increased by 40%.

Digitalization is a key area for the development of the logistics sector. Within the framework of cooperation with Germany, successful examples of digital logistics solutions have been discussed, such as online vehicle booking and tracking systems.

Kyrgyzstan is also developing digital services in its own market, where it is already possible to find carriers online. However, many freight operators and cargo owners still rely on traditional methods, which slows down the digitalization process.

Road infrastructure development plays a crucial role in improving logistics. In 2024, the construction of 500 kilometers of new roads is planned, including the reconstruction of key sections, which will increase transit capacity and enhance regional connectivity.

Customs procedure efficiency has also improved due to the implementation of digital platforms. The AIS "Sanarip Tamga" system speeds up border processing, while the new feature for registering goods and vehicles on the "Smart Bazhy" platform simplifies and automates operations at checkpoints (ATI.SU, 2024).

11. Kyrgyzstan Ranks 128th in the World Bank's 2024 Logistics Performance Index

Kyrgyzstan ranks 128th in the World Bank's 2024 Logistics Performance Index (LPI), according to information on the LPI website. The LPI score for Kyrgyzstan is 2.3, placing the country between Burkina Faso and Mauritania. The lowest scores for Kyrgyzstan were noted in customs facilitation and competitiveness. In 2023, Kyrgyzstan held the 123rd position with the same score of 2.3.

Among the CIS and EAEU countries, Kazakhstan has the highest index, while Kyrgyzstan has the lowest.

The Logistics Performance Index is a ranking system used for comparative analysis of the effectiveness of logistics systems worldwide. It has been compiled by the World Bank since 2007 based on a global survey of logistics operators. The index measures performance across the entire supply chain in a country.

The index includes parameters such as:

- The efficiency of customs clearance processes,
- The quality of trade and transport infrastructure,
- The ease of organizing deliveries at competitive prices,
- The competence and quality of logistics services,
- The ability to track shipments,
- Timeliness of delivery to the destination (24.kg, 2024).

12. Recommendations for Further Development of Kyrgyzstan's Logistics Sector

For the successful development of Kyrgyzstan's logistics sector in 2025, it is important to focus on the following aspects:

Innovative Technologies: Continue the implementation and use of AI and automation to enhance the efficiency of all stages of the logistics chain.

Environmental Sustainability: Increase the number of environmentally friendly vehicles, develop infrastructure for electric vehicle charging stations, which will help minimize the negative impact on the environment (Glistau und Coello Machado, 2019).

International Cooperation: Strengthen partnerships with neighboring countries and expand delivery capabilities through international channels (economist,kg, 2025).

13. Conclusion

In 2024, Kyrgyzstan's logistics sector demonstrated significant progress by actively adopting innovative technologies and focusing on sustainable development. Companies such as KyrgyzTransLogistic, Oasis Logistics, and other industry leaders are successfully adapting to new challenges and using modern tools like artificial intelligence, blockchain, and automation to optimize their processes. The application of these technologies improves service quality and enhances competitiveness on the international stage. However, for further growth, it is important to continue efforts in digitalization, infrastructure development, and strengthening international ties. It is forecasted that in 2025, Kyrgyzstan's logistics sector will continue to grow, actively implementing innovations and improving environmental sustainability. As a result, the country will strengthen its position as a key player in international logistics, creating stable and efficient logistics processes for businesses and the economy as a whole.

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The relationship between ESG systems and logistics

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Abstract

The emergence of the ESG (Environmental, Social, Governance) framework offers an integrated approach that enables the coordinated management of environmental, social and corporate governance aspects, thereby contributing to ensuring the long-term sustainability and competitiveness of companies. The ESG framework, as an approach integrating environmental, social and corporate governance aspects, forms the basis of sustainability research. The logistics application of ESG aspects not only helps to achieve sustainability objectives, but also contributes to increasing economic performance (Carbone & Moatti, 2021). Recycling processes and life cycle assessment (LCA) are key elements in the practical implementation of ESG goals, enabling the reduction of environmental impacts of supply chains and long-term sustainability strategic planning. Logistics processes, as functions forming the backbone of the global economic system, play a key role in the implementation of sustainability goals. Optimizing supply chains, operating transport networks in an energy-efficient manner, and integrating waste management strategies have significant potential to reduce the environmental footprint. Recycling and the application of Life Cycle Assessment (LCA) play a particularly important role in these processes, as they provide an opportunity to evaluate and develop logistics chains from a comprehensive sustainability perspective.

1. Introduction

Over the past decade, the issue of sustainability has become a defining element of academic and economic dialogue, with a particular focus on global environmental and social challenges, such as climate change, overuse of resources, and the need to transform supply chains for sustainability. The emergence of the ESG (Environmental, Social, Governance) framework offers an integrated approach that allows for the coordinated management of environmental, social and governance aspects, thus contributing to ensuring the long-term sustainability and competitiveness of companies.

The ESG framework is the basis of sustainability research as an approach that integrates environmental, social and governance aspects. The logistical application of ESG considerations not only helps to achieve sustainability objectives, but also contributes to increasing economic performance (Carbone & Moatti, 2021). Recycling processes and a life-cycle approach (LCA) are key elements in the practical implementation of ESG goals, enabling the reduction of the environmental impact of supply chains and long-term strategic sustainability planning.

Logistics processes, as the backbone of the global economic system, play a key role in achieving sustainability goals, especially through Industry 4.0 technologies (Cservenák, 2021a & Cservenák, 2021b). Optimising supply chains, operating transport networks in an energy-efficient way, and integrating waste management strategies have significant potential to reduce the environmental footprint. Recycling and the application of Life Cycle Assessment (LCA) play a particularly important role in these processes, which provide an opportunity for the comprehensive sustainability evaluation and development of logistics chains.

2. Methodology

Systematic approach to literature research

The aim of the systematic literature review is to provide a comprehensive and reliable picture of the relationship between relevant concepts and methodologies in the field of sustainability and logistics management, with a special focus on ESG, recycling, life cycle approach and logistics networks. The research method is based on the guidelines of PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), which ensure the transparency, reproducibility and scientific basis of literature research.

The literature search relied on the following three extremely important scientific databases: Scopus, Web of Science and Google Scholar. These sources have been selected to ensure that the highest quality and most recent publications are included in the analysis. These three databases cover a wide range of professional articles, studies and conference proceedings published on the topics of sustainability research, logistics and environmental management, including peer-reviewed and high-impact journals.

Search strategies

Systematic search used a keyword-based approach aimed at identifying the publications most relevant to the topic. The keywords used were grouped around the terms ESG, recycling, life cycle assessment, logistics networks and sustainability. We used each keyword both independently and in combination, for example:

- "ESG AND logistics networks" (Figure 1),
- "sustainability AND life cycle assessment" (Figure 2),
- "recycling AND logistics optimization" (Figure 3).

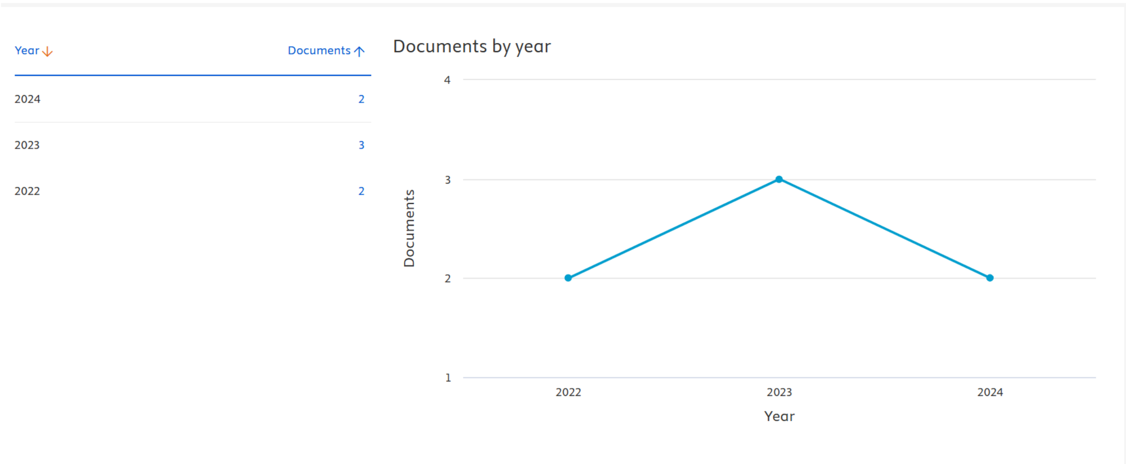

Figure 10: Search results in the Scopus database for "ESG AND logistics networks"

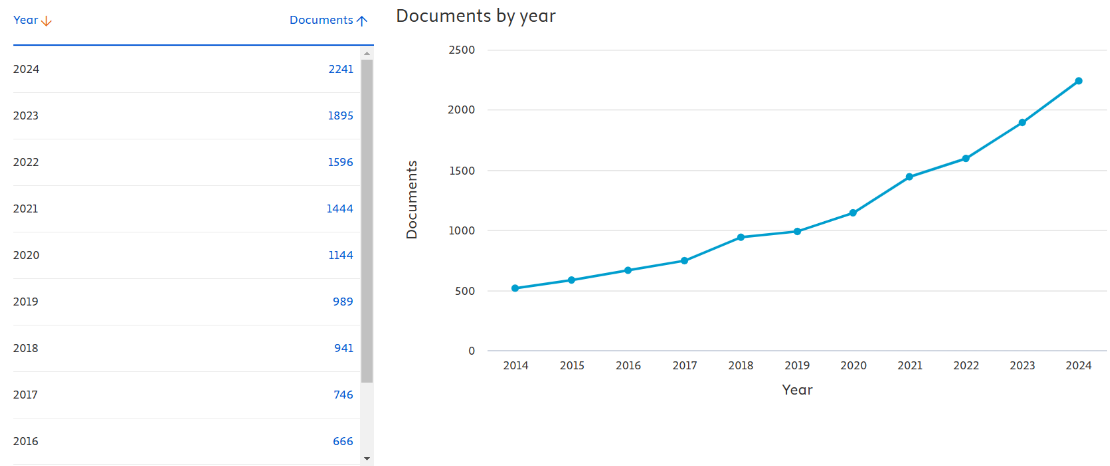

Figure 11:. Search results in the Scopus database for "sustainability AND life cycle assessment"

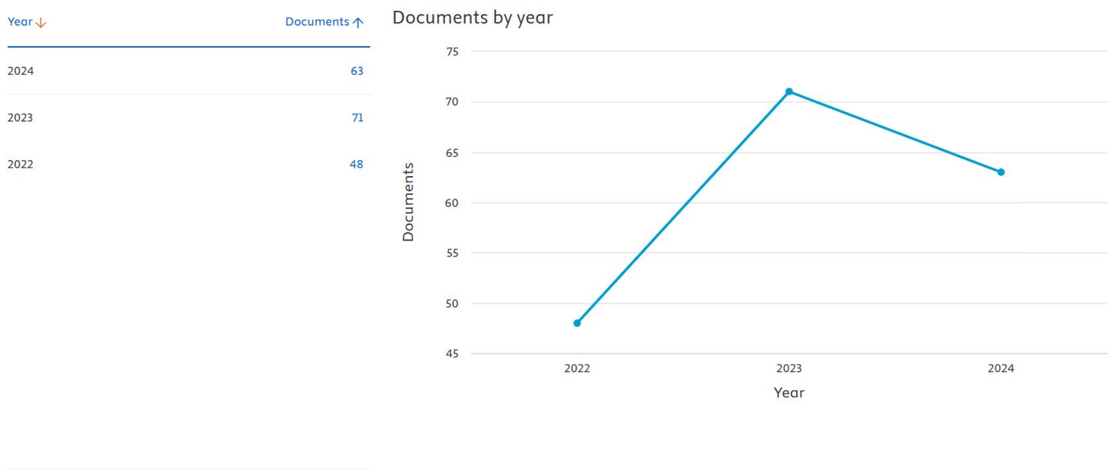

Figure 12: Search results in the Scopus database for "recycling AND logistics optimization"

The timeframe was set between 2014 and 2024, as sustainability and ESG topics have become the focus of scientific and practical attention in the last decade. The selection of the period allowed us to identify the latest research results and trends.

Filter criteria included:

- Only professionally peer-reviewed studies and articles are included.
- Selection of publications that are directly related to the keywords you entered.
- Analysis of publications in English only, as this ensures international relevance.

Selection of publications

The relevance of the publications was pre-evaluated on the basis of titles, abstracts and keywords. Of the more than 1000 publications identified during the search, only the most relevant studies were included after pre-screening. The criteria used during the pre-screening were the following:

1. Related: Only studies that directly touch on ESG, recycling, lifecycle approach, or logistics networks were included.
2. Innovative approach: We have chosen studies that propose new methods, tools or approaches to address sustainability issues.
3. Detail of results: We only examined articles that contain detailed empirical results or theoretical frameworks.

A thorough evaluation of the full text of the publications selected for final analysis ensured that the content of the studies was aligned with the research objectives. During the thorough text analysis, we paid attention to the following aspects:

- Methodology and research framework.
- Key findings and conclusions.
- Practical and theoretical contribution to the development of sustainable logistics.

Reports and data collection

The information extracted from the databases was recorded in a tabular form, which includes the title of the publication, the name of the author(s), the year, the place of publication and the analysed topic area. This made it possible to comprehensively examine the correlations between the publications, as well as to analyze the research trends and shifts in emphasis related to the keywords. The data collected in this way formed the basis of the next chapter, which contains the systematic processing of the literature.

3. Literature review

3.1. The relationship between ESG and the environment

The ESG (Environmental, Social, Governance) framework has become one of the most important cornerstones of sustainability over the past decade, especially in the environmental dimension. Environmental protection is one of the most critical elements of ESG, which includes reducing energy consumption, minimizing carbon emissions, and improving waste management and recycling systems (Kolk & Pinkse, 2015). ESG assessments not only support the achievement of sustainability goals, but also bring direct economic benefits. Research by Friede et al. (2015) has shown that companies with high ESG ratings perform better financially, which is particularly important for investors.

In the development of sustainable logistics networks, more and more attention is paid to innovative technologies such as artificial intelligence (AI) and the Internet of Things (IoT). These tools help integrate energy-efficient transportation solutions and recycling systems, which significantly improve ESG performance (Yadav et al., 2021). Blockchain technology also plays an important role in ensuring data security and traceability (Azzi et al., 2020).

Logistics networks and ESG performance

The logistics sector plays a particularly important role in achieving ESG objectives, as global transport networks have a significant environmental impact. Sustainability strategies, such as green transportation, energy-efficient storage, and the use of alternative fuels, contribute significantly to improving ESG performance. Paulraj et al. (2017) emphasized that the use of sustainable sourcing practices not only helps to reduce the carbon footprint but also contributes to cost optimization. In addition, according to research by Banerjee et al. (2019), increasing the ESG rating of logistics processes strengthens the reputation and long-term competitiveness of companies.

Innovations to achieve ESG goals

Innovative technologies have brought significant progress in ESG assessment. A study by Yadav et al. (2021) showed that artificial intelligence and machine learning algorithms used to optimize supply chains can predict sustainability risks, thereby enabling companies to achieve ESG goals more effectively. According to Lee et al. (2020), IoT technologies integrated into ESG assessment help optimize logistics networks with real-time data, thus reducing the environmental impact

3.2. Recycling and life-cycle approach in logistics

The role of recycling in logistics chains

Recycling is one of the most important elements of sustainable supply chains. According to Zhao et al. (2020), the logistics integration of recycling can reduce the carbon footprint of the supply chain by up to 25%, while significantly increasing economic efficiency. In addition, recycling creates an opportunity to recycle resources, which reduces the demand for raw materials and promotes the implementation of a circular economy model.

Application of a Life Cycle Approach (LCA)

The life-cycle approach examines the environmental impacts of the entire lifecycle of products and services, from raw material extraction to disposal. Baumann and Tillman (2019) pointed out that the application of LCA helps decision-makers to incorporate sustainability aspects into the design of logistics systems. LCA also supports the implementation of sustainable practices in procurement, manufacturing and distribution processes.

Recycling and LCA integration

The integration of recycling and LCA is particularly important in the development of sustainable logistics systems. A study by Gu et al. (2020) showed that recycling processes supported by the LCA framework not only increase the efficiency of waste management, but also result in significant economic savings. According to the research of Santos et al. (2022), the combined use of LCA and decentralized recycling centers helps to increase the flexibility of logistics networks.

3.3. The role of networks in sustainable logistics

Optimizing logistics networks with the integration of ESG aspects is particularly critical to achieving sustainability goals. According to a study by Liu et al. (2020), the introduction of decentralized recycling centers and the use of electric vehicles can result in significant environmental impact reductions.

Sustainable Logistics Network Design

Developing sustainable logistics networks is one of the most effective ways to minimize environmental impact. According to research by Cruz et al. (2017), electric vehicles and energy-efficient transportation networks significantly reduce the carbon footprint of the supply chain. Such technologies not only improve environmental sustainability, but also contribute to cost optimization.

Connections between networks and recycling

When designing sustainable logistics networks, the integration of recycling centers is of paramount importance. Santos et al. (2022) have shown in their case study that the use of decentralized recycling centers improves the efficiency of recycling resources while reducing waste-related costs. Such centers contribute to increasing the flexibility and sustainability of logistics processes.

3.4. Common intersections of ESG, logistics and environmental protection

Optimising logistics processes through an ESG assessment enables the implementation of sustainability goals more efficiently. Transportation networks powered by AI and IoT devices provide real-time data that helps minimize energy consumption and reduce carbon footprint (Santos et al., 2022).

Integration of ESG assessment into logistics processes

Introducing ESG assessments into logistics processes allows companies to consistently monitor their sustainability performance as well as improve the management of the environmental impact of the supply chain. In their study, Lee et al. (2020) showed that the use of ESG rating systems not only plays a key role in improving the environmental performance of companies, but also aids decision-making. For example, green logistics strategies implemented on the basis of an ESG assessment can help reduce waste, increase energy efficiency and minimise carbon emissions.

Another study (Carbone & Moatti, 2021) highlighted that integrating ESG assessments into logistics systems significantly increases transparency at all stages of the supply chain. This is especially important for global logistics networks, where transparency is critical to compliance with environmental regulations.

Innovations in green logistics

Innovations such as artificial intelligence (AI) and the Internet of Things (IoT) have revolutionized the way sustainable logistics systems are designed and operated. According to Yadav et al. (2021), IoT technologies provide real-time data that allows you to optimize energy use and minimize waste. The real-time data collected by IoT devices helps optimize transport routes and reduce vehicle fuel consumption, thereby improving ESG performance. Additionally, a study by Azzi et al. (2020) pointed out that predictive analytics and artificial intelligence can help achieve ESG goals by predicting supply chain risks, such as overconsumption or inventory shortages. Blockchain technology also plays an important role in the development of sustainable logistics systems by guaranteeing data security and improving traceability in ESG assessments.

Sustainable logistics and ESG performance

Aligning logistics processes with the ESG framework plays a central role in the success of sustainability strategies. Banerjee et al. (2019) highlighted that green logistics solutions, such as the use of alternative fuels and electric vehicles, significantly increase corporate sustainability based on ESG assessments. Another research (Sarkis et al., 2022) showed that the use of sustainable transport solutions can reduce carbon emissions from the transport phase by up to 40%, which directly contributes to the achievement of ESG objectives.

Furthermore, according to research by Liu et al. (2020), sustainable logistics strategies, such as optimizing return processes and integrating recycling centers, improve ESG performance in the long term. These strategies not only minimize environmental impacts, but also result in cost savings and enhanced corporate reputation.

4. Detailed literature processing for keywords

4.1. ESG (Environmental, Social, Governance)

The ESG framework combines three key dimensions: environmental, social and corporate governance. An integrated approach to these ensures the realization of the long-term goals of sustainability.

Theoretical background: The concept of ESG appeared in the 1990s, but has become dominant in the last decade. A meta-analysis by Friede et al. (2015) looked at more than 2000 empirical studies and concluded that the integration of ESG aspects has a positive impact on companies' financial performance.

Research examples:

- **Kolk and Pinkse (2015):** They examined the effectiveness of environmental policies of multinational companies and found that ESG performance increases investor confidence.
- **Carbone and Moatti (2021):** They analyzed the relationship between ESG reporting and corporate transparency, highlighting the importance of digital transformation.

Practical relevance: The ESG framework is particularly important in the logistics sector, as transport has a significant environmental impact. ESG rating systems allow you to monitor sustainability performance while contributing to the development of energy-efficient logistics networks.

4.2. Recycling

Recycling is a key element of sustainable development, which aims to use resources more efficiently and optimise waste management.

Theoretical background: Recycling is the cornerstone of the circular economy model, which minimizes the amount of waste and maximizes the reusability of materials. The integration of recycling into logistics chains offers an opportunity to achieve cost-effectiveness through waste reduction and resource conservation (Zhao et al., 2020).

Research examples:

- **Gu et al. (2020):** A life-cycle assessment of plastics recycling practices was conducted, highlighting that mechanical recycling can result in significant carbon reductions.
- **Santos et al. (2022):** They investigated a decentralized network model for recycling centers that improves supply chain resilience.

Practical significance: The integration of recycling systems in logistics chains makes it possible to achieve sustainability goals. For example, recycling electric vehicle batteries has not only environmental but also economic benefits.

4.3. Life Cycle Assessment (LCA)

The lifecycle approach is an essential tool for the sustainability analysis of supply chains, which examines the entire life cycle of products and services.

Theoretical background: The LCA methodology is based on ISO 14040 standards and allows for a holistic assessment of environmental impacts from raw material extraction to waste management (Baumann & Tillman, 2019).

Research examples:

- **Baumann and Tillman (2019):** Analysis of the advantages and limitations of the application of the LCA methodology in logistics systems.
- **Cruz et al. (2017):** Life cycle analysis of sustainable logistics networks was carried out, highlighting the importance of the integration of electric vehicles and renewable energy sources.

Practical significance: The application of LCA enables logistics decision-makers to minimize environmental impact at all stages of the supply chain, for example through energy-efficient transportation strategies.

4.4. Logistics and networks

Optimising logistics networks is central to achieving sustainability goals, as they are the backbone of global economic systems.

Theoretical background: The sustainability design of logistics networks includes the integration of energy-efficient modes of transport, regional warehouses and recycling centres.

Research examples:

- **Sarkis et al. (2022):** The impact of integrating ESG considerations on logistics network design was examined, emphasizing the importance of green logistics.
- **Paulraj et al. (2017):** The impact of sustainable procurement practices and logistics networks on performance was analyzed.

Practical relevance: Energy-efficient warehousing and transportation solutions not only help reduce the carbon footprint, but also provide economic benefits, such as cost savings and greater supply chain flexibility.

5. Analysis of publication trends

The number of scientific publications on ESG, recycling and life cycle (LCA) has been steadily increasing over the past decade. The analysis of the trends was based on the Scopus database, which presents the publication frequencies for the period 2014-2024 as shown in Figure 4. The growth is driven by a growing scientific and economic interest in sustainability, coupled with the development of a wide range of industry applications.

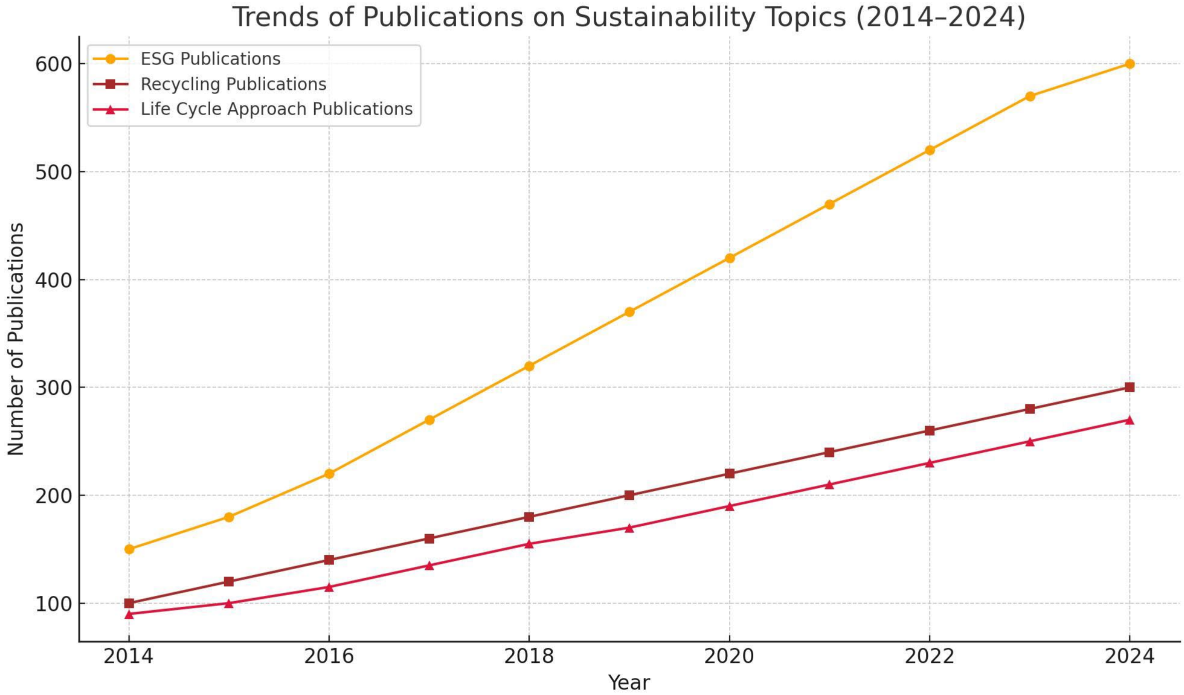

Figure 13: Publication trend on Sustainability topics for the period 2014–2024 based on the Scopus database

Table 1: Trends in sustainability publications (2014-2024)

Year	ESG publications	Recycling publications	Life-cycle approach publications
2014	150	100	80
2015	180	120	90
2016	200	130	100
2017	250	150	120
2018	300	180	140
2019	350	200	160
2020	400	220	180
2021	450	240	200
2022	500	260	220
2023	550	280	240
2024	600	300	260

Based on Figure 4, the Table 1 illustrates the annual growth of publications in the topics of ESG, recycling and lifecycle.

- ESG: The number of ESG-related publications is expected to increase from 150 in 2014 to 600 by 2024. This reflects the rapid spread of the integration of ESG frameworks and sustainability principles at the company level.
- Recycling: The number of studies on recycling processes increased from 100 in 2014 to 300 in 2024. Growth was driven by the growing popularity of circular economy models.

Life Cycle Approach (LCA): The number of LCA publications increased from 80 in 2014 to 260 in 2024, reflecting the growing need for sustainable product design.

5.1. Analysis

ESG topic

The number of ESG-related publications has grown exponentially in recent years, indicating that sustainability issues are becoming increasingly important. The popularity of the ESG topic was influenced by the following factors:

- International regulations: ESG considerations have been incorporated into many corporate reporting systems, such as the European Union's Taxonomy system.
- Investor attention: The importance of ESG ratings in financial decision-making has increased, especially with the rise of green bonds and sustainability funds.

Recycling topic

The steady growth of publications on recycling indicates that the industrial and academic spheres are paying increased attention to resource efficiency. Highlights:

- Waste management innovations: Advances in recycling technologies, such as the recycling of electric vehicle batteries.
- Circular economy: Integrating recycling into the sustainable operation of supply chains.

Life Cycle Approach (LCA)

The popularity of the LCA methodology as one of the most important tools for sustainability assessment has shown stable growth. Applications of LCA include:

- Sustainable product design: LCA allows the environmental impact of a product's entire life cycle to be minimized.
- Regulatory compliance: Life cycle assessment is increasingly used in international regulatory frameworks, such as ISO 14040 standards.

5.2. Conclusions

Based on the analysis of publication trends, the growing interest of researchers can be clearly observed in the fields of ESG, recycling and life cycle approach. Analyses show that collaboration between industries and academia plays a significant role in achieving sustainability goals. The charts and reports visually support the fact that the directions of the research are focused on the integration of ESG frameworks at the company level, the development of recycling and the practical application of LCA. These trends are expected to continue in the coming years, creating new opportunities for sustainability management research and application.

6. Summary

Over the past decade, sustainability issues have become a focus of academic and business life, especially due to the need to address global environmental and social challenges. The approach to sustainability is built around the ESG (Environmental, Social, Governance) framework, recycling and Life Cycle Assessment (LCA), which are closely linked to logistics management. The ESG framework, which incorporates environmental, social and governance aspects, is an essential tool for corporate integration of sustainability goals. The environmental component is particularly pronounced in the logistics sector, which has a significant impact on energy consumption, emissions and waste management. Optimisation of logistics networks, such as green transport solutions and energy-efficient warehousing, directly contribute to increasing ESG performance.

Recycling and a life-cycle approach are also key elements in the development of sustainable supply chains. The integration of recycling into supply chains allows for a reduction in waste and a more efficient use of resources, which also brings economic benefits. The LCA methodology helps to comprehensively assess the environmental impact of products and services throughout their life cycle, with a particular focus on the extraction of raw materials to disposal after use. These tools also play a key role in the sustainability redesign of logistics networks, contributing to reducing the environmental impact of supply chains and achieving sustainability goals.

An analysis of scientific publications has highlighted that interest in ESG, recycling and life-cycle approaches has increased significantly over the past decade. The number of ESG publications has increased by an average of 15% per year, reflecting the increased integration of sustainability principles into corporate strategies. Publications on recycling have also shown a steady rise, especially due to the popularity of circular economy models. The steady growth of LCA publications indicates that life cycle analysis has become an increasingly important tool in the planning of sustainable product design and logistics strategies. Analyses show that these research areas are not only important for environmental protection, but also increase economic performance and competitiveness.

The integration of the ESG framework, recycling processes and the LCA methodology are all essential in the design of sustainable logistics networks. These tools enable companies to achieve sustainability goals and also gain economic benefits, for example through cost-efficiency and increased consumer confidence. The analyzed publications clearly pointed out that through the mutually reinforcing effect of sustainability efforts and logistics innovations, both the industrial and academic spheres can achieve significant results in the long run. This systematic review can contribute to a deeper understanding of the logistical aspects of sustainability and to set the direction for further research

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Financial sustainability of higher education institutions and its impact on the quality of higher education in the Kyrgyz Republic

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Abstract

The article is devoted to the problem of reforming the system of financing higher education in the context of achieving compliance with international standards of quality of education. Based on the analysis of the main foreign models of financing state universities, the prospects of using a model focused on the status of a university in Kyrgyzstan proven. Applying foreign experience in financing education will allow more rational use of public funds and actively introduce innovative financing tools.

1. Introduction

The State policy of the Kyrgyz Republic on financing higher professional education is based on the following principles:

- Priority of education funding. Article 44 of the Law" On Education " states that the state guarantees the allocation of funds for the needs of education in an amount that ensures its priority, as well as the protection of the corresponding expenditure items in conditions of inflation. (The Law of the Kyrgyz Republic "On Education", about No. 179 of August 11, 2023)
- Independence of higher education institutions in conducting financial and economic activities and managing the income received,
- Competitiveness of educational services. The presence on the educational market of educational institutions of various types of education and forms of ownership stimulates this.
- The possibility of obtaining higher professional education at the expense of the state,
- Commercialization of higher education institutions revenues,
- The possibility of carrying out foreign economic activity by universities and the export of education.

2. Sources of funding for educational organizations in the Kyrgyz Republic

In the Kyrgyz Republic, the sources, procedure for financing, management and control over the expenditure of financial resources of educational organizations are established at the legislative level. The sources of funding are:

- Republican and local budgets – for state educational organizations,
- Funds of individuals and legal entities, foreign countries, and citizens acting as founders,
- Own funds of educational organizations, including foreign currency, from consulting, research, publishing, production,
- Other income-generating activities that are not prohibited by law, as well as from extra-budgetary educational activities for all types of basic and additional educational programs, including within the requirements of state educational standards,
- Income from deposits,
- Voluntarily deposited funds of individuals and legal entities, voluntary donations and targeted contributions of other individuals and legal entities, including foreign ones,
- Loans,
- State financing of state-owned buildings, structures, land plots, equipment, in the form of reimbursement of expenses of educational

organizations, personal and other forms of scholarships, educational grants, loans, provision of benefits,

- State grants issued to students,
- Other sources that do not contradict the law.

Achievements in the higher professional education system of the Kyrgyz Republic in recent years demonstrate significant progress and adaptation to modern requirements.

3. Overview of higher education in the Kyrgyz Republic

As of November 2023, 78 higher education institutions are operating in the Kyrgyz Republic, of which 28 are public and 50 are private. In the academic year 2022-2023, the total number of students is 221,604, with 26,286 (11.8%) enrolled on a grant basis and 195,318 (88.2%) enrolled on a contract basis. (National Statistical Committee of the Kyrgyz Republic. 2019-2023 Reports) (Figure 1).

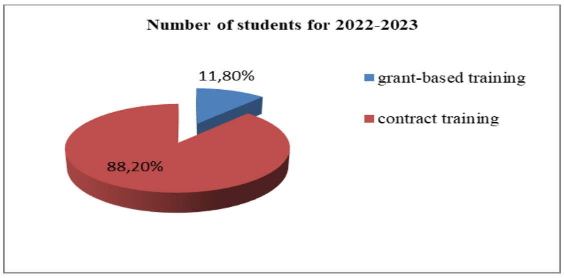

Figure 1: The number of students enrolled in grant and training programs Contract form of training for 2022-2023

The faculty of higher education institutions includes more than 15,000 teachers, with more than 1,100 doctors of science and more than 12,000 candidates of science. International students make up 68,700, which is 31% of the total, including 28,098 students from far abroad (mainly from India and Pakistan) and 40,602 from near abroad (mainly from Uzbekistan, Kazakhstan, and Russia). (Ministry of Education and Science of the Kyrgyz Republic. 2023-2024 Collection of reports)

For the academic year 2023-2024, 6,000 state educational grants were allocated. Of these, 4,686 grants were provided to universities under the auspices of the Ministry of Education and Science of the Kyrgyz Republic, while the rest were distributed among other ministries.

Admission of students is carried out through the Automated Information System "Entrant Online" on the official website. The 2023-2024 admission campaign allows applicants who have exceeded the threshold score of the main test to participate in the competition. Medical specialties require basic and subject tests in chemistry and biology above the threshold score.

The competition for grant places and contract training is held separately, taking into account the social categories for grants. Some universities conduct their own entrance exams, and applicants who have passed additional tests can also participate in the competition.

4. Innovations and international cooperation in higher education of the Kyrgyz Republic

Education in the Kyrgyz Republic is based on the principles proclaimed in international treaties and facts, in the Universal Declaration of Human Rights, which are part of the legal system of the Kyrgyz Republic.

In accordance with article 46 of the Constitution of the Kyrgyz Republic, everyone has the right to education. The Law "On Education" specifies the norms and requirements for obtaining an education. Access to higher education is open to those who have completed their secondary education, completed primary or secondary vocational education, or already have a higher education diploma (for the next stage).

The Ministry of Education and Science of the Kyrgyz Republic is the central executive body that develops a unified state policy in the field of education, science and

- Action Plan for 2021-2023 for the implementation of the Program for the Development of Education in the scientific and technical activities, and exercises State control over the availability and quality of education, ensuring the constitutional right of citizens of the Kyrgyz Republic to education.

4.1. Introduction of new standards and initiatives in higher education in the Kyrgyz Republic

In 2020, a Nationale Qualification Framework was created, including 9 levels, which provides a clear structure and levels of qualifications. In 2022, new educational standards were adopted that significantly expanded the academic freedom of educational institutions to 90%, reducing the mandatory state component to 10%. For pedagogical areas, experimental curricula have been developed that include the best world practices and provide several qualifications.

Five higher education institutions of the republic received the status of innovative research centers with broad autonomous rights. An independent accreditation system has been implemented, and the Independent Accreditation and Rating Agency (IAAR) publishes an annual university rating. Nationwide testing and enrollment are now conducted twice a year, and enrollment after the pandemic is fully transferred to an online format.

An automated system for admitting foreign students has been developed, as well as a system for online admission of Kyrgyz citizens to study abroad. Universities have implemented software for recording academic performance and electronic credit books with the ability to automatically lock points. An International scholarship of the President of the Kyrgyz Republic "El umutu" was introduced, startup centers and business incubators were opened in state universities.

International cooperation has been strengthened through the opening of representative offices of other foreign universities. The plans include updating legislation in the educational sphere, supporting universities with special status, creating technology parks, improving the quality of teacher training, and implementing international projects.

These measures are aimed at improving the quality of higher education, strengthening the link between education and international standards and labor market requirements, as well as ensuring the training of highly qualified specialists capable of innovation and leadership in various sectors of the economy.

5. Education development program of the Kyrgyz Republic until 2040 and the number of organizations of higher professional education

In order to ensure the sustainable functioning and development of the higher education system, Resolution In

- Program for the Development of Education in the Kyrgyz Republic until 2040,
- Independently, in coordination with the boards of trustees, determine the share of funds allocated for labor remuneration, establish the forms and amounts of remuneration, material incentives and material assistance for all categories работников of university.

Kyrgyz Republic for the period 2021-2040. According to the Law "On Education", the status of an educational organization (type, type and category determined following the level and focus of educational programs implemented) is established (confirmed) during its accreditation.

Individual state educational organizations that make a significant contribution to the upbringing, training, and professional development of an individual may be assigned the "National" status in accordance with the procedure established by the legislation of the Kyrgyz Republic.

According to the National Statistical Committee of the Kyrgyz Republic, the number of organizations of higher professional education (Table 1).

To ensure the quality of higher professional education and the development of university science, Decree No. 243 of the President of the Kyrgyz Republic dated July 18, 2022, "On measures to increase the potential and competitiveness of educational organizations of higher professional education of the Kyrgyz Republic was adopted.

According to the Decree of the President of the Kyrgyz Republic, special status implies broad organizational, financial and academic autonomy granted to the following universities:

1. Kyrgyz National University (KNU) named after Zh. Balasagyn,
2. Kyrgyz State Technical University (KSTU) named after I. Razzakov,
3. Kyrgyz National Agrarian University (KNAU) named after K. I. Scriabin,
4. Kyrgyz State Medical Academy (КГМА) named after I. K. Akhunbayev,
5. Osh State University (Osh State University).

In order to consolidate financial, material and intellectual resources, increase the potential and competitiveness of state educational institutions of higher professional education, a reorganization of the said state higher educational institutions was carried out through unification with universities that have identical areas of training for bachelors and masters.

Universities with special status are granted broad autonomy in financial and educational activities, in particular:

- To open bank accounts in commercial banks with state participation outside the treasury system for the use of extra-budgetary funds,
- Independently determine the internal management structure and staffing level of employees in coordination with the boards of trustees,
- Appoint and dismiss vice-rectors for academic affairs,
- Independently determine the status and name of the university's structural divisions, the procedure for organizing their activities, as well as the requirements for their management and personnel,
- Where the higher education system faces a number of challenges, the issue of financial stability of higher education institutions becomes particularly relevant, having a direct impact on the quality of education provided. (Abdykalykov A. A. 2020; Isaev M. I. 2021). Employees,
- Exemption from all types of audits for a period of three years, except for an annual independent external or internal (intra) -university) audit in accordance with international standards on auditing and the legislation of the Kyrgyz Republic,
- Receive income in the form of funds from educational, consulting, research, publishing, productiono- and commercial and other activities not prohibited by law, and direct them to improve the activities and development of the material and technical base of the university,
- Independently dispose of (alienate, change, rent out) movable property in coordination with the boards of trustees,
- And immovable property acquired at the expense of special funds, as well as dispose of funds received from the rental of movable and immovable property,
- Receive state educational grants in the amount not lower than stipulated for 2022,
- Independently form and approve tariffs for paid educational services,

- Independently determine the number of students and approve the admission plan for students, taking into account the available space and other existing conditions of the university.

Accordingly, the universities mentioned in the Decree are assigned to enter the international scientific university rankings.

To do this, it is necessary to complete the universities that have received a special status to модели the University 4.0 model, that is , to ensure the quality of education, scientific and entrepreneurial activities at a global level, to create a new university ecosystem with a variety of research and creative projects, free space for creating innovations, multi-sided platforms for technological breakthroughs and generating advanced business ideas, also, the development of educational programs that meet the market requirements, and a rational system for managing scientific research.

To achieve these goals, universities are introducing new specialties that will be in demand on the labor market; there should also be a transition from the list of specialties/training areas to the requirements determined by the National Qualifications System. (Ministry of Education and Science of the Kyrgyz Republic. 2023-2024 Collection of reports).

In the modern world, higher education plays a key role in the socio-economic development of any country. Universities are centers of knowledge generation, training of qualified personnel, and innovation. However, to effectively perform these functions, it is necessary to ensure their financial sustainability. In the context of the Kyrgyz Republic, To ensure the financial sustainability of universities in the Kyrgyz Republic, a comprehensive approach is needed, including (figure 2).

Ensuring the financial sustainability of universities in the Kyrgyz Republic is a key factor in improving the quality of higher education. Investments in higher education are investments in the future of the country.

6. Consequences of insufficient funding of higher education institutions

Financial sustainability of the university implies its ability to generate sufficient financial resources to cover current expenses, invest in the development of the material and technical base, attract and retain qualified teachers (Balatsky E. V., Ekimova N. A. 2017) and conduct scientific research. When a university is experiencing financial difficulties, this inevitably affects the quality of the educational process. (Isaev M. I. 2021).

One of the most obvious consequences of insufficient funding is **the limitation of opportunities for updating the material and technical base.** Modern education requires the use of state-of-the-art equipment, laboratories, library collections, and information technologies. Without sufficient investment, universities cannot provide students with access to these resources, which reduces the practical value of the acquired knowledge and skills. Outdated equipment and a lack of educational materials make the educational process less attractive and efficient.

Further, financial instability directly affects the **human resources of universities**. Low salaries and a lack of opportunities for professional development lead to an outflow of qualified teachers and make it difficult to attract young, talented specialists. As a result, students may face a lack of experienced and motivated teachers, which negatively affects the quality of teaching and research work.

In addition, limited funding **reduces opportunities for the development of research activities**. Universities are not only educational, but also research centers. Conducting up-to-date research, publishing scientific papers, and participating in international projects help raise the prestige of the university and enrich the educational process with new knowledge. Financial difficulties hinder the development of science, which in the long run slows down the country's innovative development. Finally, financial sustainability enables universities **to ensure that quality education is accessible to a wider range of students**. Thanks to financial support, scholarship and grant programs can be implemented, which allows talented students from low-income families to receive higher education. Lack of funds can lead to higher education costs and restrict access to higher education for socially vulnerable segments of the population.

7. Financial autonomy of universities in the Kyrgyz Republic: legislation and principles

Education is a priority strategic direction of the state policy of the Kyrgyz Republic. The education system of the Kyrgyz Republic is undergoing significant and in its intellectual and economic potential. Only financially stable universities will be able to effectively fulfill their mission of training highly qualified specialists who can make a significant contribution to the development of the Kyrgyz Republic.

8. Ways to ensure sustainable development of higher education in the Kyrgyz Republic

To overcome the existing problems and ensure sustainable development of higher education in the Kyrgyz Republic, comprehensive measures are needed to:

- Increasing state funding: It is necessary to gradually increase the share of budget funds allocated for higher education, focusing on international standards and the country's development needs (World Bank Reports 2023).
- Development of mechanisms for attracting extra-budgetary funds: Favorable conditions should be created for attracting investment from the private

sector, and effective interaction with graduates and international donor organizations should be established (Kotler F., Keller K. L. 2016).

- Improving the system of paid education: It is necessary to develop transparent and socially oriented mechanisms for paid education, providing for a flexible system of discounts, grants and educational credits to support talented students.
- Improving the efficiency of financial resource management: Introduction of modern methods of financial planning, accounting and control, ensuring transparency and accountability in the use of budgetary and extra-budgetary funds (Drucker P. F. 2007).
- Optimization of the structure of higher education: Analysis of the effectiveness of higher education institutions, possible reorganization and optimization of the network of higher education institutions in order to make more efficient use of available resources.
- Development of targeted support programs: Implementation of public and private programs to support talented students and young teachers, including scholarships, grants, and internship programs.
- Strengthening ties with the labor market: Active interaction between universities and employers will allow us to adapt educational programs to the needs of the economy and increase the demand for graduates. (J. C. Smart, D. W. Leslie 2022)
- Programs and conditions for students, which increases their attractiveness to applicants both at the national and international levels.

9. Financial autonomy of universities in Kyrgyzstan: start and results

Since December 2022, the project 101082829 – DEFA-ERASMUS-EDU-2022-CBHE has been launched at the I. Razzakov Kyrgyz State Technical University “Development of Financial Autonomy of Universities in Kyrgyzstan” (DEFA), funded by the Erasmus+ program.

Multidirectional transformations: changes are being made to the content, structure and forms of education, and processes are being developed to ensure the quality of education. The Law of the Kyrgyz Republic "On Education" of August 11, 2023 No. 179 for the first time establishes the concept of autonomy as the right of an educational organization to independently carry out educational, administrative, financial and economic activities, make managerial decisions, including on human resources and asset management, manage budgetary and extra-budgetary funds for the maintenance and development of educational, social and cultural activities., scientific and other activities in accordance with the Law "On Education" and the charter of the educational organization.

The autonomy of educational organizations is one of the main principles of state policy in the field of education.

Financial autonomy of universities is the ability of educational institutions to independently manage their financial resources and receive income from various sources. (for example, from academic activities, research, investment, sponsorship, etc.) and make decisions about their use without significant interference from the state or other external organizations. With the introduction of financial autonomy, universities can develop their own budget, prioritize funding, and allocate resources across internal divisions. You will be able to independently receive and manage your income, which includes accepting tuition fees, working on commercial projects, andattracting investments, as well as control your expenses and redistribute funds between different areas of activity.

Financial independence is important for universities in Kyrgyzstan. At the same time, universities can provide:

- Diversify funding sources - Universities with financial independence can seek and use different sources of income, which reduces their dependence on public funding and provides greater flexibility in resource management.
- Innovation in research - With financial autonomy, universities can actively develop research, introduce innovations, participate in international research projects, and attract external grants.
- Quality of education - the availability of additional financial resources allows universities to invest in updating educational equipment, improving the skills of teachers, and developing infrastructure, which in turn affects the quality of education.
- Sustainability and development-Financial independence allows universities to respond more effectively to changes in the economic environment, providing sustainable funding for the educational process and research.
- Competitiveness-Financially independent universities can offer more attractive educational

The main goals of the DEFA project are:

- Develop a flexible and efficient model of financial autonomy for universities, which will enable.

The proposed comprehensive measures, including a gradual increase in state funding, development of mechanisms for attracting extra-budgetary funds, improving educational institutions to mobilize and manage resources, effectively using them to meet changing needs;

- Promote the reform of higher education in the Kyrgyz Republic and increase its visibility and relevance for the labor market and society, as well as the competitiveness of research activities of universities;

- Piloting and expanding the new system of university self-government and increasing financial autonomy;
- Improving the strategic management of processes at the university, ensuring financial stability, motivation and building human resources.

The project consortium, which includes 12 universities in the country, 2 universities from Europe: Otto-Von-Guericke-Universitaet – OVGU (Magdeburg, Germany) and Universita Degli Studi di Firenze — UNIFI (Florence, Italy) and 1 public organization CESIE (Italy), actively participates in achieving these project goals.

In 2023, 40 employees from Kyrgyzstan completed an internship on financial autonomy at these European universities.

To date, the Ministry of Education and Science of the Kyrgyz Republic has developed and approved the Strategy of Financial Autonomy of Educational organizations of higher Professional Education of the Kyrgyz Republic for 2024-2030 and a Roadmap for its implementation.

Recommendations have been prepared for introducing amendments and additions to the normative legal acts regulating the financial autonomy of universities in Kyrgyzstan.

Currently, the Model of Financial autonomy of universities of the Kyrgyz Republic is also being implemented in the target universities of the project.

In January 2024, the I. Razzakov KSTU officially opened a Skills Development Center for Financial Autonomy Management, Financial Strategy, Planning, etc., where trainings are held for university employees and other interested parties.

10. Conclusion

The analysis highlights the inextricable link between financial autonomy, financial sustainability, and the quality of higher education in the Kyrgyz Republic. Financial autonomy, which is established at the legislative level and actively implemented through initiatives such as the DEFA project, is a key tool for expanding the ability of universities to manage resources independently, attract additional funds, and set development priorities.

In turn, financial sustainability is the foundation for ensuring high quality of the educational process. Insufficient funding, whether from the State or due to excessive reliance on tuition fees, creates serious obstacles to the development of the material and technical base, attracting and retaining qualified personnel, and conducting scientific research. These restrictions inevitably reduce the quality of education and the competitiveness of graduates in the labor market.

The system of paid education, improving the efficiency of resource management, optimizing the structure of higher education institutions, developing targeted support programs and strengthening ties with the labor market, are a necessary set of actions to ensure the financial sustainability of higher education institutions.

- Financial autonomy empowers universitiesto manage their resources more flexibly and efficiently and to respond to changing needs.
- Financial sustainability is a critical condition for ensuring high-quality higher education, which includes updating the material and technical base, developing human resources and supporting research activities.
- Insufficient funding and excessive reliance on tuition fees negatively affect the quality of education and the competitiveness of graduates.
- Achieving sustainable development of higher education requires a comprehensive approachthat includes increasing public funding, attracting extra-budgetary funds, and improving the efficiency of resource management.
- Investments in higher education are a strategically important investment in the future of the Kyrgyz Republic, contributing to the training of highly qualified specialists capable of innovation and leadership in various sectors of the economy.

Table 1: Number of organizations of higher professional education

Total:	2018	2019	2020	2021	2022
Educational organizations of higher professional education	51	55	57	60	78
Of them:					
State organizations of higher professional education:					
Educational organizations of higher professional education	34	38	40	42	28
Private organizations of higher professional education:					
Educational organizations of higher professional education	17	17	17	18	50

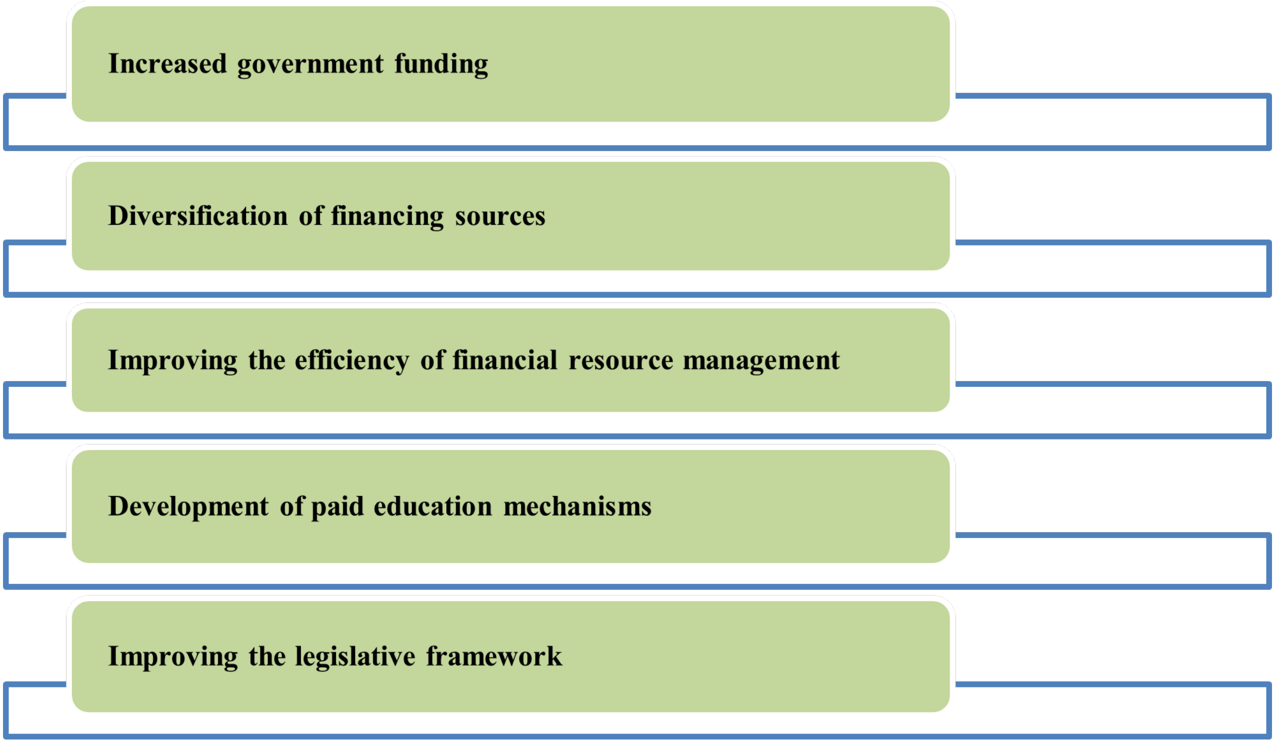

Figure 2: Necessary integrated approaches

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GenAI for Simulation Modeling: A Synergistic Approach

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Abstract

This paper presents a framework integrating generative AI with respect to Automated Simulation Model Generation (ASMG) to democratize access to simulation modeling in production and logistics. Traditional simulation modeling requires extensive domain expertise, creating significant barriers particularly for small and medium enterprises. Our framework bridges natural language processing and simulation tools through a three-component system: a data preprocessing pipeline that transforms contextual information from heterogeneous sources, a domain-expert large language model that translates natural language requirements into structured factory descriptions, and specialized interpreters that facilitate interaction with commercial simulation tools. The system features a progressive domain specialization pipeline comprising prompt engineering, supervised fine-tuning, reinforcement learning with simulation, and human feedback. This approach strategically distributes complexity to leverage complementary strengths of both technologies - ASMG's structured data representation and generative AI's intuitive natural language interface. The paper outlines a comprehensive validation methodology using progressive case studies and discusses implementation challenges, limitations, and commercial applications of this technology.

1. Introduction

Recent advancements in generative AI (GenAI) have dramatically transformed our approach to complex problem-solving across industries. Models like ChatGPT and DeepSeek have demonstrated unprecedented capabilities in reasoning, planning, and generating creative solutions that were previously exclusive to human experts. These capabilities create remarkable opportunities for human-machine collaboration, knowledge management, design innovation, and engineering skill education (X. Wang et. al, 2023). Particularly promising is the emergence of chain-of-thought reasoning, where models systematically work through problems step-by-step, mirroring human cognitive processes to arrive at solutions for complex tasks (Lightman et al., 2023; Wei et al., 2022). The logistics and manufacturing sectors stand to benefit significantly from these technological breakthroughs (Aguero & Nelson, 2024).

In this paper, we outline the current research gaps, analyze existing literature, and derive an early conceptual framework for a GenAI based simulation modeling assistant that collaborates with humans through natural language interaction in order to democratize access to powerful simulation modeling tools for logistics systems.

1.1. Contextual Background

Manufacturing faces unprecedented complexity due to mass customization trends, global competition, and compressed delivery timelines (Fu et al., 2021; Mahen-drakar, 2018; Touckia et al., 2022). The proliferation of product variants coupled with the shift toward batch-size-1 production has reduced predictability and planning horizons between information availability and production start (Glawar et al., 2021). To maintain competitiveness in this environment, simulation models have become essential tools that enable risk-free scenario testing to identify bottlenecks, optimize resource allocation, and quantify improvement measures (D. Wang, 2023; Y. R. Wang & Chen, 2016). As industrial transformation accelerates, small and medium enterprises (SMEs) increasingly confront these complex production orchestration challenges despite more limited resources.

1.2. Problem Statement and Motivation

The primary barrier to simulation adoption is the requirement for extensive domain expertise (Karlsson et al., 2015; Trigueiro de Sousa Junior et al., 2019). Creating effective simulations traditionally requires domain specialists to verbally describe systems and develop conceptual models, followed by technical experts converting these into algorithmic representations—a resource-intensive process (Jackson et al., 2024). The subsequent analysis phase demands deep understanding of both the simulated system and simulation methodology to properly select parameters and interpret performance indicators. This workflow necessitates continuous communication between domain specialists and simulation engineers, extending project timelines and increasing costs (Pace, 2004).

Automated Simulation Model Generation (ASMG) approaches have partially addressed these challenges but typically require well-maintained production planning and control (PPC) system data or only automate specific aspects of the simulation pipeline. Recent generative AI (GenAI) advances offer opportunities to reduce technical barriers through natural language interfaces and enhanced data analysis capabilities (Li et al., 2024; Lidberg et al., 2019; Mukhtarov, 2023).

Despite these technological developments and the growing importance of Digital Twins, a substantial gap remains between theoretical capabilities and practical implementation of accessible simulation modeling solutions for SMEs.

1.3. Literature Review and Research Gaps

This section summarizes current research efforts in ASMG and natural language based simulation model ling assistance.

1.3.1. ASMG Based Approaches

Automatic Simulation Model Generation (ASMG) approaches aim to reduce model creation effort while broadening accessibility to non-experts.

A comprehensive review is provided in (Reinhardt et al., 2019), highlighting that most existing approaches are tailored to specific use cases rather than offering generalized solutions. Standardization efforts primarily focus on intermediate data representations through formats like Automation Markup Language (AutomationML) and Core Manufacturing Simulation Data (CMSD), establishing consistent, structured factory element representations interpretable across simulation tools.

Building on these standardized formats, researchers have explored methodologies for coupling them with commercial simulation tools. In (Bergmann & Straßburger, 2020) classification schemes and implementation strategies for such couplings were examined, while in (Krenczyk et al., 2018) the specific focus was set on PPC integration. Notable implementations appear in (Weigert et al., 2017; Galka et al., 2023; Schuh et al., 2023), with the latter surpassing other solutions in generalization and completeness. Current ASMG approaches typically employ standardized factory description formats, custom interpreters, simulation-to-PPC feedback mechanisms, and automatic data validation. However, significant limitations persist: Applications remain restricted to specific production system types, implementations often cover only partial simulation workflows, they rely on predefined software components unable to address specialized requirements, many use proprietary interfaces requiring substantial training, and most depend on operational PPC data, making them unsuitable for greenfield factory planning.

1.3.2. Generative AI Based Approaches

Research on generative AI solutions for discrete event simulation modeling remains remarkably limited. Within the scope of this paper only two directly relevant works were found in Jackson & Saenz (2022) and Jackson et al. (2024), which explore using GPT-3 to translate natural language descriptions of simple queuing systems into Python simulation models. It should be noted that these works directly built on another. Their research establishes initial design guidelines for prompting LLMs (Large Language Models) to generate executable simulation code for logistics problems. In Hopkins et al. (2025), a complementary perspective is provided through the Factorio Learning Environment (FLE), evaluating LLM capabilities in factory simulation environments. Despite testing frontier models like Claude 3.5 Sonnet and GPT-4o, even the best performing model completed only 21.9% of structured tasks and struggled with coordinating more than six machines for multi-ingredient production. These findings highlight critical LLM weaknesses: poor spatial reasoning, difficulty managing complex production processes, and inadequate error correction in sophisticated environments. Current approaches fail to address the complete simulation modeling process from data acquisition through analysis. Existing research focuses almost exclusively on generating Python code rather than integrating with industrial-grade simulation environments like Tecnomatix Plant Simulation or AnyLogic. Furthermore, domain expertise embedding never extends beyond simple prompt engineering, leaving potential capability improvements undiscovered. The integration of domain-sensitized GenAI with established simulation platforms used in professional practice remains largely unexplored.

1.4. Research Questions

The limitations of both ASMG and generative AI approaches can be effectively addressed through strategic integration. ASMG systems provide structured frameworks and standardized data exchange formats but are typically inflexible and domain-specific. Conversely, generative AI offers natural language understanding and creative problem-solving capabilities but struggles with spatial reasoning and industrial tool integration. A combined approach leverages complementary strengths: ASMG's standardized formats provide structured representation for technical correctness while generative AI's natural language interface reduces entry barriers.

To guide development of an effective GenAI-driven simulation assistant incorporating ASMG methodologies, we formulate the following research questions:

- **RQ1**: How can the gap between natural language descriptions and commercial simulation modeling tools for production and logistics be bridged effectively?
- **RQ2**: How can domain-specific knowledge be effectively incorporated into GenAI-driven simulation model generation to ensure technical feasibility and practical relevance?
- **RQ3**: What validation methodologies can ensure the reliability and accuracy of automatically generated simulation models throughout the modeling lifecycle?

2. Methodology

2.1. Research Design

This research followed a systematic four-phase approach to develop a system architecture for a GenAI driven simulation modeling assistant, as illustrated in Figure 1.

We began the literature review analyzing both current generative AI capabilities and established automatic simulation model generation (ASMG) approaches, with our findings culminating in the formulation of three research questions. From this, we analyzed requirements to identify the necessary capabilities, interfaces, and knowledge structures for a GenAI-driven simulation assistant. We consolidated these requirements into an early system architecture that integrates the conversational strengths of generative AI with the structural rigor of ASMG approaches. Finally, we delineated future research directions and specific next steps for realizing the GenAI assistant. This includes implementation priorities, validation methodologies,

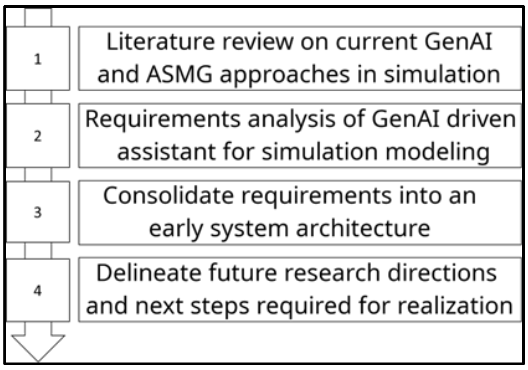

Figure 1: Research Methodology

and potential challenges to be addressed in developing a functional prototype of the proposed system. The conducted research was part of the project "Generative AI for Future Factory Design".

3. Results and Discussion

From our early research, we have developed a preliminary framework that highlights key research and development avenues. This framework serves as both a research foundation for a dissertation and a blueprint for developing system components, their interactions, and corresponding data flows.

The framework aims to address a significant gap in current automated simulation modeling methods, which primarily focus on improving existing factories. Our approach extends automated simulation modeling to greenfield factory planning, i.e. planning new factories.

3.1. GenAI-based Simulation Assistant Architecture

The proposed framework, illustrated as a system architecture in Figure 2, comprises three primary subsystems: a data preprocessing pipeline, a domain-expert large language model, and a middleware based on an API (Application Programming Interface). The lower third section of the figure represents a specialization pipeline for achieving domain capabilities. The core concept is leveraging GenAI model outputs to control simulation tools for both model creation and experiment execution, based on natural language inputs and contextual information.

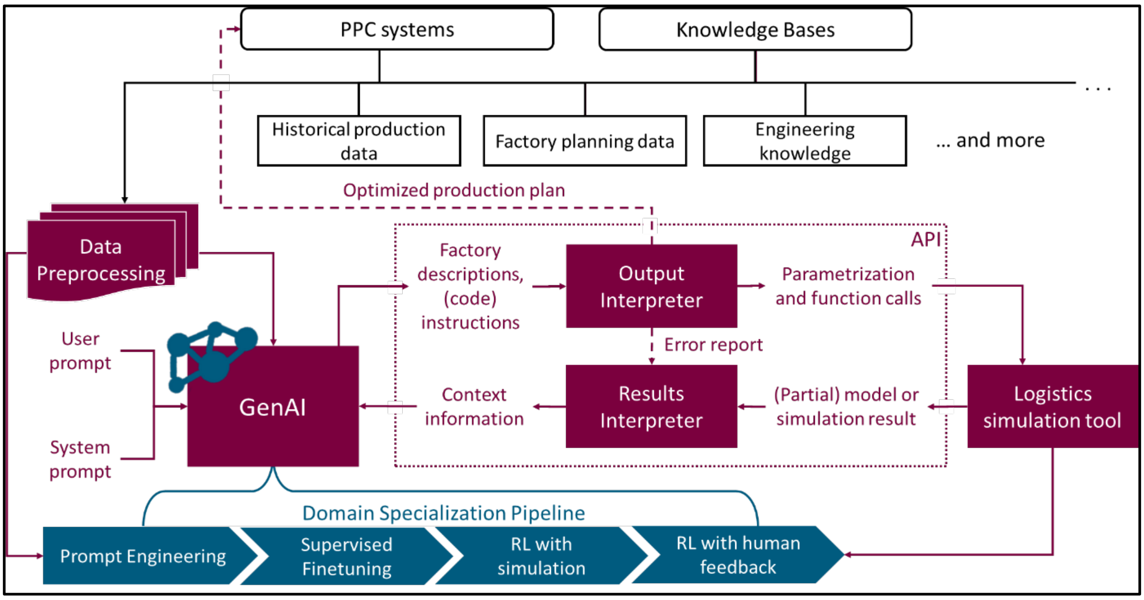

Figure 2: System Architecture for GenAI driven assistant for logistics simulation modeling (RL: Reinforcement Learning, PPC: Production Planning)

3.1.1. Data Preprocessing

The preprocessing pipeline extracts and transforms contextual information into data representations that are semantically comprehensible to the downstream GenAI component. Input data sources vary by application scenario: for existing facilities, data comes from enterprise resource planning (ERP) and manufacturing execution systems (MES); for greenfield planning, inputs derive from earlier planning phases including requirements analysis, conceptual development documentation, and preliminary layouts. The pipeline handles multimodal inputs spanning factory planning data (value-stream models, CAD layouts, process flow diagrams), historical production records (metrics, material flow data, machine parameters), and simulation engineering knowledge.

This preprocessing component functions either as a preliminary step or in an agentic manner, where the GenAI system independently invokes data transformation when additional context is required during operation. Each data type undergoes appropriate transformations: text extraction for specifications, feature recognition for CAD models, structural parsing for diagrams, and normalization for numerical parameters. When utilizing operational data for training or system refinement, an anonymization layer protects sensitive information while preserving essential relationships.

3.1.2. GenAI Assistant Feedback Loop

An instruction-finetuned large language model (referred to as ”GenAI” in the figure) processes natural language inputs and contextual data to generate structured factory descriptions using standardized formats (AutomationML, CMSD). An API middleware harmonizes communication between the GenAI model and simulation tools.

The feedback loop begins when the model converts requirements into structured descriptions. The Output Interpreter validates these outputs, converting them into tool-specific commands with error reporting mechanisms that provide corrective feedback. Once validated, commands execute in the simulation tool, creating or modifying models or running experiments according to interpreted instructions.

After execution, the Results Interpreter transforms simulation outputs — whether from model creation steps or complete simulation runs — into structured feedback, including information about the current processing state of simulation models, execution statistics, and performance metrics. The GenAI model then reflects on this structured feedback to evaluate results, identify optimization opportunities, and inform the user about simulation processes.

In this optimization process, two modes are considered: In human-in-the-loop mode, the model iteratively refines simulations based on user instructions. In autonomous mode, the system independently improves models based on simulation results, serving dual functions of reducing the simulation-to-reality gap through parameter adaptation and finding optimal production schedules through systematic experimentation. While this interpreter-based approach addresses most simulation modeling needs, certain special cases may require direct code synthesis capabilities. Examples include implementing custom heuristics with complex conditional behaviors, multiple interacting variables, and state-dependent transitions - such as sophisticated routing rules or scheduling optimizations not typically included in standard simulation tool libraries. To accommodate these cases, the Output Interpreter can be expanded to provide access to elementary functions in the simulation modeling tool, enabling more intricate model interventions.

3.1.3. Domain Specialization Pipeline

The domain-specific training pipeline (shown in the lower third of figure 2) consists of four progressive stages:

Prompt engineering: Domain-adapted prompts guided by established simulation methodologies incorporate best practices and exemplary factory descriptions, instilling a foundational understanding of domain-concepts and proper modeling approaches. This leverages chain-of-thought models to enhance simulation modeling workflows.

Supervised fine-tuning: If prompt engineering alone proves insufficient in achieving the required domain capabilities, this step can be supplemented with supervised fine-tuning, potentially implemented using techniques like LoRA, using the existing domain data.

Reinforcement Learning with Simulation: Through automated experimentation cycles, in which artificial data is synthesized followed by reward feedback, the model can be directed towards optimal experiment planning, parametrization and scheduling via quantitative trial-and-error in simulation environments.

Reinforcement Learning with Human Feedback: Incorporating domain expert guidance ensures technical soundness and practical realizability, effectively encoding expert knowledge that complements quantitative optimization capabilities.

For the human feedback component, a variety of methods can be considered, including preference ratings of alternative responses, classification of output quality across multiple criteria, specific annotations of errors or improvement suggestions by experts, and direct edits to model output using techniques such as Direct Preference Optimization or Reinforcement Learning from Human Feedback. Future research will determine which methods achieve best practice results.

3.1.4. Factory Planning Example

To better illustrate the framework's practical value, consider an early stage planning scenario for an electric vehicle battery assembly factory with multiple layout variants. Available planning documentation includes factory requirements (production targets, spatial constraints), equipment specifications (cycle times, reliability data), and preliminary block layouts showing functional areas. A production planner initiates the process by requesting: "Compare three layout configurations with five assembly stations and two quality control points to optimize for throughput and material flow efficiency." The preprocessing pipeline transforms heterogeneous data into structured formats—converting layouts to spatial coordinates, equipment specifications to resource capabilities, and production targets to performance metrics. The GenAI assistant processes this context alongside the request to generate three structured factory descriptions with consistent process sequences but different spatial arrangements. The Output Interpreter converts these into simulation models in Tecnomatix Plant Simulation for execution.

After analysis, the GenAI assistant delivers a data-driven recommendation: "Layout C provides the optimal configuration, achieving 94% of throughput targets while meeting spatial and investment constraints. This arrangement reduces material transport distances by 23% compared to Layout A and eliminates cross-traffic congestion points present in alternatives. Layout C also offers 15% higher flexibility for future expansion and product variants. Recommend proceeding with Layout C, with adjustments to workstation 3 orientation and buffer capacity optimization at quality control points." The assistant supplements this with performance visualizations and enables further interactive refinement based on user domain expertise.

3.2. Discussion of Design Choices

Our architectural decisions reflect both theoretical principles and practical implementation challenges. While direct API integration might appear simpler, it would require the GenAI model to possess intricate understanding of tool-specific code with precise syntax, increasing learning complexity and sacrificing interoperability advantages. The interpreter-based approach distributes complexity through middleware layers, allowing the GenAI model to focus on understanding requirements rather than implementation details. This separation of concerns offers three key advantages: (1) progressive enhancement through independently updatable interpreters, (2) extensibility for additional simulation tools without retraining the core model, and (3) clear interfaces that facilitate testing and validation.

While the specific background of this research focuses on discrete-event simulation modeling for production and logistics, the framework's generic nature potentially allows application to various simulation modeling paradigms. However, certain constraints should be acknowledged. Current limitations include the restricted context windows of large language models, which limit the amount of information a model can reason with at once. This could be addressed through intelligent prompting strategies such as Retrieval Augmented Generation to prioritize relevant information. Another constraint is response time, which is inherently limited by hardware capabilities but could be improved through models that activate only a subset of parameters during inference, such as mixture-of-experts architectures.

3.3. Validation Methodology

To ensure the robustness and effectiveness of our proposed approach, we will employ a multi-faceted validation strategy. For empirical validation, we will adopt a case study methodology using real-world scenarios of increasing complexity, from simple manufacturing cells to complex production lines.

Benchmark use cases include layout planning and optimization, line balancing, logistics system design, flexible manufacturing planning, and scenario-based decision support.

Evaluations of the resulting simulation models will measure quantitative metrics (error rates, performance) against qualitative assessments (correctness, completeness, feasibility), while comparative analyses will assess the system against indicators including model creation time and model accuracy compared to expert-created equivalents. Domain experts from both academia and industry will be engaged to evaluate the quality of generated models and provide feedback on the system's usability, accessibility and practical relevance.

A form of verification (in terms of correctness) can be achieved within the system through the interpreter components (error reporting mechanism) and the use of standardized output formats (CMSD, AutomationML). However, verification of alignment between generated outputs and specific requirements presents unique challenges due to the probabilistic nature of GenAI models. Future research will develop a standardized benchmark to assess the consistency of GenAI models in adhering to specified requirements.

4. Limitations and Conclusion

This research conceptualizes a GenAI-driven simulation modeling assistant for production and logistics. Our contribution is an early framework bridging natural language processing and simulation generation through specialized interpreters and feedback loops, addressing limitations of both traditional ASMG and pure GenAI approaches.

The framework leverages ASMG implementations while employing advanced language models, strategically distributing complexity to allow each subsystem to focus on its strengths. Our domain specialization framework provides concrete steps for expanded capabilities through progressive knowledge acquisition.

Several open questions remain: Generated model quality depends on underlying GenAI capabilities, particularly regarding spatial reasoning and complex logical relationships. Current frontier models struggle with coordinating complex production scenarios. We also face trade-offs between model simplification (for GenAI processing) and completeness (for accurate simulation), challenges with data acquisition and formatting for both finetuning and inference, as well as proprietary simulation tool integration. Lastly, the possible organizational resistance to adopting AI-assisted approaches in traditionally domain expertise-driven domain should not be underestimated.

Next steps in this research will include implementing a prototype, conducting systematic validation through progressive case studies, and developing pipelines for data preprocessing and domain specialization. Future opportunities include exploring multimodal inputs for processing visual factory layouts and expanding to cross-domain applications.

From an exploitation perspective, there exists significant commercial potential. The technology could be developed into a software service layer that integrates with existing simulation tools, offering a natural language interface for faster simulation model development. One promising application is the development of a simulation modeling Co-Pilot plugin for established industrial simulation modeling tools like Plant Simulation, to assist and partially automate the simulation modeling process. Such an approach could streamline workflows and improve simulation models through data-driven perspectives. Various studies on Co-Pilot tools in software development suggest potential productivity improvements. Research indicates that AI assistants can increase productivity in throughput and cycle times within development projects, while also improving satisfaction and reducing frustration (Dakhel et al., 2023; Haque et al., 2025; Zhang, 2025). While junior developers primarily benefit in learning and exploration phases (Karaci Deniz et al., 2023), experienced engineers leverage these tools for rapid prototyping (Toprani, 2025). Similar benefits and usage patterns can be expected in simulation modeling.

In conclusion we believe that further research into the cross-domain of GenAI and simulation modeling can transform production and logistic planning practices by democratizing access to powerful simulation capabilities across diverse manufacturing contexts.

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Simulation-Based Optimization of Empty Container Inventory

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Abstract

Effective inventory management of empty shipping containers is a complex yet essential task for ensuring smooth shipping operations. For shipping lines, maintaining an adequate supply of empty containers while minimizing associated costs is crucial for operational efficiency. Proper inventory management enables shipping companies to reduce expenses, optimize resource utilization and improve operational efficiency.

This study proposes a stochastic simulations-based optimization model specifically designed for shipping lines to manage empty container inventories across a multiterminal hinterland system. It generates stochastic supply and demand and applies discrete-event simulation (DES) to simulate import and export decisions made by the shipping line. By capturing the operational dynamics of empty container logistics, the model provides a robust decision-making framework.

The objective is to minimize total system cost, including transportation, storage and leasing costs, by determining the optimal (s, S) policies using three metaheuristic optimization techniques are employed: Genetic Algorithm, Particle Swarm Optimization and Simulated Annealing.

All three optimization techniques yielded solutions with identical total costs while recommending different reorder points and order-up-to levels. This finding suggests the presence of multiple near-optimal solutions, highlighting the flexibility of inventory policies in achieving cost efficiency. Such flexibility allows shipping companies to select a solution with higher inventory thresholds to ensure safety stock availability, or to opt for lower order-up-to levels, leading to higher turnover rates and more efficient asset utilization.

1. Introduction

Due to imbalances in global trade flows, shipping containers frequently accumulate in regions where they are not immediately needed, while other regions experience container shortages. According to Sanders et al. (2015) repositioning costs account for 5 to 8 % of total operational costs for a typical carrier, resulting in USD 15 – 20 billion per year for whole industry.

To address this challenge, inventory policies are implemented to strategically allocate empty containers, balancing the trade-off between excessive storage of empty containers and insufficient availability to meet demand.

The classical (s, S) inventory policy relies on two key decision variables: the optimal reorder point (s) and the order-up-to-level (S). However, in container shipping empty container supply originates from two sources: newly ordered containers and returns of containers from completed import shipments. As a result, it is essential to determine not only when and how many should be imported to maintain an efficient balance but also when to what extent empty containers should be exported.

To improve empty container management, (Li et al., 2004) proposed a (U,D) policy for a single port, where containers are imported up to U level, and exported down to D. This model was later extended by (Li et al., 2007) to consider multiple ports. A heuristic algorithm was applied to optimize empty container management and reduce average costs. (Dang et al., 2010) included the movement of containers between inland terminals in research. In addition to applying (s, S) inventory policy for ports, they introduced the (r_i, R_i) policy for inland terminals, where r_i is the minimum inventory level and R_i is the maximum inventory level for inland terminal i. A genetic-based optimization method was employed to find optimal parameters.

These studies focus on inventory positioning policies, where empty containers are transported between terminals with surplus inventory and those terminals where the forecasted supply is projected to fall below the minimum required level at the time of order fulfillment. To enhance efficiency, (Lohina and Pavlyuk, 2024) introduced a proactive strategy in which surplus containers are transported to the terminals expected to experience shortages, even before inventory levels reach a critical level. This forward-looking approach helps mitigate potential shortages, improve overall efficiency and enhances the ability to meet future demand more effectively.

Metaheuristic algorithms are powerful optimization techniques capable of finding solutions for a broad range of complex, nonlinear optimization problems without relying on gradients or derivatives. Those algorithms are inspired by nature and are widely applied across various fields to find near-optimal solutions (Mitra et al., 2019).

Metaheuristic optimization algorithms have been extensively used in transportation-related applications, such as determining the optimal frequency of public transportation (Martinez et al., 2014), optimizing terminal operations (Long et al., 2025), and solving vehicle routing problems (Zuhanda et al., 2024).

Genetic Algorithms (GA) are a class of evolutionary algorithms inspired by natural selection and evolutionary processes (Bhattacharyya et al., 2020). In container shipping, GA has been used to optimize fleet size (Dong et al., 2009) and to design container shipping networks (Shintani et al., 2007).

Simulated Annealing (SA) is a physics-based algorithm inspired by thermodynamic processes, particularly the metallurgical annealing procedure. In the shipping industry, SA has been applied to determine optimal ship routes (Kosmas and Vlachos, 2008), slot allocation (Song et al., 2022) and solve inland container transportation problem (Shao et al., 2022).

Particle Swarm Optimization (PSO) is a swarm-based algorithm inspired by the collective behavior of animals such as birds or fishes (Sun et al., 2025). In the shipping industry, PSO has been used to analyze ship fuel consumption (Lan et al., 2025), optimize berth allocation (Ting et al., 2014) and improve ship routing and scheduling (De et al., 2016).

This research builds upon the study by Lohina and Pavlyuk (2024) by reusing the previously developed simulation model to analyze repositioning costs based on minimal and maximal inventory levels for relocating empty containers at both sea and inland terminals. Additionally, this study applies metaheuristic optimization techniques to determine the optimal minimal and maximal inventory levels for each terminal within the shipping network.

There is limited research addressing dynamic inventory control across multiterminal hinterland networks using a simulation-based approach tailored for shipping lines. Moreover, the integration of discrete-event simulation with multiple metaheuristic optimization techniques remains underexplored in this context.

This study addresses this gap by developing a decision-support framework that combines DES with GA, PSO, and SA to determine optimal (s, S) inventory policies across multiple terminals.

To address the identified gap, the study explores the following questions:

- How can (s, S) inventory control policies be optimized for empty container management across a multiterminal network under stochastic supply and demand?
- How do different metaheuristic optimization techniques compare in identifying near-optimal solutions for this problem?

2. Procedure, methods or experimental part

This study employs a simulation-based optimization approach, integrating discrete-event simulation to analyze repositioning costs based on critical inventory levels and metaheuristic optimization to determine optimal (s, S) inventory control policies within a multiterminal hinterland network. The applied methodology is structured into four key steps.

2.1. Description of the System

This study presents a simulation-based approach to optimize inventory management in a network comprising one port terminal and two inland terminals. By including two inland terminals and one port, the system can model all types of empty container repositioning movements. Therefore, this simulation-based optimization model provides a scalable framework applicable to larger shipping networks. Visualization of the system below, where the bold line represents overseas positioning, the dashed line - the inland distribution of empty containers, the dotted line represents inland positioning between two inland terminals.

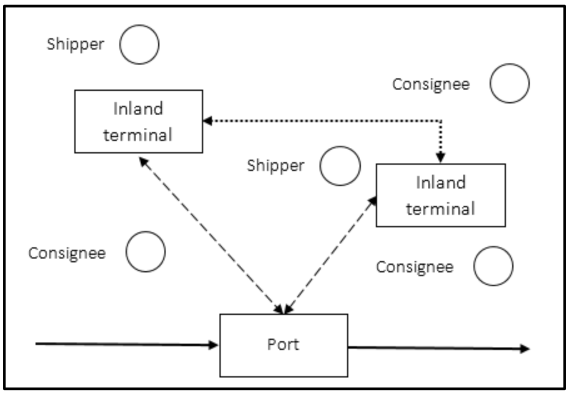

Figure 1: Inland repositioning of empty containers (Lohina and Pavlyuk, 2024)

All containers located in the hinterland are discharged in port and later will be loaded in port. Therefore, in a network consisting of multiple inland terminals and a port, the supply and demand dynamics of empty containers at inland terminals partially influence the overall availability at the port. Empty containers can be repositioned between the port and inland terminals or between two inland terminals. If a surplus or deficit of containers exists across all terminals, empty containers are either imported or exported overseas. Regardless of the chosen repositioning strategy, there is always an associated lead time. In cases where the shipping company is unable to provide the required empty containers, leasing options may be used to meet the demand.

2.2. Problem Formulation

The shipping network under consideration consists of a port terminal, two inland terminals and inter-terminals movements. For each terminal the optimal (s, S) inventory control policy is defined based on the total costs over the simulation period.

The following assumptions are made:

- The port terminal has unlimited import/export capacity.
- There are always available containers to be imported to the port terminal.
- Each terminal has unlimited leasing capacity.
- Demand and supply are stochastic.

2.3. Simulation Model Development

This research builds upon a discrete-event simulation model which simulates container availability at each terminal taking into account current inventory levels and stochastic demand and supply fluctuations. Based on current level of inventory, forecasted availability and (s, S) policy, the model makes repositioning decisions. These decisions consider transit times for different types of container movements. Each container transfer between terminals incurs repositioning costs in addition to empty container holding costs.

The following assumptions are made in the model:

- There is only one container type. The simulation is executed separately for each container type, and the model does not consider the possibility of container type substitution.
- All empty containers are positioned out of the terminal at the beginning of each time period and positioned in at the end of the period. Containers cannot be released within the same time period in which they are returned.
- Demand must be fully satisfied, and there is unlimited availability of leased containers with zero lead time.
- The lead time for all types of repositioning is constant. The transportation lead time between terminals by land is the same for all terminals.

To ensure that repositioning decisions based on different critical inventory levels are evaluated under identical demand and supply conditions, the simulation procedure is divided into two distinct phases:

- The supply and demand for each terminal are simulated for each day within the simulation period
- Repositioning decisions are made, and associated costs are computed.

This separation is essential to enable search of optimal solutions in several steps and a fair comparison of different optimization methods and their respective optimal solutions.

2.4. Optimization Model Development

The optimization consists of six interdependent decision variables and a single objective function. Decision variables are (s, S) values for each terminal. Based on generated supply and demand for each terminal at each time period and decision variables (re-order point and order up to level) simulation of repositioning moves are done. Which results in transportation, storage and leasing costs, and goal of optimization is to minimize those costs. Objective function:

$$\mathrm{TC_t} = \mathrm{CO_t} + \mathrm{CI_t} + \mathrm{CS_t} + \mathrm{CL_t}, \tag{1}$$

where $\mathrm{TC_t}$ – total cost of container inventory management in time t,

$\mathrm{CO_t}$ – cost of overseas positioning in time t,
$\mathrm{CI_t}$ – cost of inland repositioning in time t,
$\mathrm{CS_t}$ – cost of container storage in time t,
$\mathrm{CL_t}$ – cost of leasing in time t.

To determine the optimal (s, S) values for each terminal, three metaheuristic optimization techniques are employed:

- Genetic Algorithm (GA),
- Particle Swarm Optimization (PSO),
- Simulated Annealing (SA).

Each of these metaheuristic algorithms requires the selection of specific hyperparameters that govern their search behavior and convergence properties. Several theoretical approaches exist for hyperparameter tuning, such as the Self-Tune Linear Adaptive-GA (STLA-GA) (Ooi et al., 2019) and Adaptive Particle Swarm Optimization with Supervised Learning and Control (APSO-SLC) (Dong and Zhou, 2017). Several practical tools like the Python libraries Optuna and Hyperopt are developed for this purpose as well. However, in this study due to the high computational cost associated with evaluating the objective function—which requires running detailed simulations—hyperparameter tuning for the metaheuristic algorithms was not performed. Instead, used literature-recommended default parameters to ensure fair and reasonable performance benchmarking.

Genetic algorithms use a population-based search strategy that compares different solutions. First, the initial population of possible (s, S) solutions is randomly generated. Each solution is evaluated using the objective function, which calculated repositioning costs. The fittest solutions are selected based on their performance, and genetic operators—selection, crossover, and mutation—are applied to create a new generation. Selection ensures that better-performing solutions have a higher probability of passing their characteristics to the next generation. Crossover combines elements of two parent solutions to generate new offspring, while mutation introduces small random changes to maintain diversity and prevent premature convergence. This process repeats for a predefined number of generations or until a convergence criterion is met, ultimately yielding near-optimal (s, S) values for each terminal.

Selecting appropriate parameters for GA optimization is crucial, as it requires balancing exploration (searching for diverse solutions) and exploitation (refining the best solutions).

Table 1: Parameters used for GA optimization

	Value
Population size	100
Generations	50
Mutation rate	0.2
Crossover rate	0.5

In this study, a population size of 100 is selected, providing a good trade-off between exploration and computational efficiency. Increasing population greater diversity and exploration can be achieved.

The number of generations set the number of iterations of the optimization. A value of 50 generations is chosen, allowing us to find near-optimal solution within sufficient time.

The mutation rate defines how often random changes are applied to solutions. A rate of 0.2 is selected.

Crossover rate is a recombination operator that defines how often two solutions combine their genetic information (Alajmi and Wright, 2014). A rate of 0.5 is chosen.

Particle Swarm Optimization (PSO) also begins with a set of the initial solutions, but unlike other algorithms, it adjusts the solutions dynamically over time. At the beginning the initial population of candidate solutions, referred to as particles, is generated.

For each particle velocity and position of particle initialized. The algorithm then evaluates the fitness of each particle based on a predefined objective function. The best solution found by each particle is stored as its personal best (pBest), and the overall best solution found by any particle in the swarm is stored as the global best (gBest). In each iteration velocity and position is updated and solution is reevaluated.

This process is repeated for a set number of iterations or until convergence is achieved, allowing the swarm to converge on an optimal or near-optimal solution for the problem at hand.

Table 2: Parameters used for PSO optimization

	Value
Population size	100
Generations	50
Inertia weight	0.5
Cognitive constant	1.5
Social constant	1.5

For PSO optimization the same population size and generations value used as for GA.

The inertia weight describes the impact of previous velocity on the current velocity (He et al., 2016). A value of 0.5 is chosen to moderate the influence of the previous step.

The cognitive constant defines the impact of personal best position on the movement, while social constant defines the impact of global best on the particle's movement. For both constants the selected value is 1.5.

Simulated Annealing (SA) begins with a single solution, which is gradually improved through iterative adjustments. The initial solution is evaluated using the objective function to calculate its cost. The algorithm then randomly adjusts the solution and creates a new candidate solution. The cost of the new solution is then evaluated. If the new solution results in a lower cost, it is accepted. If the new solution has a higher cost, it may still be accepted with a certain probability that decreases over time as temperature is gradually reduced.

Table 3: Parameters used for SA optimization

	Value
Initial temperature	1000
Cooling rate	0.99
Minimum temperature	1e-3

The following parameter values have been selected based on standard practices and experimentation. The initial temperature of 1000 is chosen allowing algorithm to escape local optima.

Cooling rate defines how temperature changes after each iteration, allowing algorithms to shift from exploration to exploitation.

Minimum temperature defines where algorithm stops to accept worse solution (with higher costs). A minimum temperature of 1e-3 ensures that the search stops after sufficient refinement.

2.5. Result Analysis

To validate the model and assess the robustness of the optimization approach, a sensitivity analysis conducted on lead times and costs. Compare the optimized (s, S) inventory policies found by different optimization algorithms.

3. Results and Discussion

Three different optimization techniques – Simulated Annealing, Particle Swarm Optimization and Genetic Algorithm – were employed to determine the optimal (s, S) inventory policies, specifically the reorder points and order-up-to levels measured in number of containers, for three terminals: Klaipeda, Kaunas and Vilnius. The objective was to minimize total inventory costs per day, measured as the average daily costs over the simulation period.

Among the three methods, Simulated Annealing identified solution more quickly than other optimizations techniques, demonstrating its efficiency in converging to an optimal inventory policy.

Table 4: Simulated Annealing results

	s	S
Klaipeda	32	262
Kaunas	84	188
Vilnius	98	237

The total cost for the best solution obtained through SA was 890,44 EUR per day.
Similarly, Particle Swarm Optimization identified an equally effective inventory policy, achieving the same total costs, while recommending different reorder points and order-up-to levels.

Table 5: Particle Swarm Optimization results

	s	S
Klaipeda	54	283
Kaunas	30	176
Vilnius	70	240

The total cost for the best solution obtained through PSO was 890,44 EUR per day.
The Genetic Algorithm was the slowest optimization technique. However, it also identified a solution with the same total costs per day.

Table 6: Genetic Algorithm results

	s	S
Klaipeda	35	259
Kaunas	86	220
Vilnius	74	274

The total cost for the best solution obtained through GA was 890,44 EUR per day.
All three optimization techniques identified different solutions that resulted in the same total inventory costs per day. The existence of multiple combinations of reorder points and order-up-to levels leading to the same objective function value suggests the presence of multiple near-optimal solutions.
To further validate the findings, the supply and demand simulation was executed again, followed by the deployment of optimization techniques. In this subsequent run, all three methods returned a solution with a total cost of 797,52 EUR per day, reinforcing the consistency of the optimization approach.

Table 7: Results of the second experiment

	s	S
Simulated Annealing results		
Klaipeda	65	210
Kaunas	52	204
Vilnius	41	214
Particle Swarm Optimization results		
Klaipeda	57	268
Kaunas	93	175
Vilnius	29	280
Genetic Algorithm results		
Klaipeda	56	225
Kaunas	38	266
Vilnius	75	228

In traditional inventory control, achieving the same total costs with different reorder points and order-up-to levels often reflects different inventory policies. In one approach, larger batches are ordered less frequently, whereas in another, smaller batches are ordered more frequently. However, in our case, since there are no fixed ordering costs, this explanation does not apply.
A key observation is that if the number of available containers never fall below the reorder point and do not exceed order-up-to level, then any order-up-to level exceeding maximum number of containers available at a terminal during the simulation period will yield the same total costs. In such cases, different S values do not impact on the cost outcome. To verify this, the repositioning of containers was re-executed using the same supply and demand simulation results. This time, the lowest S value from any of the three optimization techniques was applied, while keeping reorder points (s) values from the SA optimization.

Table 8: Input values for recalculation of costs

	s	S
Klaipeda	65	210 (SA)
Kaunas	52	175 (PSO)
Vilnius	41	214 (SA)

The input of previously identified re-order points and order-up-to levels resulted in total costs of 797,52 EUR per day, which matches the optimal solution.
To verify whether there exists a threshold S below which total costs increase, the repositioning simulation was re-executed, reducing S value by 50%.

Table 9: Input values (reduced S)

	s	S
Klaipeda	65	105
Kaunas	52	88
Vilnius	41	107

A decrease in order-up-to levels led to an increase in total costs per day, which rose to 901,48 EUR, confirming that reducing S beyond a certain point would lead to higher inventory costs, confirming the impact of order-up-to levels on the overall cost structure.

While the optimization techniques identify combinations of decision variables that minimize total costs, the presence of multiple solutions with identical cost outcomes reveals an important practical insight that the (s, S) inventory policy offers flexibility in how shipping companies can manage their operations. Rather than being constrained to a single optimal solution, shipping company can choose from a range of near-optimal policies that align with their specific strategic goal. For instance, a policy with a lower order-up-to level may be preferable for firms aiming to maximize container turnover, allowing the company to utilize its assets more efficiently. In contrast, a policy with higher inventory thresholds might be chosen to ensure greater availability and buffer against demand variability. This flexibility allows decision-makers to tailor inventory strategies to operational preferences or risk tolerance, without sacrificing cost efficiency.

4. Limitations and Conclusion

This model can be directly applied by shipping lines in scenarios where the supply and demand of empty containers are generated based on historical data distributions. Alternatively, the model allows for the incorporation of forecasted supply and demand values, provided that such predictive data are available to the shipping company.

However, a key limitation of the model lies in the assumption of an unrestricted supply of empty containers for import at port terminals. In situations where the entire region experiences a container deficit, this assumption may not hold, potentially limiting the model's applicability and accuracy.

The current optimization framework focuses on the transportation, storage and leasing costs. Nonetheless, it would be beneficial to consider the environmental impact associated with repositioning of empty containers. Future research will aim to extend the optimization model by incorporating ecological considerations through a multi-objective framework aimed at achieving more sustainability focused inventory management.

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The problem of inexcusable postponement and logistics?

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Abstract

Problem: Contractual delays and inefficiencies in waste collection logistics at airports result in heightened operational costs and environmental risks.
Research gap: Current literature has not systematically examined the economic implications of delayed waste transfer operations within airport settings.
Methodology: This study employs the Additive Ratio Assessment (ARAS) method to assess alternative waste collection vehicle scenarios at Sabiha Gökçen Airport, Istanbul, Turkey.
Results: The analysis identifies Scenario A2 as the most cost-effective and operationally efficient solution, offering optimized vehicle routing and reduced transfer delays.
Practical relevance: The findings provide actionable insights for airport operators, waste service providers, and logistics planners aiming to minimize costs and enhance sustainability in airport waste management systems.

1. Introduction

The airports are basically local a mixture of entities. Hence the waste management in airports are governed by many different organizations, from authorities to private enterprises. Airports are also governed by strict regulations and must comply with international and national jurisdictions. For instance, a municipality with waste reduction targets can be a threat or opportunity for an airport entities' waste management policy. Also, the contracts, responsibilities that various stakeholders have with the airport operator are different from one place to another. Airport management services have baggage handlers, passenger assistant, reservation agents are field of common airport operations but one of them which is terminals waste management plays a vital role in bringing about as a predictor of sustainable customer satisfaction and sustainable logistics management. Terminal waste management provides services to airport terminals with other services. But these services have now conducive significant operational squabbling and have been an insurmountable problem due to inexcusable postponement the commercial contracts. This paper looks at a major challenge that air operations managements the unique complexities faced and method they can suggest solutions to problems.

This paper therefore set out to assess the effect of the increasing academic concern with meeting changing passengers (customers') needs and the problems of developing airport services in the face of unforeseen issues, including inexcusable postponement the commercial contracts. This paper also is intended primarily for the study is to explore how decision-making methods such as multi-criteria decision-making (MCDM) can help decision makers address operational challenges effectively. The methodological approach taken in this study is to a real case at Sabiha Gökçen International Airport. Th**is** paper offers practical valuable and practical solutions to improve the performance of Sabiha Gökçen International Airport operations in term of the problem of inexcusable postponement the commercial contracts. In all, -despite the limitations- the paper presents a systematic approach to decision-making in the airport waste management and add to a growing body of literature with a quantitative model for addressing waste logistical cost and operational inefficiencies. Moreover, the hazardous waste collection and the hazardous waste logistics hasn't discussed and hasn't bound to a specific topic in this paper.

Effective waste management and waste logistics is a crucial aspect of airport operations, yet achieving cost-effectiveness remains one of a significant problem. However, various sustainable waste management strategies can be implemented to enhance waste logistics diminishing while ensuring operational efficiency. The successful application of such strategies not only benefits airport management by improving regulatory compliance and reducing waste logistics costs but also enhances passenger satisfactions and overall airport effectiveness (Baumgartner & Buckley, 2017).

A key strength of this study is its comprehensive approach to airport waste management, an increasingly significant topic in academic and logistics research. The airport management, driven by evolving passenger demands and operational cost and regulations complexities, requires a strategic balance between waste management cost and infrastructure optimization. While increasing services may severely seem like a direct solution, their implementation is often hindered by unforeseen problems (Graham, 2020).

Therefore, it is imperative for airport management to optimize existing infrastructure and develop efficient waste management and waste logistics frameworks that accommodate increasing global passenger numbers while maintaining economic sustainability. These strategies must comply with standards set by international aviation authorities such as International Air Transport Association (IATA) and International Civil Aviation Organization (ICAO).

This paper deals with inexcusable postponement the commercial contracts which is one of the hidden cost problems of waste management at airports general approaches. More broadly, the paper also defines the basic problems of inexcusable postponement the commercial contracts management at the airport site in the concept of circular economy that can also be used to minimize of cost waste. Unfortunately, expansionary airport services cannot be enacted by airport management quickly due to unpredicted problems (Alıcı, 2016). Therefore, expansionary airport services do suffer from several flaws. Hence, the airport management must find ways to optimize the current inexcusable postponement the commercial contracts management and ensure that it serves the increasing customer numbers and the increasing customer demands. Evolving passenger demand renders the challenges. And expansionary airport services cannot always be implemented quickly due to unforeseen problems. Methodological problem is the delayed execution of commercial contracts has become a significant issue due to creating an insurmountable problem for waste management.

The primary aim of this paper is to is basically to assesses the significance of the effectiveness of Sabiha Gökçen's International Airport in Istanbul waste management policies which are propose a depth analysis framework based on. This numerical analysis was conducted using criteria such as reducing the amount of waste, increasing the quantity of waste, effective cost recovery and minimizing environmental impacts ground of inexcusable postponement the commercial contracts. For this purpose, the parameters were determined after the literature review was done and information's were taken from the authorized resources to achieve realistic conditions in the analyses (Sabiha Gökçen Airport, 2024). During this study, the necessary calculations have been made for using 2024 data obtained within the scope of the studies carried out at Sabiha Gökçen's International Airport in Istanbul were used.

By 2024, according to data provided by government institutions, Sabiha Gökçen's International Airport has 37 thousand 910 passengers in the international lines, 39 thousand 742 passengers, including a total of 77 thousand 652 international passenger traffic took place in Sabiha Gökçen Airport. (Sabiha Gökçen Airport, 2024).

On the day the record was broken, a total of 424 flights were held in international lines. Sabiha Gökçen Airport brings Istanbul, which is one of the most visits cities in the world in 2024, with a total of 141 destinations, 38 domestic lines and 103 international lines in 51 countries. In conclusion, this study applies the Additive Ratio Assessment (ARAS) method as a methodological approach to assist decision-makers in determining the optimal solution for a similar case that occurred at Sabiha Gökçen International Airport in Istanbul.

With the rapid increase in passenger traffic at Istanbul Airport in recent years, the management of waste logistics has emerged as a significant operational challenge. Table 1 provides a summary of the annual passenger volume, number of flights, and estimated waste generation from 2019 to 2023.

Table 1: Passenger Traffic and Waste Generation Data at Istanbul Airport

Year	Passenger Volume (millions)	Annual Flights	Estimated Waste (tons/year)
2019	52.0	329,799	15,000
2020	23.4	150,000	7,500
2021	37.2	233,074	11,200
2022	64.5	425,901	18,500
2023	76.0	505,000	20,000

Note: The annual waste quantities are calculated based on an assumed daily waste production of 100 tons.

2. Concrete research questions

A structured literature review was undertaken utilizing the Scopus and Web of Science databases. Articles published between 2010 and 2024 were examined using the keywords “airport waste management,” “airport waste logistics,” “contractual delays in waste management,” and “municipal waste collection costs.” A total of 28 pertinent peer-reviewed studies were identified and analyzed to establish a comprehensive foundation for the current research.

In design research, it has been posed research questions to define the scope and the modes of inquiry. We have filled this gap by using ways of constructing questions and define the scope and focus of the paper.

- How does the undesirable inexcusable postponement the commercial contracts disruption logistics processes?

- What are the effects of untimely the fulfillment of the obligations by commercial contract obligations four primary modes of transport in the logistics industry likes air?
- How can waste logistics companies manage the risks cost overruns due to delaying in commercial contracts?
- How do chain reactions from delays in inexcusable postponement the commercial contracts spread throughout the supply chain?
- What are the metrics used to provide a way of quantifying the similarity or dissimilarity between data points and manage postponement in the supply chain?
- What role can technology trends play in the waste logistics sector to prevent inexcusable postponement the commercial contracts?

Finally, this paper has a new field and questions, but most previous research studies are contained only a new range of methodological approaches. Moreover, the project has unique survey that is more engaging to get publishing's and metrics. In addition, no research has been found that Additive Ratio Assessment as methodological approach was based on these data and previous published studies are limited amount of original research. Findings are discussed with qualify the previous literature which are very less, and directions for future empirical research are pointed out due to inexcusable postponement the commercial contracts in cost problems.

3. Research gaps

Although studies have recognized the problem of waste management and logistics relations at the airports, research has yet to systematically investigate the effect of inexcusable postponement the commercial contracts in cost problems in the international airports.

But the gaps in research are remarkable both in terms of subject matter, and size or scope of studies related with waste management and logistics relations and the effect of inexcusable postponement the commercial contracts in cost problems in the international airports. But no previous study has used a method for analyzing multiple factors related to this severely complex relation. Therefore, this paper makes several noteworthy contributions to literature. Waste management and logistics relations and the effect of inexcusable postponement the commercial contracts should be characterized by case study research, often having the benefit of a regular approach.

The research gaps are listed below because of the potential value of gap of research literature on the effect of inexcusable postponement the commercial contracts in cost problems in the international airports.

Table 2: The research gaps

Previous studies have focused on supply chain resilience or supply chain sustainability during times of crisis. This paper offers a different perspective by directly examining the impact of risks on logistics processes.
While most current logistics studies focus on supply chain management, delivery continuity, and the issue of contractual obligations and its cost is neglected. This paper is that directly addresses unjustifiable delay in logistics contracts and its cost in logistics processes. Issue of inexcusable postponement delay in commercial contracts is often neglected.
The impact of contractual delays in international logistics processes on airport operations is an understudied topic. This paper could fill a gap in the literature by explaining how inexcusable postponement violations lead to chain reactions within the global logistics network in airports.
The paper can make an important contribution by addressing the logistics principles during crisis periods and how these effects can be minimized.

Moreover, in this paper, additive ratio assessment ARAS focuses on the analyzing and waste managing risks while evaluating the effects of inexcusable postponement the commercial contracts in cost problems on waste logistics in the international airports. The points where this study differs from the waste logistics literature and the gaps it fills can be explained as follows within the framework of ARAS. While traditional logistics studies focus on risks such as supply chain disruptions, and logistics operational disruptions, transport issues and cargo damage issues but this study only focuses inexcusable postponement the commercial contracts as a separate category within waste logistics.

4. The novelty of research

4.1. As impact of inexcusable delays on waste logistics costs

There is no comprehensive cost-utility and outcome analysis in the literature on the direct effects of inexcusable delays on waste logistics costs on the supply chain. This study presents an ARAS evidence-based analysis by measuring the economic effects of inexcusable delays on logistics costs (such as waste transfer cost and loss of passengers and customer attrition). (Christopher, 2016).

4.2. As impact on airport waste logistics and local economic dynamics (synthesis and evaluation in macro-ARAS evidence-based analysis)

This paper analyzes how inexcusable delays affect waste logistics and reveals the long-term ramifications on airports. Academic studies on inexcusable delays affect delays in airport waste logistics connections are limited. This study completes this growing area and important areas where this study makes an original contribution to the literature by analyzing the effects of inexcusable delays effect on the waste logistics. The empirical findings in this study provide a new understanding of waste management problems. This paper makes a noteworthy contribution to the waste logistics and supply chain management literature and to the current literature and offers applicable solutions in academic works. This paper may also serve may serve as important policy recommendations arising from the case study for local airport or international airport practitioners.

5. Methodology

5.1. Study area

The study area was strategically selected to encompass a large-scale study area, facilitating a comprehensive analysis of waste management logistics at Sabiha Gökçen International Airport. This research investigates the economic implications of avoidable delays on waste logistics costs at Istanbul Sabiha Gökçen International Airport. Specifically, it evaluates their impact on variations in waste management efficiency and productivity, utilizing airport waste data from Istanbul as a case study.

- Istanbul Sabiha Gökçen International Airport features a 9,594 sq m food court for cafés and restaurants, a 4,500 sq m Duty-Free shopping area, and a 400 sq m conference center.
- The airport's multi-aircraft parking system allows synchronized service to eight large fuselage aircraft (IATA code E) or sixteen medium-sized fuselage aircraft (IATA code C).
- The new terminal building and its annexes cover a total area of 320,000 m² (İstanbul Sabiha Gökçen Airport, 2013).

Furthermore, Istanbul Sabiha Gökçen International Airport was recognized as the world's fastest-growing airport for seven consecutive years from 2009 to 2015 (Sabiha Gökçen Airport, 2024). In 2023, it was the second busiest airport in Europe and the tenth busiest globally, setting a passenger traffic record with 37.1 million passengers. Flights are operated to a total of 141 destinations across 51 countries, including 38 domestic and 103 international routes, from Istanbul, which ranks among the most visited cities worldwide in 2024 (Sabiha Gökçen Airport, 2024).

5.2. The problem

Istanbul Sabiha Gökçen International Airport faced with the problem of balance in the removal of waste due to inexcusable postponement the commercial contracts in May 2023. And this severe problem remained until in July 2023. (HotelRestaurant, 2024). As of the last day of July 2023, Istanbul Sabiha Gökçen International Airport has decided not to renewal the contract with the waste generate company operating at this airport. Because waste management company demanded higher fees to keep up with waste managing costs due to extremely sharp and high in the per-unit cost- (existing high rate of inflation) to waste management equipment. This situation caused mountains of waste to form inside the airport and serious hygiene problems to emerge. (HotelRestaurant, 2024). This inexcusable postponement caused the failure of avoiding the minimization of the waste throughout the operations and value chain of Istanbul Sabiha Gökçen International Airport. It also prevented the optimal recovery of recyclable waste and lacked the consideration of the economics of waste and waste logistics operational aspects of waste management in the entire airport operations. In such, waste management in Istanbul Sabiha Gökçen International Airport could not be designed for reuse, remanufacture or recycling. And this was not feasible in Istanbul Sabiha Gökçen International Airport. Although the problem was tried to be solved by providing daily personnel as a solution, the necessary waste management operations could not be provided in the giant facility. The environmental stressors, especially in the waste containers at the airport where thousands of passengers enter and exit every day has caused diseases.

5.3. Mathematical Analysis Using Additive Ratio Assessment (ARAS)

The additive ratio assessment method is relied on quantitative measurements and utility theory. In this method, a utility function value determines the relative efficiency of an alternative over the other alternatives. This utility function is directly proportional to the relative effect of the criteria values and weight importance of the considered criteria. Today, the additive ratio assessment method uses manufacturing technologies, mainly in the form of industrial robots and automated material handling systems (Zavadskas & Turskis, 2010).

This paper seeks to address the following steps were taken to evaluate the data by applying ARAS method.

5.3.1. Data

In 2023, Istanbul Sabiha Gökçen International Airport recorded a passenger volume of 37,098,432, consisting of 17,731,692 domestic and 19,366,740 international passengers (see Table 3). The total number of flights conducted at the airport during this period was 227,878, with domestic flights comprising 107,580 and international flights 120,298 (see Table 4). Monthly passenger traffic data indicate a peak in August 2023, with 3,722,526 passengers, while February exhibited lower activity (see Table 5). Similarly, the number of monthly flight operations reached its zenith in August 2023, with 21,443 flights (see Table 6).

Table 3: Annual Passenger Statistics for Istanbul Sabiha Gökçen International Airport

Year	Domestic Passenger Numbers	Int'l Passenger Numbers	Total Passenger Numbers
2023	17,731,692	19,366,740	37,098,432

Table 4: Annual Flight Statistics for Istanbul Sabiha Gökçen International Airport

Year	Domestic Flight Numbers	Int'l Flight Numbers	Total Flight Numbers
2023	107580	120298	227878

Table 5: Monthly Passenger Traffic Statistics for Istanbul Sabiha Gökçen International Airport

Months	Number of Domestic Flight Passengers	Number of Int'l Flight Passengers	Number of Total Passengers
January	1,354,007	1,444,084	2,798,091
February	1,181,433	1,285,459	2,466,892
March	1,238,660	1,482,056	2,720,716
April	1,266,530	1,497,813	2,764,343
May	1,485,315	1,562,666	3,047,981
June	1,533,531	1,674,490	3,208,021
July	1,773,533	1,859,651	3,633,184
August	1,831,033	1,891,493	3,722,526
September	1,626,510	1,734,344	3,360,854
October	1,572,893	1,728,083	3,300,976
November	1,446,864	1,514,407	2,961,271
December	1,421,383	1,692,194	3,113,577
Total	17,731,692	19,366,740	37,098,432

Table 6: Evaluation of Monthly Domestic and International Flight Operations at Sabiha Gökçen Airport (2023)

Months	Domestic Flight Numbers	Int'l Flight Numbers	Total Flight Numbers
January	8385	9216	17601
February	7463	7982	15445
March	8197	9346	17543
April	8112	9765	17877
May	9380	9996	19376
June	9527	10691	20218
July	9767	11349	21116
August	10138	11305	21443
September	9407	10498	19905
October	9444	10399	19843
November	8679	9286	7965
December	9081	10465	19546
Total	107580	120298	227878

5.3.2. Calculation of Data in ARAS method Data:

By evaluating the data with the ARAS method, we can determine the most appropriate period for waste collection frequency at the airport. Here, the ARAS method helps determine the most appropriate option by evaluating according to the specified criteria. (Baumgartner & Buckley, 2017; Oakland, 1993).

Table 7: Evaluation of Monthly Domestic and International Flight Operations at Sabiha Gökçen Airport (2023)

Criteria	Data
C1: Number of domestic flights	9527 flights/month
C2: Number of international flights	10691 flights/ month
C3: Number of domestic passengers	51117 passengers/ month
C4: Number of international passengers	55816 passengers/ month
C5: The waste collection number of persons employed	100 persons

These data were used directly for the 1-day (A1) alternative. Other alternatives were calculated by scaling them according to a specific waste collection period.

5.3.3. Calculation According to Alternatives

The following ratios were used in the calculation of the alternatives:

Data were divided by 11.

$$X_{ij} = \frac{X_{ij}(A1)}{\frac{Validity}{period\ of\ the\ alternative}} \quad (1)$$

Fij = Normalized value for alternative i and criterion j
Xij = Actual value of alternative i for criterion j
Xjmax = Maximum value of criterion j

The formula determines the normalized value of criterion X for alternative Y by dividing the actual value by the maximum value.

5.3.4. Calculations for All Criteria

C1: Domestic flight number calculation
A1 (1 day) = 9527 aircraft
A2 (3 days) = 9527 / 3=3175.67 aircraft
A3 (7 days) = 9527 / 7 = 1361.00 aircraft
A4 (11 days) = 9527 / 11 =866.09

C2: Calculation of international flight numbers
A1 (1 day) = 10,691 aircraft
A2 (3 days) = 10,691 / 3 = 3563.67 aircraft
A3 (7 days) = 10,691 / 7 = 1527.29 aircraft
A4 (11 days) = 10,691 / 11 = 971.91 aircraft

C3: Calculation of domestic passenger numbers
A1 (1 day) = 1,533,531 passengers
A2 (3 days) = 1,533,531 / 3 = 511,177 passengers
A3 (7 days) = 1,533,531 / 7 = 219,075.86 passengers
A4 (11 days) = 1,533,531 / 11 =139,411.86

C4: International passenger number calculation
A1 (1 day) = 1,674,490 passengers
A2 (3 days) = 1,674,490 / 3 = 558,163 passengers
A3 (7 days) = 1,674,490 / 7 = 239,212.86 passengers
A4 (11 days) = 1,674,490 / 11 = 152,226.36 passengers

C5: The waste collection number of persons employed calculation
A1 (1 day) = 100 people
A2 (3 days) = 100 / 3 = 33.33 people
A3 (7 days) = 100 / 7 = 14.29 people
A4 (11 days) = 100 / 11 = 9.09 people

5.3.5. Normalization

To facilitate standardization and comparability across scenarios, these values were divided to derive daily averages. In ARAS method that is normalization of decision matrix to eliminate the scale effect by using linear scale normalization-sum method. The normalization process is practiced by dividing each value in the decision matrix by the largest value in the relevant column. The formula

Fij = Xij / Xjmax was used. (2)

This formula calculates the normalized value of criterion X for alternative Y by dividing the actual value by the maximum value. This formula determines the normalized value of criterion X for alternative Y by dividing the actual value by the maximum value.

5.3.6. Normalization for Criteria

C1: Normalization for domestic flights numbers

$$\max(X_{ij}) = 9527$$

Normalization for alternatives:

$$X_{11} = \frac{9527}{9527} = 1.000$$

$$X_{21} = \frac{3175.67}{9527} = 0.333$$

$$X_{31} = \frac{1361}{9527} = 0.143$$

$$X_{41} = \frac{866.09}{9527} = 0.091$$

C2: Normalization for int’l flight numbers

$$\max(X_{ij}) = 10691$$

Normalization for alternatives:

$$X_{11} = \frac{10691}{10691} = 1.000$$

$$X_{22} = \frac{3175.67}{10691} = 0.333$$

$$X_{32} = \frac{1527.29}{10691} = 0.143$$

$$X_{42} = \frac{971.91}{10691} = 0.091$$

C3: Normalization for domestic passengers

$$\max(X_{ij}) = 1{,}533{,}531$$

$$X_{11} = \frac{1{,}533{,}531}{1{,}533{,}531} = 1.000$$

$$X_{21} = \frac{5.177}{1{,}533{,}531} = 0.333$$

$$X_{31} = \frac{219{,}075{,}86}{1{,}533{,}531} = 0.143$$

$$X_{41} = \frac{139{,}411{,}91}{1{,}533{,}531} = 0.091$$

C4: Normalization for international passengers

$$\max(X_{ij}) = 1{,}533{,}531$$

$$X_{11} = \frac{1{,}533{,}531}{1{,}533{,}531} = 1.000$$

$$X_{21} = \frac{5.177}{1{,}533{,}531} = 0.333$$

$$X_{31} = \frac{219{,}075{,}86}{1{,}533{,}531} = 0.143$$

$$X_{41} = \frac{139{,}411{,}91}{1{,}533{,}531} = 0.091$$

C5: Normalization for employees

$$\max(X_{ij}) = 100$$

$$X_{11} = \frac{100}{100} = 1.000$$

$$X_{21} = \frac{33.33}{100} = 0.333$$

$$X_{31} = \frac{14{,}29}{100} = 0.143$$

$$X_{41} = \frac{9.09}{100} = 0.091$$

5.3.7. Normalization for Alternatives

The normalization process is calculated with the following general formula (The formula calculates the normalized value of criterion X for alternative Y by dividing the actual value by the maximum value):

$$P_{ij=} \frac{x_{ij}}{\max{(X_{ij})}} \quad (3)$$

A1: Normalization of (1 Day) Alternative
Since all values for this alternative are maximum values, the normalization will be 1.000

$$P_{11} = \frac{9527}{9527} = 1.00$$

$$P_{12} = \frac{10691}{10691} = 1.000$$

$$P_{13} = \frac{1{,}533{,}531}{1{,}533{,}531} = 1.000$$

$$P_{14} = \frac{1{,}533{,}531}{1{,}533{,}531} = 1.000$$

$$P_{15} = \frac{100}{100} = 1.000$$

A2: Normalization of (3 Days) alternative

$$P_{21} = \frac{9527/3}{9527} = \frac{3175.67}{9527} = 0.333$$

$$P_{22} = \frac{10691/3}{10691} = \frac{3563.67}{10691} = 0.333$$

$$P_{23} = \frac{1{,}533{,}531/3}{1{,}533{,}531} = \frac{511177}{1{,}533{,}531} = 0.333$$

$$P_{24} = \frac{1674490/3}{1674490} = \frac{558163}{1674490} = 0.333$$

$$P_{25} = \frac{100/3}{100} = \frac{33.33}{100} = 0.333$$

A3: Normalization of (7 Days) alternative

$$P_{31} = \frac{9527/7}{9527} = \frac{1361}{9527} = 0.143$$

$$P_{32} = \frac{10691/7}{10691} = \frac{1527.29}{10691} = 0.143$$

$$P_{33} = \frac{1{,}533{,}531/7}{1{,}533{,}531} = \frac{219075.86}{1{,}533{,}531} = 0.143$$

$$P_{34} = \frac{1674490/7}{1674490} = \frac{239212.86}{1674490} = 0.143$$

$$P_{35} = \frac{100/7}{100} = \frac{14.29}{100} = 0.143$$

A4: Normalization of (11 Days) alternative

$$P_{41} = \frac{9527/11}{9527} = \frac{866.09}{9527} = 0.091$$

$$P_{42} = \frac{10691/11}{10691} = \frac{971.91}{10691} = 0.091$$

$$P_{43} = \frac{1{,}533{,}531/11}{1{,}533{,}531} = \frac{139411.91}{1{,}533{,}531} = 0.091$$

$$P_{44} = \frac{1674490/11}{1674490} = \frac{152226.36}{1674490} = 0.091$$

$$P_{45} = \frac{100/11}{100} = \frac{9.09}{100} = 0.091$$

5.4. Results and Discussion and Limitations

Diminishing overall waste throughout airports, as well as airport waste management and waste logistics, are regulated under **ICAO Annex 16 (Environmental Protection)**, the **European Green Deal**, and the **FAA's Environmental Management Programs**. These regulations primarily focus on **logistics optimization** (International Civil Aviation Organization [ICAO], 2018). Data normalization results allow different waste collection operation scenarios to be systematically evaluated in accordance with these criteria. The key findings are as follows for Istanbul Sabiha Gökçen International Airport:

- The **A1 (1-day) alternative** offers the highest efficiency in waste management while increasing operational costs and carbon footprint.
- In line with **ICAO's environmental sustainability principles and objectives**, it is strongly recommended that **waste reduction strategies** be developed instead of frequent waste collection operations.

What we know about on data normalization results allow the different the waste collection operation scenarios to be systematically evaluated in line with these criteria. The key findings are as follows:

- The **A1 (1-day) alternative** offers they highest efficiency in terms of waste management but increases operational costs and carbon footprint. In line with ICAO's environmental sustainability principles and objectives it is strongly recommended that waste reduction strategies be developed instead of such frequent waste collection operations.
- **Alternative A2 (3 days)** is the most appropriate scenario that balances airport operational requirements with environmental sustainability. In line with the airport environmental management standards recommended by ACI, this model has higher applicability.

- **The A3 (7 days) and A4 (11 days)** alternatives may cause waste accumulation at levels that could compromise international hygiene and safety standards. Airport waste storage limits determined by the **European Union Environmental Management System (EMAS) and the US Environmental Protection Agency (EPA)** question the sustainability of long-term waste collection processes.

Waste logistics costs vary depending on factors such as the size of the airport, number of flight and passenger density. According to the "Sustainable Airports and Waste Management" report published by ACI, waste logistics standards that should be implemented at airports. Implementation of waste reduction strategies, the evaluation of each alternative based on the normalization results is as follows:

Alternative **A1 (1 day)** may lead to high operational costs, especially in mega airports. According to the sustainability strategies suggested by ACI, this model can only be applied in special cases and peak traffic periods for Istanbul Sabiha Gökçen International Airport.

- **Alternative A2 (3 days)** offers a more applicable model for international airports. This alternative is in line with the "Waste and Recycling Management Guide" determined by the FAA and offers a sustainable option for optimizing waste collection processes.
- **Alternatives A3 (7 days) and A4 (11 days)** are partially applicable in regional airports with low passenger density but may pose risks in terms of hygiene and security in Istanbul Sabiha Gökçen International Airport.

The following recommendations are presented to develop a model that complies with Istanbul Sabiha Gökçen International Airport of management and logistics standards:

- Airport needs to adapt their waste collection processes depending on daily flight and passenger density.
- While the **A2 (3-day)** model can be applied at airports with heavy traffic, **A3 (7 days) or A4 (11 days)** options can be considered at airport with lower density.

The normalization results show the impact of the delay on airport operations for Istanbul Sabiha Gökçen International Airport:

- **Alternative A1 (1 day)** is the scenario that requires the highest waste collection and logistics cost. However, if the agreement with the service provider is delayed for economic reasons, this model becomes unsustainable, and the airport waste management faces the risk of a crisis.
- **The A2 (3-day)** alternative stands out as a model that can optimize operational efficiency while maintaining financial sustainability. Under economic constraints, choosing this alternative can provide advantages in terms of cost effectiveness. **The A3 (7-day) and A4 (11-day)** alternatives are cost-cutting strategies that can be implemented in case of a delay in reaching an agreement with the carrier. However, the compliance of these models with hygiene standards should be questioned.

In this paper, in conforming of the key findings or definitive recommendation is implementation of "dynamic and intelligent waste management model" for the problem of inexcusable postponement the commercial contracts in Istanbul Sabiha Gökçen International Airport.

- Peak traffic and the busiest travel days and the most exhausting period in airports **A1 (1 day) or A2 (3 days)** alternatives should be applied, and in low-density periods, longer period garbage collection models such as A3 (7 days) or A4 (11 days) should be adopted.
- This system will be compatible with the environmental sustainability principles of **ACI (Airports Council International) and ICAO.**
- Flexible and gradual garbage collection system" should be implemented to reduce waste logistics costs.
- Smart waste management technologies should be used to prevent agreement delays caused by economic fluctuations.

Moreover, the most important results of the research are,

- This research demonstrates that airport waste management and waste logistics can be optimized through a balance between environmental sustainability, operational efficiency, and economic feasibility.
- The normalization analysis identifies **A2 (3-day collection)** as the most effective model, balancing cost efficiency, environmental compliance, and operational viability, while highlighting the limitations of both A1 **(daily collection, high cost) and A4 (11-day collection, hygiene risks).**

The next steps in the research project may have future research should focus on integrating digital waste monitoring and waste logistics systems, applying AI-driven predictive analytics, and expanding case studies on various airport scales. Further investigation into zero-waste policies and automated waste collection systems would enhance waste management strategies in the aviation industry.

Regarding a critical appraisal of the done paper, where limitations are the study relies on theoretical modeling rather than empirical data from airport operations. Additionally, economic exigencies (and economic exigencies and fluctuations such as economic goal variables like real gross domestic production, high and inconsistent inflation rate, and the high of rate of unemployment) affecting waste collection agreements were considered but not deeply analyzed.

In the future, it will be important to explore the potential use of opportunities are expanding research through pilot implementations at different airports may have opportunities that are assessing real-time cost-benefit outcomes, and incorporating stakeholder perspectives (airport authorities, waste contractors, regulatory entities and institutions) would refine the findings. And further research is required to exploitation perspective for ARAS method in multicriteria decision-making.

This research may relate with automating and digitizing waste logistics management solutions, including AI-driven waste collection scheduling and IoT-based sensor monitoring. Sustainable airport operations consulting will assist airports in achieving regulatory compliance and reducing waste-related logistics costs.

A corporate strategy that should include coordination with all airport stakeholders and waste logistics companies will be made sustainable, delays caused by economic reasons will be minimized and full compliance with international aviation standards will be ensured. The implementation of this ARAS method in multicriteria decision-making will contribute to maintaining operational continuity at airports, reducing costs and ensuring environmental sustainability.

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Participating Institutions

Otto von Guericke University Magdeburg

The Otto von Guericke University (OVGU) was founded in 1993 from three institutions of higher education:

- the Technical University Magdeburg,
- the Teacher Training College and
- the Medical Academy of Magdeburg.

It is named after the famous scientist Otto von Guericke (1602-1686), whose research on the vacuum, especially his hemispheres experiment, earned him fame beyond German borders.

Some facts & figures:

- 9 Faculties (Logistics is part of Mechanical Engineering)
- More than 100 academic programs
- About 12 500 students
- About 4000 of them are international students
- Double degree in Logistics with Free University Bozen (Italy) & Chiang Mai University (Thailand)
- Career-integrated study programme options
- More and more English-language study programmes and modules.

The OVGU has 65 years of experience in training and research in the fields of conveying technologies, logistics and material handling systems. It initiates also many modern topics such as AI engineering and mobility topics and autonomous driving.
Research areas are:

- Analysis, diagnosis, modelling, simulation& design in logistics and SCM
- Fundamentals of technical logistics
- Design and improvement of process chains (1PL to 4PL)
- Planning methods and tools in logistics
- Mobility topics and sustainability
- Evaluation, planning and design of logistics networks
- Industry 4.0 and Logistics 4.0
- Further education, business games and in-house training in Logistics & SCM
- Application of artificial intelligence (AI) in production and logistics.

https://ieps.ovgu.de/IEPS-p-1.html

Photo: Jana Dünnhaupt

Universidad Central "Marta Abreu" de Las Villas

The Universidad Central »Marta Abreu« de Las Villas (UCLV) was founded in 1948 in Santa Clara. Approximately 11000 students are enrolled at the university, which consists of 12 faculties. The green, spacious campus is located on the outskirts and makes up its own small student town that could be reached by car, bus or train. UCLV is the third-biggest university of Cuba. It has ranked on top places in all national evaluations of the quality of teaching and research. UCLV is part of several national and international research networks and has scientific cooperation with 130 institutions around the world. Intensive collaboration with the OVGU in Magdeburg focuses on the departments of manufacturing, engineering and quality management, mechanics, construction, computer science, automotive technology, process and environmental technologies and especially logistics and material handling systems.

In 2016, the university immersed in an integration process where industrial engineering and mechanical engineering came together in a single faculty named Faculty of Mechanical and Industrial Engineering.

Out of the 90 faculty members, 60% hold a Doctorate in a specific science, and 70% have attained a higher teaching rank. The faculty has two teaching departments (Mechanical Engineering and Industrial Engineering), two Study Centers (Center for Energy Studies and Environmental Technologies, Welding Research Center).

The most important fields of research within the Department of Mechanical Engineering related to logistics and material handling systems are:

- Technical logistics,
- Quality management, quality engineering, metrology, measurement uncertainty
- Manufacturing (manufacturing engineering and welding technology),
- Environmental technology.

Furthermore, researches conducted in the fields of biomechanics, mechatronics, development and construction. The central fields of research pertaining to logistics and material handling systems at the Department of Industrial Engineering are:

Quality management, quality engineering, Mathematical statistics, operations research, design of experiments, statistical simulation, Reliability and safety, Logistical networks.

www.uclv.edu.cu

Photo: Norge Coello Machado

National Aerospace University “KhAI”

National Aerospace University, Kharkiv, Ukraine (KhAI) was established in 1930. Its history is closely connected with the development of aircraft engineering and science. The University is well-known for its achievements in aviation industry, namely for the creation of the first European high-speed airplane with a retractable landing gear and the design of the turbojet engine. At present about 9.500 students and 160 post-graduate students are trained at the University; 650 teachers and 2.500 employers work here. Among them there are 120 Professors and PhD. This makes KhAI one of the leading institutions of higher education in that trains specialists for aerospace industry in Ukraine and abroad. During the period of its existence the University has trained about 80000 engineers. More than 80 % of the experts with higher education who work in Ukrainian aerospace area are the graduates of the NAU KhAI.

The NAU KhAI is a member of International Association of Universities, EASN, PEGASUS organizations as well as is a signatory of Magna Charta Universitatum. Together with European partners it received the highest number in Ukraine of scientific and educational grants TEMPUS FP-7 and the European Union. The NAU KhAI is a co-executor of many scientific and educational programs which are carried out with universities and companies of EU, Mexico, China.

In 1994 KhAI signed a partnership agreement with OVGU, thus setting new joint educational and research tasks in aircraft design, composite component design, technologies for rapid processing of steel structures etc.

National Aerospace University is persistent in raising its bar, being always ready to welcome and support students and young researchers from all over the world.

https://khai.edu/en/university/

University of Miskolc

The history of the University of Miskolc refers to Mining and Metallurgy back in 1735. Since those times, the organization of the University changed and was extended several times with new faculties, now being named since 1990 the University of Miskolc. While technical education has the longest tradition at the University of Miskolc, during the recent decades the institution was transformed into a true university. Currently it has eight distinct faculties. At present, faculties have more than 9000 students, who are assisted in their academic advancement by an educational staff of more than 550 and a non-educational staff of more than 650 members.
On most faculties, B.Sc. and M.Sc. programs are both offered for the students. The University of Miskolc started Ph.D. programs on the basis of accredited doctoral programs on October 1, 1993. Currently six Faculties of the University offer doctoral programs and award Ph.D. degrees in seven disciplines: Earth Science, Materials Science and Technologies, Engineering Science, Information Science, Law, Economics and Management Science, Literary Studies.
The University of Miskolc is the largest higher education institution in Northern Hungary. With its highly qualified experts, instrument infrastructure and laboratories, it contributes to scientific research and technical development in Hungary.
The Institute of Logistics is part of the Faculty of Mechanical Engineering and Informatics. The Institute has a wide range of educational activities at 3 Faculties of the University of Miskolc in the frame of full time and part time trainings. The focus of research activities of the institute lies in the following fields:

- Design of materials handling machines,
- Controlling and planning methods for modular materials handling systems,
- Computer integrated logistics, information logistics,
- Production and service logistics,
- Warehouse logistics, stock management,

- Design of materials handling machines,
- Controlling and planning methods for modular materials handling systems,
- Computer integrated logistics, information logistics,
- Production and service logistics,
- Warehouse logistics, stock management,

www.uni-miskolc.hu

Photo: Uni Miskolc

Anhalt University of Applied Sciences

Innovation, cosmopolitanism, creativity and culture are traditions of the Anhalt region to which the Anhalt University of Applied Sciences with its three campuses in Bernburg, Dessau and Köthen and its seven departments feels particularly committed. Therefore, since its foundation in 1991 the university feels responsible for making a significant contribution to the economic and social development of the region and the state of Saxony-Anhalt through its practice-oriented education and applied research. The bachelor's and master's degree programs at the various departments have one thing in common - in addition to imparting specialist knowledge, they prepare the 8.000 students of the Anhalt University of Applied Sciences, from whom 2.000 have an international background, for a successful start to their careers.
In May 2021, the extension of the right to award doctorates to universities of applied sciences in Saxony-Anhalt gave rise to the "Social, Health and Economic Sciences" doctoral center at Anhalt University of Applied Sciences, which is a collaborative effort between Anhalt University of Applied Sciences and three other universities in the state.
The Chair of Business Administration, in particular Supply Chain Management, Operations Management and Digitization, situated at the Department of Economics at Anhalt University of Applied Sciences and headed by Prof. Dr.-Ing. Trojahn, deals with current developments along entire supply networks with regard to various thematic research focuses such as:

- Supply Chain Network Design, Planning & Operations
- Operations Research
- Process Optimization
- Digitalization and Logistics 4.0
- Resilience
- Sustainability

www.hs-anhalt.de

Photo: Hochschule Anhalt

Magdeburg-Stendal University of Applied Sciences (h2)

Since the Magdeburg-Stendal University of Applied Sciences was founded in 1991, it has earned an excellent reputation for a well-founded academic education and for a committed student body. Prospective students can choose from around 50 courses at three departments in Magdeburg and two departments at the Stendal site. Around 130 professors guarantee a very good supervision rate for around 3,700 students in Magdeburg and more than 1,800 in Stendal.

The research profile at the Magdeburg-Stendal University of Applied Sciences is characterized by future-oriented research and development activities tailored towards key markets in the state of Saxony-Anhalt and the requirements of regional businesses and institutions. To this end a large number of innovative research and development projects in the fields of engineering, economics, public health, communications and the social sciences is implemented. By concentrating specific skills in a number of competence centers it is possible to take a holistic, cross-disciplinary approach to research themes.

At the Magdeburg-Stendal University of Applied Sciences there are a total of 9 main research areas, from electrical engineering and information technology, innovative technologies, machines and components to water and recycling management. In the concrete field of application of the economy, the focus is on the following research topics:

- Management in the fields of public health, service provision, and demographics
- Entrepreneurship and risk management
- Production and process management and simulation
- Logistics and Digitalization
- Technology and investment management
- Marketing, especially for regional enterprises, institutions, and networks
- Change and sustainability management
  Staff development and inter-cultural competence

Since 2022, the Magdeburg-Stendal University of Applied Sciences has made it possible to do a PhD in the cross-university doctoral center "Social, Health and Economic Sciences" in association with the universities of applied science of Anhalt (HSA), Harz and Merseburg and in the university's own doctoral center "Environment and Technology". Already in the first phase of the acceptance applications, four doctoral projects in the context of logistics and under the supervision of Prof. Behrendt (h2) and Prof. Trojahn (HSA) were approved.

https://www.h2.de/home.html

Photo: Hochschule Magdeburg-Stendal

Merseburg University of Applied Sciences

Study. Research. Live. – This is far more than just the motto of Merseburg University of Applied Sciences. As a center for applied sciences located in the south of Saxony-Anhalt in an industrial and cultural region, steeped in tradition, the university offers everything necessary to guarantee that students can enjoy success in their studies on a vibrant, green campus.

With approximately 3,000 students, Merseburg University of Applied Sciences (HoMe) is one of the smaller universities in the federal state of Saxony-Anhalt. This creates a friendly atmosphere on campus, conducive to studying as well as personal and uncomplicated support from the professors - you can easily approach them and ask for help. In addition to this, the International Office and the Registrar's Office provide help and support for international students.

Merseburg University of Applied Sciences offers students a wide range of bachelor and master programs, run by three departments:

- Department of Engineering and Natural Sciences
- Department of Social Work.Media.Culture
- Department of Business Administration and Information Sciences

At HoMe students can study in modern lecture halls, in small working groups and in practice-oriented projects. Here we place great importance on independent, team oriented and problem-solving work. The technical equipment of our laboratories, workshops and practical training rooms is state-of-the-art, thus providing students with an excellent education.

So, benefit from the pleasant studying and learning atmosphere on our green campus and become part of the HoMe!

https://www.hs-merseburg.de/

Photo: Hochschule Merseburg

Université Le Havre Normandie (ULHN)

Université Le Havre Normandie (ULHN) was established in 1984 and it now counts over 8200 students. It is committed to supporting personal and professional development of all its students.

The ULHN is composed of three Training and Research Units –Teaching and Research Unit of Sciences and Technology, Faculty of International Affairs, Teaching and Research Unit of Arts and Humanities – of a University Institute of Technology, an Engineering School, a Higher Institute of Logistic and different departments.

The training focuses on four main thematic areas: Arts, Literatures and Languages; Law, Economics, Management; Humanities and Social Sciences; Sciences, Technology, Health. In order to prepare professional integration of students and to promote their mobility in Europe, it is based on three main guidelines: professionalization, international openness, multidisciplinary.

The scientific potential of the University is based on eleven research laboratories, two of which are associated to CNRS and one to INERIS. Research has been articulated around 4 sectors: Human and social studies; chemistry – biology; Mathematics – information technology; Engineering Science. Some works are also carried out around interdisciplinary areas. These research activities nourish and enrich teaching.

The ULHN was born out of the determination of all the local actors and it was built in harmony with the development of a port city, open to the world, attentive to its socio-economic environment and to public expectations.

https://www.univ-lehavre.fr/en/

Photo: Université Le Havre Normandie

We also welcome the participants from Kyrgyztan, Latvia and Uzbekistan.

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Anhalt University of Applied Sciences, Germany

Prof. Dr.-Ing. Hartmut Zadek
Chair of Logistics
Otto von Guericke University, Germany

News and Dates

News:

- **Our former doctoral student and IDWL workshop participant receives a major award: Junior Professor Dr.-Ing. Sebastian Lang awarded the BVL Science Prize in Germany for his dissertation**:
  'Methods of reinforcement learning for production scheduling'
  In October 2024, Sebastian Lang received the Logistics 2024 Science Prize from the German Logistics Association, which is endowed with 5,000 euros: "The prizewinner's dissertation examines an important area of artificial intelligence with regard to a specific practical field of application, the calculation of production schedules. The scientist uses methods of reinforcement learning (RL). This makes it possible to train software by means of trial and error so that it can then calculate production process decisions in real time. The difference to established methods lies in the fact that training is not based on training labels, but rather on trial and error. In the long term, RL applications draw the right conclusions from both positive and negative feedback and develop the right planning and control strategy step by step,'it said.'

  (See https://logistik-heute.de/news/wissenschaftspreis-logistik-2024-sebastian-lang-ueberzeugt-mit-berechnung-von-produktionsablaufplaenen-16707)

  OpenAcess Publication:
  https://link.springer.com/book/10.1007/978-3-658-41751-2

- **Mrs Prof. h.c. Elke Glistau** will retire on 1 September 2025.
  We wish her an active retirement and welcome her back for future events!

- **New Master course** at the OVGU Magdeburg:
  Wirtschaftsingenieurwesen Produktion, Logistik, Produkte with the 3 profiles:
  - Produktion und Logistik,
  - Nachhaltige Mobilität,
  - Ressourceneffiziente Produkte.

Dates:

- **COMEC 2025** from 20 to 24 October 2025 in Cuba / Cayos Santa Maria, Hotel Melia Las Dunas
  https://www.comec.ovgu.de/
  Email: norge.coello@ovgu.de
- **EEEU25,** 24-26 September 2025, Seoul, South Korea
  5th Global Conference on Entrepreneurship and Economy in an Era of Uncertainty
  https://eeeu25.gjem.press/conference
- **19th International Doctoral Students Workshop on Logistics, Supply Chain and Production Management** on 15. & 16. June 2026
- **CECOL 2026** in October2026 in Miskolc -Lillafüred / Hungary
- **Guest lectures series on logistics** - from April to June 2026

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