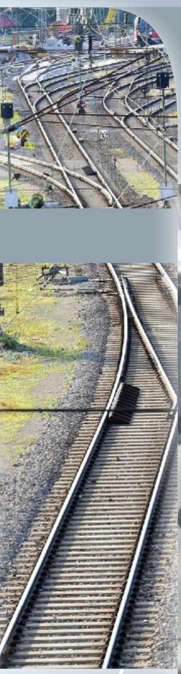
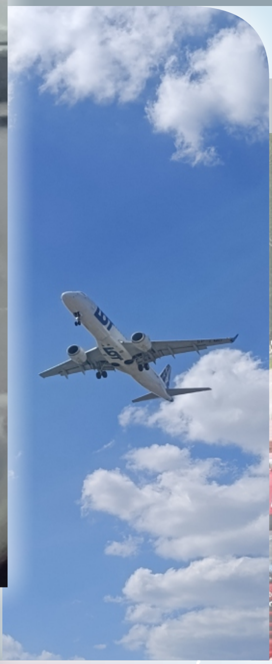
CZESTOCHOWA UNIVERSITY OF TECHNOLOGY

Logistics Challenges: Global and Local Approaches

Editor
Beata Ślusarczyk





Częstochowa 2024

Czestochowa University of Technology

Logistics Challenges: Global and Local Approaches

Editor
Beata Ślusarczyk

Monograph

Publishing Office of Czestochowa
University of Technology

Częstochowa 2024

Reviewers
Joanna Nowakowska-Grunt
Magdalena Biel
Marko van Deventer
Joanna Górniak
A. Hariharasudan
Bilal Khalid
Joanna Krzywda
Aleksandra Laskowska
Re-an Müller
Paula Pypłacz
Hana Stverkova
Manuela Tvaronavicene
Joanna Wiśniewska

Proofreading
Zdzisława Tasarz

Make-up
Dorota Boratyńska

Cover design
Dorota Boratyńska

ISBN 978-83-65976-10-9
e-ISBN 978-83-65976-11-6
DOI: 10.17512/CUT/9788365976116

The Publishing Office of Czestochowa University of Technology
Poland, 42-200 Częstochowa, al. Armii Krajowej 36 B
Editorial Team – wydawnictwo.pcz.pl, phone 34 325 04 80, e-mail: wydawnictwo@pcz.pl
Distribution – sklep.pcz.pl, phone 34 325 03 93, e-mail: sklep@pcz.pl

CONTENTS

Introduction 5

PART I.
Modern Technologies and Innovations in Logistics

Chapter 1. AI Support in Inventory Management: A Case Study on New Possibilities
Péter Veres 9

Chapter 2. The SDP3 System as a Tool Determining the Efficiency of Transportation in the Production Process
Nicoletta Baskiewicz, Michał Ciuk 19

Chapter 3. Innovation in Logistics Clusters in Poland
Anna Horzela-Miś, Jakub Semrau 33

Chapter 4. Trends in Green Innovation Research Development
Anuphat Thirakulwanich 45

Chapter 5. The Symbiosis of Web 2.0, Web 4.0 Technologies and Supply Chain Management: Insights from Bibliographic Analysis and Topic Modeling
Gabrielė Radavičiūtė 67

PART II.
Sustainable Development and Logistics Process Optimization

Chapter 6. CSR Concept in Management of Logistics Enterprises – Analysis of Implementation of Sustainable Development Goals
Julia Wieczorek, Marta Kadłubek 83

Chapter 7. Advancing Sustainable Development: Transport Decarbonization Pathways to Carbon Neutrality in Poland
Oksana Seroka-Stolka 98

Chapter 8. Optimisation of Milkrun-based Material Supply through Process Integration
Tamás Bányai 109

Chapter 9. Evaluation of Reverse Logistics in the Supply Chain of Bottling Companies: A Case Study of Junac and La Sien Water Bottling Company
Anna Budzik, Gift Oriaku Eke Agwu 122

PART III.
Transport and Logistics Economics

Chapter 10. **Urban Road Transport in a Large City: Identification of Key Challenges**
Marta Daroń 137

Chapter 11. **Factors Shaping Freight Rates in Road Transport**
Katarzyna Grondys, Aleksandra Placek....................................... 148

Chapter 12. **Investigating the State of Autonomous Vehicles on Supply Chain: a Literature Review**
Negar Sohaee, Sara Sohaee Urbina,
Navidreza Ahadi, Farnaz Azadjoutabari 162

Chapter 13. **Logistics Market Forecasting and Analysis: Using Information Standards to Reduce Risk**
Katarzyna Sukiennik, Tomasz Szczepanik.................................. 179

Chapter 14. **Integration of Technological Innovations with Renewable Energy Sources in the Construction Industry**
Jakub Semrau, Anna Horzela-Miś 195

INTRODUCTION

This monograph, titled *Logistics Challenges: Global and Local Approaches,* is the result of scientific meetings and discussions held during the Global Conference on Logistics (GCoL2024). The conference took place at the Faculty of Management of Czestochowa University of Technology on October 17-18, 2024, and was co-financed by the state budget funds granted by the Minister of Science and Higher Education under the program "Excellent Science II – Support for Scientific Conferences". Agreement No. KONF/SP/0377/2023/01.

The aim of the Global Conference on Logistics was to disseminate the latest research findings and achievements of scholars at an international forum, as well as to discuss current issues in the fields of logistics and management.

The event brought together researchers from various countries, including Canada, South Africa, the United States, India, Indonesia, Lithuania, Germany, Hungary, Slovakia, and numerous academic institutions in Poland. Presentations, discussions, and the poster session covered topics such as innovative logistics solutions, supply chain optimization, sustainable development in the context of global economic and environmental changes, and management in a competitive global economy. The keynote speakers were distinguished experts in logistics and sustainable management who shared their knowledge and experience regarding critical challenges in the modern economy. The conference created a unique platform for knowledge exchange, allowing participants to compare diverse research approaches and findings.

This monograph presents a multifaceted perspective on the challenges and opportunities of contemporary logistics, showcasing both scientific research and practical solutions in this field. It is divided into three parts, each focusing on different but complementary aspects of modern logistics: advanced technologies and innovations, sustainable development, and the economics of transport and logistics. The review process involved a substantive evaluation of submitted papers by two experts through anonymized peer reviews.

The first part, *Modern Technologies and Innovations in Logistics*, explores the role of innovative technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and Web 4.0 technologies in enhancing the efficiency and adaptability of logistics processes. This section includes analyses of AI applications in inventory management, highlighting the benefits of neural networks and machine learning. The authors discuss the development of IT systems, such as SDP3, aimed at optimizing transport in production processes. Additionally, the significance of logistics clusters in Poland is examined, emphasizing their role as catalysts for innovation through collaboration, technology development, and integrated networks of enterprises. The chapters in this part provide invaluable insights into the role of technology in increasing logistics competitiveness and adaptability to changing market conditions.

The second part, *Sustainable Development and Logistics Process Optimization*, focuses on the role of logistics in achieving sustainable development goals and optimizing processes in response to environmental and economic challenges. A key topic is the decarbonization of transport, requiring significant CO_2 emission reductions by 2050. The authors present decarbonization scenarios for Poland, emphasizing the need for new technologies and regulatory frameworks. They also highlight the "milkrun" concept, which enhances operational efficiency by integrating supply and return processes. An important aspect of this part is the analysis of CSR practices in the logistics sector, covering sustainable development objectives in environmental, social, and governance areas. Practical examples and studies underscore the necessity of an integrated logistics approach that combines innovation with environmental responsibility.

The third part, *Transport and Logistics Economics*, addresses economic and strategic aspects of logistics and transport. One of the discussed topics is the formation of freight rates in the face of rising operational costs, such as fuel prices and road tolls. These analyses rely on the Total Cost of Ownership (TCO) methodology, indicating cost optimization directions for transport companies. Another key issue is the impact of autonomous vehicles on supply chains in Europe, considering economic savings and increased efficiency. The authors also examine the significance of information exchange standards, such as EDI, GS1, and XML, in market forecasting and operational risk reduction. These standards enable faster data exchange, improved transparency, and better disruption management in supply chains. The final chapters in this section focus on integrating technological innovations with renewable energy sources in construction, highlighting logistics' potential contributions to sustainable practices.

The monograph *Logistics Challenges: Global and Local Approaches* serves as a valuable resource for researchers, practitioners, and students interested in contemporary logistics challenges. The collected chapters provide a comprehensive overview of the most significant aspects of this dynamically evolving field, integrating theory with practice. The conclusions presented in this publication may support decision-making in the logistics sector, contributing to its further development and adaptation to changing economic and technological conditions.

All chapters in this publication were subject to a double-blind review procedure and were also verified by the anti-plagiarism system.

On behalf of the GCoL2024 organizers, I would like to express our sincere gratitude to all conference participants, including distinguished speakers, panelists, and authors, whose contributions were crucial to the success of this event. Their valuable research and carefully prepared presentations significantly enriched our knowledge and inspired further studies.

Our special thanks go to the members of the Program Committee and the reviewers who dedicated their time to a thorough assessment of the submitted materials. Their professionalism and commitment were essential in ensuring the high academic quality of this publication. We also extend our heartfelt appreciation to the authors who shared their knowledge and expertise. Thanks to their collective efforts, this publication has achieved a high scientific standard, for which we are immensely grateful.

We believe that this conference will become a lasting part of the academic calendar, offering a platform for exchanging ideas, the latest discoveries, and fostering collaboration in the dynamically evolving global economy.

PART I.

Modern Technologies and Innovations in Logistics

Chapter 1

AI SUPPORT IN INVENTORY MANAGEMENT: A CASE STUDY ON NEW POSSIBILITIES

Péter Veres

University of Miskolc, Institute of Logistics, Hungary
peter.veres@uni-miskolc.hu ORCID 0000-0001-9924-9196

Abstract: To stay profitable in a competitive market, a company increasingly needs to utilize digitalization tools to optimize its operations. One of the key tools is the recently popularized AI, which, if applied effectively, can enhance, digitally manage, and improve our existing systems, aligning with the principles of Industry 4.0. The shown case study examines the impact of Artificial Neural Networks (ANN) and Machine Learning (ML) on inventory management, emphasizing AI's role in enhancing efficiency and adaptability. It focuses on how these technologies help manage stock levels more accurately and respond dynamically to market changes. This study is a continuation of a previous work with an additional study addresses the human factor, exploring the balance between technology and workforce skills to ensure that AI supports rather than replaces human decision-making. Through a practical example, this research highlights the benefits and challenges of leveraging AI in modern inventory systems.

Keywords: artificial intelligence, industry 4.0, ABC analysis, procurement

Introduction

In recent years artificial intelligence has become substantial element in enhancing the logistics processes, offering significant advancements in automation, optimization, and predictive capabilities. From the integration of Industry 4.0 technologies to the use of machine learning algorithms for decision-making, AI can help increase the efficiency of traditional transport networks, reducing operational costs, and unlocking new strategic potentials. Woschank et al. (2020) states that integrating Industry 4.0 technologies, such as AI, machine learning, and IoT, enhances logistics processes by making them more flexible, adaptive, and efficient. By enabling real-time monitoring and predictive maintenance, AI can be used to optimizes workflows and improves overall supply chain performance (Woschank et al., 2020).

In its core this study focuses on data collected from a specific automotive supplier company to develop an artificial intelligence model. The goal of the trained AI is to outperform human workers in evaluating and categorizing incoming parts, which can enhance operational efficiency and decision-making within the company’s supply chain. This research serves as an extension of a previously published study (Veres, 2023), now introducing new parameters to further refine the model's capabilities and applicability in the real-world.

The chapter is organized into three major sections. The first section presents a comprehensive systematic literature review, which summarizes the findings of other researchers in the field of AI, logistics and procurement, highlighting relevant methodologies, technological applications, and previous successes. In the second section, the study shows the design and development of the ANN system, explaining its architecture and the iterative improvements for better accuracy approximations. Finally, the third section offers a case study conducted within the supplier company. This case study is supplemented by a questionnaire distributed to 4 company procurement workers. The findings from these workers compared to the AI generated method are analysed. The article concludes by summarizing the key findings and providing a forward-looking discussion on future research directions and potential industry applications, aiming to further improve AI integration into logistics.

Literature review

Artificial Intelligence is rapidly transforming logistics. The ever growing complexity of global supply chains and the need for real-time decision-making have led to a significant shift towards AI-driven solutions. Scholars such as Wang (2021), have discussed the role of AI alongside technologies like the Internet of Things (IoT) and big data in automating and improving supply chain operations. They argue that AI-driven predictive analytics allow for more accurate forecasting of demand and inventory levels, which is crucial in procurement to prevent stockouts and overstocking (Wang, 2021). Similarly, Richey et al. and associates point out that AI in logistics, particularly in procurement, enables more effective supplier selection, risk management, and cost reduction by analysing large datasets and providing actionable insights (Richey et al., 2023, p. 532).

Reinforcement learning, another AI methodology, is gaining attention in logistics as well, with scholars such as Liu and colleagues as well as Akkad and Bányai discussing its potential to go beyond replicating human decision-making (Liu et al., 2023). Instead, it can autonomously discover optimal procurement strategies through data simulation, making supply chain operations more resilient and cost-effective (Akkad & Bányai 2023).

These researchers collectively demonstrate the growing consensus on the importance of AI in modernizing procurement processes. By automating repetitive tasks, enhancing supplier collaboration, and enabling data-driven decisions, AI is paving the way for more responsive and efficient logistics systems (Koumpan et al., 2023, p. 105).

Procurement is a fundamental component of logistics, as it is critical for ensuring the availability of the materials and resources needed for manufacturing and service delivery. Without effective procurement processes, production would be disrupted, and services could not be provided. In every industry, there are dedicated procurement professionals responsible for acquiring items, but they also involve managing supplier relationships, negotiating contracts, and ensuring cost efficiency (Walker et al., 2013, p. 588). To meet the growing demands of modern industries and keep pace with the complexities of global supply chains, procurement professionals must continuously develop their skills and adapt to new technologies, particularly in the principles of Industry 4.0 (Bányai et al., 2020, p. 66).

Procurement can also be found in medical research: although AI research in medicine has grown rapidly, its implementation in clinical practice remains limited due to a lack of consensus on integration and maintenance. AI implementation is often mapped onto the Plan-Do-Study-Act framework, which shows a focus on the "Plan" and "Study" phases, with less emphasis on the "Do" and "Act" stages. These findings highlight challenges in adopting AI in healthcare, particularly in low- and middle-income countries, where research representation is minimal (Khan et al., 2024). In agriculture others are also try to implement AI systems for Green Public Procurement (GPP) systems, which can significantly enhance efficiency, optimize resources, and improve sustainability outcomes in areas such as energy use, supply chain management, and waste reduction, with the right legal and policy tools (Parashar & Chaurasia, 2022, p. 371).

An example of AI in procurement is demonstrated by Atwani et al. (2022) where AI is used to address supply chain challenges like demand uncertainty and external disruptions, improving processes such as planning, procurement, and distribution. Similarly, Kiefer & Ulmer show that AI models, such as MLP ANN, outperform traditional methods like ARIMA in forecasting for procurement, though further enhancements are needed to handle specific challenges like holiday-related demand fluctuations (Kiefer & Ulmer, 2019, p. 69).

This study is highly influential in the field, offering a well-developed model, clear explanations, and practical case studies. It provides a comprehensive approach to supply chain design. The study integrates traditional ABC analysis with multi--criteria inventory classification to better manage inventory, proposing the use of AI-based techniques like support vector machines (SVMs), backpropagation networks (BPNs), and k-nearest neighbor (k-NN) algorithms. Comparative analysis reveals that AI-based methods outperform traditional multiple discriminant analysis (MDA), with SVM showing the highest classification accuracy. These findings suggest that AI-based techniques could enhance inventory management in enterprise resource planning (ERP) systems (Yu, 2011). This article owes a great deal to this study, as it provides numerous valuable insights and descriptions.

Based on the above-discussed sources, research on milk-run supply systems reveals significant advancements and directions as follows:

- *Predictive analytics for procurement*: Predictive analytics powered by AI helps prevent stockouts and overstocking by analyzing demand trends. AI tools such as machine learning models predict procurement needs more effectively by processing huge amounts of historical data (Atwani et al., 2022; Richey, et al. 2023; Wang, 2021)
- *Supplier selection and risk management*: AI-driven algorithms analyse supplier performance data, reduce risks, and improve contract negotiations by identifying potential issues and optimizing decision-making processes (Koumpan et al., 2023; Richey et al., 2023)
- *Reinforcement learning for procurement optimization*: Reinforcement learning enables AI systems to develop procurement strategies independently through simulations (Akkad & Bányai, 2023; Liu et al., 2023)

- *Multi-criteria inventory classification and forecasting*: AI techniques such as SVM, backpropagation networks, and k-NN algorithms improve traditional inventory classification methods like ABC analysis. AI models also outperform conventional statistical methods like ARIMA in forecasting procurement needs (Kiefer & Ulmer, 2019; Yu, 2011).

Based on the literature review, integrating AI into procurement is crucial for enhancing processes such as demand forecasting, supplier selection, risk management, and inventory classification. Predictive analytics powered by AI improves the accuracy of demand forecasts, helping to prevent stockouts and overstocking. AI-driven algorithms enhance supplier selection and risk management by analysing performance data and optimizing decision-making. Reinforcement learning further enables AI systems to autonomously develop procurement strategies through simulations, providing more resilient and efficient solutions. AI techniques also outperform traditional methods in inventory classification and forecasting. A research gap remains in exploring how AI can be more effectively integrated into existing procurement systems, particularly in dynamic environments, and in further improving AI's ability to handle extreme demand fluctuations and supplier risks.

Development of ANN trained method

Within the frame of this chapter, an AI model is described and applied to train a dataset. The model used is an Artificial Neural Network, a straightforward yet effective tool within the Machine Learning family, ideal for training datasets to categorize or predict parameter values. To create an industrially viable ANN model, two initial steps are necessary: data mining and defining the layers. The sequence of these steps depends on whether existing data is available for testing or if the system is being created from scratch, with data collection to follow. In this case, access was granted to corporate data, which was cleaned and pre-processed before being used as a test dataset. The company gave permission to use the data, but it needs to be anonymised to protect confidentiality.

Since the data was available first, layer definition became the second step. There is no strict rule for determining the number of hidden layers or the number of nodes, but for tasks with a reasonable number of parameters, most recommendations suggest using between 1 and 3 layers. The same is true for the number of nodes in each hidden layer; while formulas exist, the ideal number is task-dependent. For fewer than 100 input parameters, it's common for the first hidden layer to have up to twice the number of input and output nodes, while subsequent layers typically have between 2/3 and 1/2 of the previous layer's nodes (Karsoliya, 2012).

After processing the corporate data, 11 input parameters were selected, with 4 outputs: predicting item classification into ABC & XYZ categories, relative order lot size and relative order indicator level. The last two are related to the size of the warehouse pallet capacity. Given the relatively low number of inputs and the problem's perceived simplicity, I designed the model with 3 hidden layers containing 16,12 and 8 nodes, respectively. The 3 layers are needed, because there are two different tasks in the output layer. The first two is categorising output, and a last two is value prediction. These parameters and layers are illustrated in Figure 1.1.

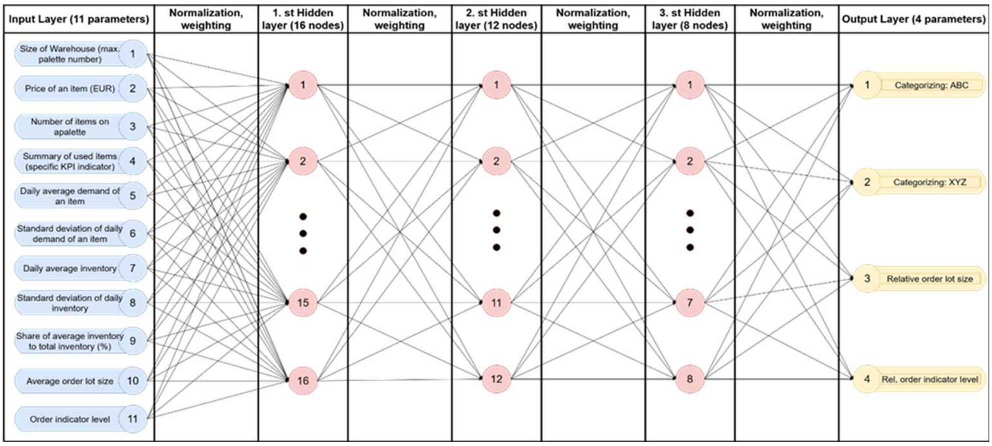


Figure 1.1. Structure of specific ANN model for this task

Source: Own study based on research.

Pre-processing the data is often necessary in addition to cleaning. Initially, the dataset had nearly 140 parameters, which was too much. Input parameters 1-4 (warehouse size, item price, items per pallet, and a KPI for item usage) remained unchanged. Parameters 5-10 were calculated: average daily demand and its standard deviation, average daily inventory and its standard deviation, the average daily warehouse occupancy percentage and the average order lot size. The goal was to avoid redundant data or parameters derived from others unless necessary due to complex relationships.

The corporate dataset covered around 3,200 items over a month, but about 1,800 items were inactive, reducing the usable training data. After data cleaning, only 255 items remained, which was sufficient to train the AI. Figure 1.2 shows part of the cleaned dataset, with yellow columns representing company-defined Order Indicator level and ABC/XYZ classifications (the supervised outputs), the green columns count as input parameters, and the grey columns containing daily data used to calculate inputs 5-10.

In my previous study, a detailed explanation was provided why the ABC/XYZ categorization was selected, and its importance were highlighted in managing inventory efficiently. The categorization plays a crucial role in distinguishing high-value and high-movement items from less critical ones, which allows for better prioritization within supply chain processes.

In this current study, two significant key factor was added: the order lot size and the warehouse reorder level. The order lot size refers to the specific quantities of raw materials that need to be procured at a given time, ensuring that the supply chain remains optimized without overstocking or running into shortages. Meanwhile, the warehouse reorder level is a critical parameter that signals when inventory has dropped to a point where new stock must be ordered. This ensures that procurement teams can act proactively, maintaining smooth operations and preventing disruptions in the whole supply chain.

Item no.	Warehouse size (palette)	Price of item (EUR)	Number of item on palette	Used palette number of item (KPI)	Daily average demand (palette)	SD of daily average demand (palette)	Daily average inventory (palette)	SD of daily average inventory (palette)	Average daily stock ratio	Average order lot size (palette)	Order Indicator level (palette)	ABC (Corp.)	XYZ (Corp.)	Initial stock factory total (no. items)	Initial stock factory total (palette)	Income (no. item) 03.25.2022	Used items (no. item) 03.25.2022	Remains (no. item) 03.25.2022	Stock (palette) 03.25.2022	Income (no. item) 03.26.2022
N1	1155	258.46	24.00	6.83	23.43	9.22	58.43	15.34	0.0506	49.63	16.00	A	X	2208	92	0	552	1656	69	...
N2	1155	169.96	48.00	1.71	11.71	6.80	26.71	28.16	0.0231	14.96	8.00	A	Y	624	13	0	480	144	3	...
N3	1155	100.52	32.00	6.25	28.57	14.33	133.57	51.17	0.1156	53.17	24.00	A	Y	8224	257	0	1312	6912	216	...
N4	899	48.33	80.00	1.54	17.57	7.16	40.86	22.81	0.0454	19.28	18.00	A	X	2000	25	0	1760	240	3	...
N5	899	40.70	105.00	0.50	7.43	3.69	11.00	7.55	0.0122	9.65	5.00	A	X	945	9	945	945	945	9	...
N6	899	48.32	64.00	1.48	13.57	8.44	4.29	11.95	0.0048	52.85	10.00	A	Y	704	11	0	1344	-640	-10	...
N7	899	25.30	36.00	4.53	23.29	11.16	41.29	11.18	0.0459	42.77	18.00	A	X	2124	59	864	1116	1872	52	...
N8	1155	23.83	80.00	0.94	10.71	5.56	38.71	12.54	0.0335	97.54	20.00	A	Y	3680	46	0	1280	2400	30	...
N9	899	50.07	48.00	0.85	5.86	5.70	31.71	11.29	0.0353	12.93	8.00	A	Y	624	13	384	0	1008	21	...
N10	1155	25.89	48.00	1.69	11.57	5.44	42.43	22.71	0.0367	12.41	5.00	A	X	1152	24	0	480	672	14	...
N11	1155	137.22	48.00	0.23	1.57	2.07	3.86	3.02	0.0033	5.98	3.00	A	Y	288	6	0	0	288	6	...
N12	1155	21.50	50.00	0.72	5.14	9.25	74.29	24.74	0.0643	32.62	17.00	A	Y	1700	34	1700	1150	2250	45	...
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

Figure 1.2. Example for training data

Source: Own study based on research.

Based on the corporal data the training was concluded on the specified ANN network with a great result. Each outcome parameters approximation is above 85%, but the previous study already contained ABC/XYZ and average order lot size is also an input parameter only the order indicator limit values are interesting now. As we can see on Figure 1.3 with approximately 5,800 iterations (which took more than 22 hours) and each iteration contains a 500 population a 95% to guess the value within 1 pallet quantity. As we can see on the graph, which is broken down into 100 iterations, at the beginning it was roughly between 10% and 15% to guess correctly, which is not surprising since most parts are bought in quantities of less than 10 pallets at a time. A candlestick chart format was used to show the distribution between the best and worst trained methods in the current iteration. The standard deviation (SD) is represented by the thick part of the candle.

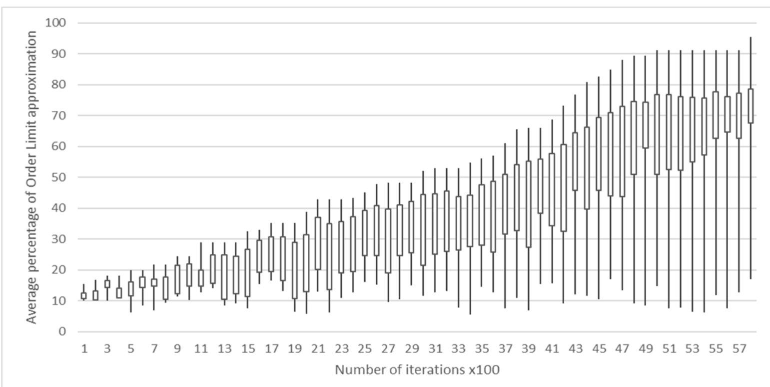


Figure 1.3. Training process of ANN model to determine the value of the order limit

Source: Own study based on research.

From the chart, we can deduce that there was significant volatility in the first 1,000 iterations, but after that, the proportion of SD relative to the entire column gradually decreased, indicating continuous improvement of the methods. Another observation is that, until the end of the iteration process, there are some poorly performing methods that barely reach 10-15%. This is because, in each iteration, new individuals are generated based on the previous ones, which can produce poor values even with small changes, as the engine of the training model in this case is based on a genetic algorithm.

Evaluation of trained AI model

In this section, the AI crated method introduced in the previous sections is evaluated using a test dataset comprised of 22 items, as shown in Figure 1.4. This test table has been designed to include a small but representative variety of data points for a short analysis. The dataset includes 10 existing parts that have been in use for an extended period, and these parts also included in training the model. In addition, 6 new items are included in the evaluation. These new parts are either freshly acquired by the company or are planned for introduction in the near future. This allows the model to be tested on completely unfamiliar data, helping to gauge its predictive power and adaptability. Furthermore, the test includes 6 randomly generated items. These were introduced as a control to avoid any potential bias or overfitting in the model's predictions. By including random items, we ensure that the model is not simply memorizing patterns from the training data, but rather it can handle a wide range of input values. These random items were carefully generated to maintain a balance in the dataset without pushing the values to extremes, ensuring that the test results remain realistic.

	Item no.	Warehouse size (palette)	Price of item (EUR)	Number of item on palette	Used palette number of item	Daily average demand (palette)	SD of daily average demand (palette)	Daily average inventory (palette)	SD of daily average inventory	Average daily stock ratio	Average order lot size (palette)	Order Indicator level (palette)	ABC (Corp.)	XYZ (Corp.)
Exist items	N1	1155	25.89	48.00	1.69	11.57	5.44	42.43	22.71	0.0367	12.41	5.00	A	X
	N2	899	40.70	105.00	0.50	9.00	11.00	9.00	0.01	0.0100	9.65	5.00	A	X
	N3	899	48.32	64.00	1.48	21.00	4.29	-10.00	0.00	-0.0111	52.85	10.00	A	Y
	N4	899	6.04	648.00	0.01	1.29	0.76	5.14	2.54	0.0057	13.67	6.00	B	Y
	N5	899	6.40	560.00	0.01	0.57	0.53	0.71	0.95	0.0008	2.13	2.00	C	Y
	N6	899	24.11	90.00	0.01	0.14	0.38	9.86	1.07	0.0110	21.95	3.00	C	Z
	N7	899	0.17	100.00	0.00	0.00	0.00	0.00	0.00	0.0000	4.34	2.00	C	Y
	N8	899	40.57	105.00	0.05	0.71	0.76	1.14	0.69	0.0013	8.42	3.00	B	Y
	N9	795	69.03	33.00	0.03	0.14	0.38	124.14	18.54	0.1562	75.00	3.00	A	Z
	N10	346	316.40	18.00	0.17	0.43	1.13	3.57	1.13	0.0103	3.66	2.00	B	Z
New items	N11	795	1.41	2000.00	0.00	0.00	0.00	12.86	6.41	0.0162	15.50	7.00	B	Y
	N12	586	1.33	500.00	0.03	2.43	1.90	0.43	11.15	0.0007	12.00	7.00	B	Y
	N13	795	24.33	48.00	0.00	0.00	0.00	0.00	0.00	0.0000	0.00	0.00	C	Z
	N14	795	1.52	300.00	0.00	0.00	0.00	0.00	0.00	0.0000	0.00	0.00	B	X
	N15	795	1.51	300.00	0.00	0.00	0.00	0.00	0.00	0.0000	0.00	0.00	B	Z
	N16	795	66.66	60.00	0.58	5.00	8.77	1.00	7.94	0.00	13.67	20.00	A	Y
Random items	N17	647	231.19	44.00	0.63	13.05	9.97	19.45	2.41	0.09	n.a.	n.a.	A	X
	N18	1112	6.02	962.00	0.82	1.95	0.36	6.38	1.23	0.0499	n.a.	n.a.	C	Z
	N19	488	45.62	73.00	0.15	7.29	3.60	20.39	10.23	0.0975	n.a.	n.a.	B	X
	N20	968	0.31	37.00	0.83	0.37	0.71	21.97	9.75	0.1094	n.a.	n.a.	C	Z
	N21	801	108.57	382.00	0.35	3.42	6.32	14.82	9.79	0.0690	n.a.	n.a.	A	Y
	N22	649	5.28	800.00	0.23	1.81	0.34	21.17	3.64	0.12	n.a.	n.a.	C	Y

Figure 1.4. Bases of the survey: data of 22 purchasable parts

Source: Own study based on research.

For all new items, the standard ABC/XYZ categorization was carried out, which is a key part of the evaluation process. However, for the randomly generated items, it was not possible to assign the two additional output parameters, as these are dependent on practical, real-world data.

To evaluate the effectiveness of the AI-generated method, 22 parts alone are not sufficient to provide validation of its overall performance. Ideally, a much larger dataset would be necessary to assess all potential outcomes and scenarios. However, the primary objective in this case is not simply to prove whether the method functions flawlessly, but rather to determine if it can surpass the decision-making capabilities of human labour. To conduct this assessment, four employees were called from the company, each with varying levels of experience in procurement. This range of experience (11, 6, 5 and 2 years) ensured that the results would reflect different levels of human expertise, allowing for a fair comparison between the AI model and human judgment. Each participant was provided with the same table containing information about the 22 parts and was given 10 minutes to complete the task. They were asked to classify each part into its ABC/XYZ category and set an order limit based on the given data.

In terms of AI, not only the latest model was used but also the older version designed solely for ABC/XYZ analysis, which also performed quite well. As shown in Figure 1.5, both models achieved over 90% accuracy. In the table, yellow highlights the errors. As can be seen, both AI models slightly outperformed even the colleague with 11 years of experience, but not with significant amount.

#		AI 2024 April		AI 2024 August			Employee 11 years exp.			Employee 6 years exp.			Employee 5 years exp.			Employee 2 years exp.		
		ABC	XYZ	ABC	XYZ	Order Indicator	ABC	XYZ	Order Indicator	ABC	XYZ	Order Indicator	ABC	XYZ	Order Indicator	ABC	XYZ	Order Indicator
Exist items	N1	A	X	A	X	5.04	A	X	5	B	X	5	A	X	5	B	X	10
	N2	A	X	A	X	4.99	A	X	5	A	X	5	A	X	5	A	X	10
	N3	A	Y	A	Y	10.32	A	Y	10	A	Y	10	A	X	10	A	Y	5
	N4	C	Y	C	Y	6.11	B	Y	5	B	Y	5	B	Y	5	C	Y	5
	N5	C	Y	C	Y	2.00	C	Y	2	C	Y	3	C	Y	2	C	Y	5
	N6	C	Z	C	Z	4.26	B	Y	3	B	Y	3	B	Z	5	B	Y	5
	N7	C	Z	C	Y	2.01	C	Y	2	C	Z	3	C	Y	2	C	Z	3
	N8	B	Y	B	Y	2.86	A	Z	3	A	Z	3	A	Z	5	A	Z	3
	N9	A	Z	A	Z	3.04	A	Y	2	A	Z	3	A	Z	3	A	Y	5
	N10	B	Z	B	Z	1.97	A	Z	2	A	Z	3	A	Z	3	A	Z	3
New items	N11	B	Y	B	Y	7.09	B	Z	10	B	Z	20	B	Y	30	B	Z	40
	N12	B	Y	B	Y	7.11	B	Y	2	B	Y	5	B	Y	2	B	Y	2
	N13	C	Z	C	Z	1.56	A	Z	0	A	Z	0	A	Z	0	A	Z	0
	N14	B	Y	B	X	0.78	B	X	0	B	X	0	B	X	0	B	X	0
	N15	B	Z	B	X	0.77	B	Z	0	B	Z	0	B	Z	0	B	Z	0
	N16	A	Y	A	Y	19.68	A	Y	20	A	Y	25	A	Y	20	A	Y	10
Random items	N17	A	X	A	X	n.a.	A	Y	n.a.	A	Y	n.a.	A	X	n.a.	A	Y	n.a.
	N18	B	Y	C	Z	n.a.	C	Y	n.a.	C	Z	n.a.	C	Z	n.a.	B	Z	n.a.
	N19	B	X	C	X	n.a.	B	X	n.a.	B	X	n.a.	B	X	n.a.	B	X	n.a.
	N20	C	Z	C	Z	n.a.	C	Z	n.a.	C	Z	n.a.	C	Z	n.a.	C	Y	n.a.
	N21	A	Y	A	Y	n.a.	A	Y	n.a.	A	Y	n.a.	A	Y	n.a.	A	Y	n.a.
	N22	B	Y	C	Y	n.a.	C	Y	n.a.	C	Y	n.a.	C	Y	n.a.	B	Y	n.a.
Correct %		**86**	**91**	**91**	**95**	**88**	**82**	**73**	**88**	**77**	**77**	**81**	**82**	**86**	**75**	**64**	**68**	**44**

Figure 1.5. Evaluation table of the survey

Source: Own study based on research.

One of the most notable mistakes for AI occurred with parts N13-15, where all employees entered a value of 0 for the order indicator limit, as they know there should be no limit, because it the part is yet not used in manufacturing. While the AI correctly estimated two of the three values, they were far from 0. Another error to note is that most employees made mistakes with parts N6-10. When asked, they explained that for the ABC analysis, they primarily considered the price and the number of items per pallet, while for the XYZ analysis, they focused on the average daily demand, its deviation, and the stock quantity. This approach worked fairly well for the new and random items.

Another interesting observation is that the human workforce can easily predict the order indicator because they rely on a well-established system. They have specific values for certain combinations, such as “AX” almost always 5 palettes, and below “BY” typically uses around 2-3 pallets. The only exception from this knowledge was the employee with 2 years of experience, who couldn't do this as she is not involved in setting indicators.

Conclusion

This study explores how Artificial Neural Networks and AI can enhance decision-making and operational efficiency in supply chain management. Using real corporate inventory data, 11 input and 4 output parameters were identified, including ABC/XYZ classification and order indicator level, all linked to warehouse pallet capacity. A 3-layer ANN was trained on 255 pre-processed procurement records, achieving over 85% accuracy of ABC/XYZ classification and 95% accuracy in predicting values within one pallet quantity after nearly a day of training.

ABC/XYZ categorization helped prioritize high-value, high-movement items, while two additional parameters – order lot size and reorder level – optimized inventory management and prevented overstocking or shortages. A test of 22 items (10 old, 6 new, and 6 random) was conducted to evaluate both the AI and four employees with varied procurement experience. While humans relied on heuristical statistics, errors occurred with unfamiliar items. The AI also made mistakes with parts not yet in production, predicting incorrect order limits where humans entered zero.

Despite minor errors, the AI achieved over 90% accuracy in classifying parts and setting order limits, surpassing human performance in these tasks. This method demonstrates how AI can effectively manage tasks infrequently performed by employees, showcasing its potential to improve inventory processes.

Currently, this AI model is designed to assist procurement teams, rather than replacing workers, it enhances their performance, ensuring procurement processes are more efficient and accurate.

While the findings are encouraging, there are several opportunities for further research to enhance AI integration in supply chains. Testing the model on a larger and more varied dataset could provide more consistent and reliable results. Additionally, future research could explore reinforcement learning, which would allow the AI to go beyond mimicking human work and use data simulations to discover even better solutions.

Acknowledgment

EKÖP
Egyetemi Kutatói Ösztöndíj Program

MINISTRY OF CULTURE AND INNOVATION

„Supported by the University Research Scholarship Program of the Ministry for Culture and Innovation from the Source of the National Research, Development and Innovation Fund."

References

Akkad, M.Z., & Bányai, T. (2023). Energy consumption optimization of milk-run-based in-plant supply solutions: An Industry 4.0 approach. *Processes*, 11(3), 799.

Atwani, M., Hlyal, M., & Elalami, J. (2022). A review of artificial intelligence applications in supply chain. In ITM Web of Conferences (Vol. 46, p. 03001). EDP Sciences.

Bányai, Á., Efimenko, D., Béla, I., Tamás, P., & Bányai, T. (2020). Multi-channel supply chain optimisation in cyber-physical environment under quantity discounts. *Journal of Production Engineering*, 65-70.

Battal, M. (2023). Artificial intelligence integration of large logistics companies. *Journal of International Trade, Logistics and Law*, 9(2), 273-281.

Karsoliya, S. (2012). Approximating number of hidden layer neurons in multiple hidden layer BPNN architecture. *International Journal of Engineering Trends and Technology*, 3(6), 714-717.

Khan, S.D., Hoodbhoy, Z., Raja, M.H.R., Kim, J.Y., Hogg, H.D.J., Manji, A.A.A., ..., & Sendak, M.P. (2024). Frameworks for procurement, integration, monitoring, and evaluation of artificial intelligence tools in clinical settings: A systematic review. *PLOS Digital Health*, 3(5), e0000514.

Kiefer, D., & Ulmer, A. (2019). Application of Artificial Intelligence to optimize forecasting capability in procurement. In Wissenschaftliche Vertiefungskonferenz: Informatik-Konferenz an der Hochschule Reutlingen, 27. November 2019 (pp. 69-80). Hochschule Reutlingen.

Koumpan, E., & Topol, A.W. (2023, February). Procurement of the future: Investing today in the technologies of tomorrow. In International Congress on Information and Communication Technology (pp. 97-107). Singapore: Springer Nature Singapore.

Liu, Y., Tao, X., Li, X., Colombo, A. W., & Hu, S. (2023). Artificial intelligence in smart logistics cyber-physical systems: State-of-the-arts and potential applications. *IEEE Transactions on Industrial Cyber-Physical Systems*, 1, 1-20.

Parashar, B., & Chaurasia, A. (2022). Role of Artificial Intelligence in green public procurement: (with special reference to European economic deal). In International Conference on Data Analytics in Public Procurement and Supply Chain (pp. 361-371). Singapore: Springer Nature Singapore.

Richey Jr, R.G., Chowdhury, S., Davis-Sramek, B., Giannakis, M., & Dwivedi, Y.K. (2023). Artificial intelligence in logistics and supply chain management: A primer and roadmap for research. *Journal of Business Logistics*, 44(4), 532-549.

Veres, P. (2023). Increasing the efficiency of warehouse analysis using artificial intelligence. *Acta Logistica* (AL), 10(3).

Walker, H., Schotanus, F., Bakker, E., & Harland, C. (2013). Collaborative procurement: a relational view of buyer–buyer relationships. *Public Administration Review*, 73(4), 588-598.

Wang, S. (2021). Artificial intelligence applications in the new model of logistics development based on wireless communication technology. *Scientific Programming*, 2021(1), 5166993.

Woschank, M., Rauch, E., & Zsifkovits, H. (2020). A review of further directions for artificial intelligence, machine learning, and deep learning in smart logistics. *Sustainability*, 12(9), 3760.

Yu, M.C. (2011). Multi-criteria ABC analysis using artificial-intelligence-based classification techniques. *Expert Systems with Applications*, 38(4), 3416-3421.

Chapter 2

THE SDP3 SYSTEM AS A TOOL DETERMINING THE EFFICIENCY OF TRANSPORTATION IN THE PRODUCTION PROCESS

Nicoletta Baskiewicz*, Michał Ciuk

Czestochowa University of Technology, Faculty of Management, Poland
*nicoletta.baskiewicz@pcz.pl ORCID 0000-0002-9166-435X

Abstract: Modern manufacturing companies face increasing challenges related to efficient transportation management within complex production processes and dynamic supply chains. In response to these needs, this article focuses on optimizing transportation through the use of advanced IT systems. In the face of intense competition, effective transportation management plays a key role in reducing costs, shortening production times, and improving efficiency. The article demonstrates how innovative technologies can automate transport processes, facilitate data analysis, and support faster decision-making, enabling companies to adapt to changing market conditions.

Keywords: efficiency, transport, production process, SDP3 system

Introduction

In today's business environment, complex production processes and dynamic supply chains present companies with challenges related to effective transportation management (Jain & Benyoucef, 2008; Swaminathan et al.,1998). In the context of intense competition and increasing market complexity, efficient transportation management becomes a key factor in optimizing costs, reducing production time, and enhancing overall organizational efficiency (Serdarasan, 2013).

The primary goal of this article is not only to identify areas for potential optimization within the transportation process but also to implement a dedicated IT system that enables effective management and optimization of key transportation elements in the production process (Crainic et al., 2009; Greeff & Ghoshal, 2004). By introducing innovative solutions, companies can automate transport processes and provide real-time data analysis, speeding up strategic decision-making and enabling adaptation to dynamic market conditions (Pandey at al., 2011; Taylor & Raden, 2007).

The use of IT systems to support the monitoring and optimization of component or finished product flow is one of the most critical elements in well-functioning manufacturing companies (Jain & Lad, 2017). Advanced technologies not only facilitate the digitization and computerization of production processes but also set a new path for development, guiding companies worldwide. It is important to highlight major technology centers such as Tokyo, Shanghai, and California, where engineers face challenges daily and develop advanced IT systems to verify internal and external logistics processes, identifying gaps and areas for improvement (Chen et al., 2017; Sahay et al., 2003; Sturgeon, & Lester, 2004).

The modern world forces manufacturers to follow trends and rapidly evolve, without which it is impossible to maintain high performance. The increasing demand for IT and logistics engineers clearly shows how the market and its requirements have changed over the past decades of rapid development. (Blumberg, 1999; Grets, 1997).

This study goes beyond the conventional approach to transportation optimization in the production process and focuses on innovation through the use of advanced IT technologies. The ultimate aim is to analyze and implement a solution that enhances the competitiveness of the company while respecting sustainable development and harnessing the potential of modern technologies. This work serves as a bridge between traditional transportation management and the dynamic, demanding market environment, supporting the growth of companies in the era of digital transformation. The implementation of an advanced IT system provides an opportunity for better analysis and verification of these processes, leading to increased efficiency. The use of analytical tools aims to demonstrate a clear improvement over time and simulate the application of the mentioned system in the daily operations of a production line within a company.

Factors determining the efficiency of transportation processes

Modern companies are increasingly recognizing the importance of internal transport efficiency and its impact on overall business operations. In the rapidly developing industries, effective movement of goods within production facilities is a crucial aspect not only operationally but also strategically (Cohen & Lee, 1985; Holweg & Helo, 2014). The pursuit of maximum optimization of transport processes is a challenge faced by all companies aiming for growth and competitiveness in their respective sectors (Best, 2001; Ríos-Mercado & Borraz-Sánchez, 2015). Years of experience gained by companies and their employees have led to identifying the most important factors influencing this efficiency. Modern technologies are an integral part of the solutions being implemented to optimize processes and ensure the company's participation in the ongoing technological transformation (Porter & Heppelmann, 2015; Rüßmann et al., 2015; Westerman et al., 2014). The complexity of internal transport efficiency involves many factors that affect its level.

A critical aspect of internal transport organization is the arrangement of routes and logistics areas within the company. Those responsible for internal logistics face the challenge of logically organizing transport routes to enhance the efficiency of operations performed by internal logistics operators. Proper planning of transport routes is crucial at the early stages of designing production halls and implementing new production lines (Scallan, 2003). Efficient movement of operators and internal transport equipment between the production line and warehouses is essential for maintaining high efficiency and safety (Erengüç, 1999). All transport routes should be designed in accordance with principles and standards, such as the Polish standard for transport route dimensions PN-M-78010:196829. Proper signage of transport routes is also crucial to maintain order and, most importantly, safety for those using these routes. These same considerations are also relevant in low or high storage warehouses, where safety plays an extremely important role (Richards, 2017; Sugathadasa et al., 2021). Workplace accidents can not only pose a threat to the continuity of internal transport processes but, in extreme cases, can also bring those processes to a halt. Such situations can be avoided by properly marking transport routes and areas. The wide variety of equipment requires these elements to be adapted to the conditions within the company, and this should be addressed in the early stages of launching projects or approving areas related to production and internal logistics (Frazelle, 2020; Sheffi, 2012).

In an era of rapid development, automation and process management in logistics are critical factors affecting transport process efficiency. Modern IT systems are helpful in this regard, as they enable real-time monitoring of operations and the collection of statistical data (Azvine et al., 2006; Habeeb et al., 2019). This information allows for the verification of operation times, which can contribute to optimizing transport routes and the equipment used for handling goods. Collecting large amounts of data over time provides a solid foundation for drawing conclusions and implementing solutions to improve efficiency (Glasgow et al., 2004). This is also reflected in calculating the energy consumption of devices, which can lead to shortening transport routes or relocating storage areas closer to loading or unloading points. Automation is also applicable to conveyor belts on production lines. (Stankovic, 2003). Proper synchronization combined with time monitoring allows for an objective view of ongoing processes, enabling the identification and elimination of bottlenecks. Undoubtedly, automation and technological advancements contribute to the overall efficiency of transport processes in companies (Barreto et al., 2017; Rüßmann et al., 2015).

The condition of the equipment used for transporting goods also affects transport process efficiency. Proper maintenance of the technical aspects and functionality of machines is crucial to avoiding breakdowns and interruptions in deliveries. This applies to devices directly on production lines (conveyor belts, rollers) as well as forklifts or manipulators (Bouh & Riopel, 2015). This issue is particularly important when using electric forklifts, which must be charged at the appropriate time to avoid running out of power and ensure uninterrupted operations for internal logistics operators. A similar issue applies to fuel supplies for older types of forklifts powered by diesel or LPG. Ensuring adequate fuel supplies and spare parts for these vehicles is essential to quickly respond to critical situations, such as repairing a malfunction or refueling. The condition of forklifts and hand trucks significantly impacts efficiency, making it crucial to organize regular maintenance and servicing to keep them fully operational (Harmon, 1993).

Another important factor influencing efficiency is the proper organization of work time. The way production and logistics processes are planned plays a key role in the functioning of these areas of the company (Mentzer et al., 2008; Romano, 2003). Logistic peaks, which occur during increased orders or deliveries, are particularly significant. These situations require intensified activity and work, and without maintaining an appropriate buffer, may lead to failing to meet set goals. Such phenomena often occur in companies where seasonality plays a major role, such as sporting goods manufacturers or farmers (Connell et al., 2015; Dawson et al., 2011). Planners should have the skills to forecast such periods based on acquired experience. Proper handling of these situations helps maintain operations in line with Lean or Just-In-Time principles, ensuring sufficient efficiency is maintained (Macharia & Mukulu, 2016; Pinto et al., 2018).

Every aspect of a company's operations requires regular investment and keeping up with trends. Investing in the development of warehouses, equipment, and staff training can yield tangible benefits in the form of high efficiency. The largest companies in the world continuously strive for maximum efficiency, which cannot be achieved without investment (Christensen & Bower, 1996). Modern equipment and warehouse areas are key elements of an efficiently functioning business environment. Staff training is also crucial for those managing logistics processes in the company. From management staff to team leaders and physical workers, the role of training plays an important part in ensuring efficient and effective team performance. (Elnag & Imran, 2013; Tabassi et al., 2012). Proper and precise communication helps avoid mistakes and misunderstandings that can impact the overall efficiency of the company. Proper planning, implementation, management, and monitoring of all these aspects are key to maintaining high efficiency and effectiveness in internal transport processes within companies (Marlow & Casaca, 2003; Sabbaghi & Vaidyanathan, 2008).

Presentation and implementation of the SDP3 system in optimization

SDP3 is an IT system developed by IT specialists and technologists at ZF. It is a global tool used in many company locations, which has been improved and expanded over the years with additional modules (Li et al., 2023). SDP3 incorporates elements of MRP and ERP-class software, allowing for its broad application across different sectors of the enterprise (Cliff, 1969). The system is based on cloud data storage, which offers several advantages (Dronamraj, 2010; Kunnath et al., 2021):

- Accessibility from anywhere in the world.
- Long-term data storage.
- No need for additional server rooms, reducing costs.
- Ease of use.
- Possibility for further expansion.
- Instant data transfer and real-time insights.
- However, using a cloud-based system also comes with certain drawbacks:
- Dependence on network connection.
- Risk of hacker attacks (despite high-quality security measures).
- Necessity of training employees to use the system.

SDP3 is designed so that expansions and updates do not pose a risk of data loss and do not affect the current operation of the system. This allows for the introduction and testing of new modules without interfering with the existing setup. It is worth noting that access to the system is restricted to authorized employees only (Wu & Boyd, 1996). Each access request must be justified to obtain an individual login and password, ensuring security and preventing unauthorized access. This is not the only security measure; the system also features built-in antivirus software to detect any threats and automatically logs the user out after 5 minutes of inactivity.

SDP3 consists of several core modules that are crucial for the daily functioning of the enterprise (Lasserre, & Magron, 2019; Van Apeldoorn et al., 2017):

- Production Module: This component handles the entry of production orders and forwards them to production managers for scheduling. It also allows real-time monitoring of ongoing orders and their progress. The module stores historical data, enabling the verification of production line efficiency throughout its operation. It is a useful tool for confirming performance against client requirements and serves as an indicator of the production staff's work.
- Quality Module: This module presents essential data about each manufactured unit, including serial numbers, product numbers, production line numbers, order numbers, and quality status (OK/NOK). It is crucial for verifying the correctness of production operations and is useful in handling customer complaints, as it allows for the verification of every product along with its parameters. The module also shows the completion time for each unit, which helps calculate the total time required for production.
- Packaging Module: This part of the system is responsible for verifying the inventory of packaging materials and automatically ordering them when they run out on the production line. It is integrated with scanners used by logistics operators to add empty packaging to stock. After completing a production order, the module automatically removes empty packaging from inventory, reflecting the real quantity, thus ensuring smooth flow of finished products and reducing the risk of packaging shortages.
- Internal Transport Module: This element supervises all aspects of the company's internal logistics. It controls the receipt of components, delivers the right quantities to the production line, monitors warehouse movements, and transports finished products to high-storage warehouses. Like the Packaging Module, it is connected to the operators' scanners and is mainly used by logistics managers and warehouse leaders to verify current activities and ensure continuous supply. A valuable feature of this module is the ability to track the time required for all transport movements, enabling the optimization of transport routes or storage areas to minimize these times.
- Time and Quantity Module: This is the module of most interest in the context of SDP3. It provides direct insight into transport processes on the production line, allowing the verification of the time for each movement and the quantities of components, semi-finished products, and finished goods. It can track the number of units moved between production operations and show the time needed to transport each unit. This module is particularly useful for assessing the efficiency of implemented solutions on the production line and identifying bottlenecks. It enables the implementation of improvements aimed at optimizing these processes and continuously enhancing inter-operational transport.

SDP3 will be utilized in the proposed optimization due to its capabilities in monitoring transport processes on the production line. A critical aspect of its implementation is the ability to verify the time required to move units between individual operations. The goal of its deployment is to create the conditions for observing these processes and identifying areas for improvement to increase efficiency. The system's ease of use, along with the devices available on the production line, should allow for synchronization between both elements, which should have a measurable impact on the optimization goal (Chappell & Large, 2005).

Analysis of the transport process in the production process

The subject of the analysis is the production line for the driver's airbag for the Audi DAB product. This production line consists of five operations:

1. Assembly of the airbag and installation in the cover.
2. Installation of the gas generator into the housing.
3. Screwing the cover to the housing.
4. Installation of the wiring harness and electrical parameter testing.
5. Visual inspection, printing of the final label, and packing into the container.

Each operation takes place at a dedicated station equipped with specific tooling. During one production shift, a total of five production operators are working, with one operator assigned to each station. The transport between operations is carried out using 2-meter-long conveyor belts, activated by the press of a button by the operator. The employee sending the semi-finished product to the next station must press a button to activate the conveyor belt. The receiving operator must also confirm the receipt of the semi-finished product by pressing a button. These actions are logged with SENT/RECEIVED messages, but without recording the transport time between the stations.

This setup results in a situation where, if the sending operator works faster, they must wait until the receiving operator completes their tasks before being able to send the next unit. The situation can also be reversed in the case of a slower sending operator, forcing the receiving operator to wait for the next unit to arrive.

To assess the current state and efficiency of the transport processes in production, a performance audit was conducted (Table 2.1).

Table 2.1. Performance audit results

Working hours	Total work time	Number of units produced (in units)	Average time per unit (in minutes)	Average inter-operational transport time (in minutes)
6:00 - 7:00	60:00	26	02:30	00:30
7:00 - 8:00	60:00	28	02:14	00:26
8:00 - 9:00	60:00	27	02:22	00:28
9:00 - 10:00	60:00	28	02:14	00:26
10:00 - 10:30	30:00	13	02:30	00:30
10:30 - 11:00	Break 0:30 h – no production			
11:00 - 12:00	60:00	28	02:14	00:26
12:00 - 13:00	60:00	27	02:22	00:28
13:00 - 14:00	60:00	28	02:14	00:26
	Total = 07:30 h	Average ≈ 27 units/h	Average time ≈ 02:20 min	Average time ≈ 00:28 min

Source: Own study based on the available performance audit results from the production line.

The obtained data comes from the time logs of machines at individual production stations. The average transport time is derived from the sum of the operating times of all transport belts. The above results show the average number of units produced during 7.5 hours, which equals one production shift. As we can observe, the average production time per unit was 2 minutes and 20 seconds, of which the inter-operational transport time accounted for an average of 28 seconds. Based on the gathered data, the following results can be derived:

- Total number of units produced during one shift:
  27 units x 7.5 h ≈ 202 units
- Total number of units produced in one day:
  27 units x 7.5 h x 3 shifts ≈ 607 units
- Total number of units produced in one week:
  27 units x 7.5 h x 3 shifts x 5 days ≈ 3035 units
- Total number of units produced in one year:
  27 units x 7.5 h x 3 shifts x 5 days x 50 weeks ≈ 151,750 units

These calculated values will be needed during the simulation and comparison of the proposed optimization of internal transport in the production process on the selected line. To obtain the most accurate comparative analysis, it is important to calculate the total time required for inter-operational transport over time:

- Total number of units produced during one production shift:
  27 units x 7.5 h ≈ 202 units
- Average inter-operational transport time during one production shift:
  202 units x 28 seconds ≈ 5656 seconds ≈ 94.26 minutes ≈ 1:34 h
- Average inter-operational transport time in one day:
  1:34 h x 3 shifts ≈ 4:42 h
- Average inter-operational transport time in one week:
  4:42 h x 5 days ≈ 23:34 h
- Average inter-operational transport time in one year:
  23:34 h x 50 weeks ≈ 1178:20 h

The prepared data will serve as the basis for a comparative analysis with the data obtained from the performance trial after the test implementation of the optimization. In the analysis, it is important to focus on the reduction of inter-operational transport time, which directly impacts efficiency. If the time reduction is successful, it will indicate an increase in process efficiency, confirming the validity of the proposed solution.

Research results: proposal for process improvement using the SDP3 system

The optimization project for transport processes on the production line will be based on the implementation of the SDP3 system to improve inter-operational transport. The project consists of three stages:

1. Replacing the SENT/RECEIVED buttons with automatic sensors that detect the presence of semi-finished products and automatically activate the transport belt.

2. Synchronizing the production belts with the SDP3 system and installing a module responsible for controlling and monitoring transport processes between operations.
3. Conducting a simulation and performance audit to gather data for comparative analysis with the state before optimization.

To assess the time required for implementing the proposed solution, consultations were held with individuals responsible for similar tasks. The time needed for replacing buttons with sensors on the transport belts is estimated at 4 working hours. Synchronization of the transport belts and implementation of the SDP3 system is expected to take 8 hours, which can be done in parallel without disrupting serial production. During the implementation phase, semi-finished products will be transported manually by production operators. The simulation and performance audit will be conducted simultaneously during one production shift, lasting 7.5 hours. After this period and the verification of results, interviews with employees will be conducted to gather their opinions on the proposed solution.

The first stage of optimization took place on September 11, 2023, and was carried out by the Maintenance Department mechanics under the supervision of a technologist representing the Development Department. During the replacement of the buttons with Keyence sensors, no issues or installation difficulties were noted. Sensor functionality tests were conducted and successfully completed. A representative from the Health and Safety Department also inspected the sensors to ensure their safe operation. A total of 8 sensors were installed, with one at the beginning and one at the end of each of the four transport belts.

The second stage involved installing the SDP3 system and connecting it to the sensors responsible for controlling the transport belts. An IT specialist, experienced in handling transport tools and working with the system, was appointed for this task. The installation began on September 11, 2023, immediately after the mechanics completed their work on the production line. Although the installation was successful, there were issues during the synchronization of the transport belts with the system. Three synchronization attempts were made, but none were successful. Due to the late hour and the end of the working day for the responsible individuals, further attempts were postponed to the next day. On September 12, 2023, another attempt was made to synchronize the system with the transport belts and sensors, but it also failed to achieve the desired result. To resolve the issue, a consultation was held with a representative from Keyence, the supplier of the sensors, via a Microsoft Teams meeting. During the meeting, we were informed that the latest drivers for the sensors needed to be installed. After receiving the necessary software, the update was carried out directly on the production line. A total of 5 attempts were made, all of which were successful. The driver update produced the expected result, allowing the synchronization of the transport belts with the SDP3 system to proceed. Programming the solution took about 5 hours and was successfully completed.

A simulation and performance audit with the new solution was initially scheduled for September 13, 2023, but due to the need for operator training, it was postponed to September 14, 2023. On September 13, 2023, training was conducted for the production operators, presenting the new solution. The training was conducted by production leaders from each of the three shifts and concluded with the signing of training protocols.

On September 14, 2023, the simulation of a full production shift with the implemented solution began to test the stability of the system and its correct operation with the transport devices on the production line. The production started at 6:00 AM and ended at 2:00 PM. Below are the results of the performance audit conducted (Table 2.2): SDP3 is an IT system developed by IT specialists and technologists at ZF. It is a global tool used in many company locations, which has been improved and expanded (Table 2.2).

Table 2.2. Performance audit results after optimization implementation

Working hours	Total work time	Number of units produced (in units)	Average time per unit (in minutes)	Average inter-operational transport time (in minutes)
6:00 - 7:00	60:00	28	02:14	00:26
7:00 - 8:00	60:00	29	02:06	00:25
8:00 - 9:00	60:00	29	02:06	00:25
9:00 - 10:00	60:00	28	02:14	00:26
10:00 - 10:30	30:00	14	02:14	00:26
10:30 - 11:00	Break 0:30 h – no production			
11:00 - 12:00	60:00	27	02:22	00:28
12:00 - 13:00	60:00	28	02:14	00:26
13:00 - 14:00	60:00	27	02:22	00:28
	Total = 07:30 h	Average ≈ 28 units/h	Average time ≈ 02:14 min	Average time ≈ 00:26 min

Source: Own study based on results from the SDP3 system.

Based on the obtained data, the following results were achieved:

- Total number of units produced during one shift:
  28 units x 7.5 h ≈ 210 units
- Total number of units produced in one day:
  28 units x 7.5 h x 3 shifts ≈ 630 units
- Total number of units produced in one week:
  28 units x 7.5 h x 3 shifts x 5 days ≈ 3,150 units
- Total number of units produced in one year:
  27 units x 7.5 h x 3 shifts x 5 days x 50 weeks ≈ 157,500 units
  The results are a simulation of production efficiency, considering the tested transport process optimization using the SDP3 system.
  Calculated times after optimization:
- Total number of units produced during one production shift:
  27 units x 7.5 h = 210 units
- Average inter-operational transport time during one shift:
  210 units x 26 seconds = 5,460 seconds = 91 minutes = 1:31 h

- Average inter-operational transport time per day:
  1:31 h x 3 shifts = 4:33 h
- Average inter-operational transport time per week:
  4:42 h x 5 days = 22:45 h
- Average inter-operational transport time per year:
  23:34 h x 50 weeks = 1,137:30 h

The obtained results were compared with the data from before the optimization was implemented (Table 2.3).

Table 2.3. Comparative summary of results before and after optimization

	Before optimization	After optimization	Difference
Average number of units produced (In units)	27 units/hour	28 units/hour	1 units/hour
Average time per unit (In minutes)	02:20	02:14	00:06
Average inter-operational transport time (In minutes)	00:28	00:26	00:02
Total number of units produced during one shift	202	210	8
Total number of units produced in one day	607	630	23
Total number of units produced in one week	3035	3150	115
Total number of units produced in one year	151 750	157 500	5750
Average inter-operational transport time during one production shift (In hours)	01:34	01:31	00:03
Average inter-operational transport time per day (In hours)	04:42	04:33	00:09
Average inter-operational transport time per week (In hours)	23:34	22:45	00:49
Average inter-operational transport time per year (In hours)	1178:20	1137:30	16:50

Source: Own study based on obtained results.

The prepared summary demonstrates and confirms the positive impact of the proposed optimization on the transport processes of the selected production line. Each analyzed element showed an improvement in efficiency after the performance audit was conducted. Based on this data, the following conclusions can be drawn:

1. The average number of units produced per hour increased by 1 unit.
2. The average time spent on producing one unit was reduced by 6 seconds.
3. The average inter-operational transport time for one unit was reduced by 2 seconds.

4. The total number of units produced during one shift increased by 8 units.
5. The total number of units produced in one day increased by 23 units.
6. The total number of units produced in one week increased by 115 units.
7. The total number of units produced in one year increased by 5,750 units.
8. The average inter-operational transport time during one shift was reduced by 3 minutes.
9. The average inter-operational transport time per day was reduced by 9 minutes.
10. The average inter-operational transport time per week was reduced by 49 minutes.
11. The average inter-operational transport time per year was reduced by 16 hours and 50 minutes.

Over the 5-year product lifecycle, the implemented optimization will allow for the production of 28,750 additional units of finished products. The analysis clearly proves that the proposed implementation of the SDP3 system in transport processes on the production line results in a tangible effect in the form of increased efficiency, which was the objective of the project.

Summary

Understanding the mechanisms of internal and external transport processes is essential for implementing effective logistics improvements. This knowledge, built upon years of research and publications, is a valuable resource for logistics specialists worldwide. Although logistics often remains invisible to the average person, its impact is widespread and felt in many aspects of life. In the production sector, the efficiency of transport processes plays a significant role, influencing the supply of components, the distribution of products, and the transport of raw materials such as fuel and energy, which power the modern economy.

The rapid development of technology forces experts working on transport optimization to continuously improve processes in order to achieve the best possible results. Modern logistics relies on the use of advanced IT systems, which are applied in every aspect of its operation.

In conclusion, the optimization project using the SDP3 system yielded positive results and improved the efficiency of transport within the production process. A comparison of results before and after the solution was implemented showed a clear improvement, which was the primary goal of the project. The system accelerated inter-operational transport through proper synchronization with production lines, which, although yielding seemingly small results, brings significant long-term benefits. The time savings, amounting to more than two days per year, can be utilized for machine maintenance or other necessary tasks. This data confirms that the optimization was successfully implemented, contributing to increased transport efficiency in production processes.

References

Azvine, B., Cui, Z., Nauck, D.D., & Majeed, B. (2006, June). Real time business intelligence for the adaptive enterprise. In The 8th IEEE International Conference on E-Commerce Technology and

The 3rd IEEE International Conference on Enterprise Computing, E-Commerce, and E-Services (CEC/EEE'06) (pp. 29-29). IEEE.
Barreto, L., Amaral, A., & Pereira, T. (2017). Industry 4.0 implications in logistics: an overview. *Procedia Manufacturing*, 13, 1245-1252.
Best, M. (2001). *The new competitive advantage: the renewal of American industry*. Oxford University Press.
Blumberg, D.F. (1999). Strategic examination of reverse logistics & repair service requirements, needs, market size, and opportunities. *Journal of Business Logistics*, 20(2).
Bouh, M.A., & Riopel, D. (2015, October). Material handling equipment selection: New classifications of equipments and attributes. In 2015 International Conference on Industrial Engineering and Systems Management (IESM) (pp. 461-468). IEEE.
Chen, Z., Dong, J., & Ren, R. (2017). Urban underground logistics system in China: opportunities or challenges?. *Underground Space*, 2(3), 195-208.
Christensen, C.M., & Bower, J.L. (1996). Customer power, strategic investment, and the failure of leading firms. *Strategic Management Journal*, 17(3), 197-218.
Cliff, R.A. (1969). Recent improvements in the SPD-3 computer (No. NASA-TM-X-63632).
Cliff, R.A. (1969). The SDP-3-A computer designed for data systems of small scientific spacecraft (No. NASA-TM-X-63470).
Cohen, M.A., & Lee, H.L. (1985). *Manufacturing strategy: concepts and methods*. In *The management of productivity and technology in manufacturing* (pp. 153-188). Boston, MA: Springer US.
Connell, J., Page, S.J., & Meyer, D. (2015). Visitor attractions and events: Responding to seasonality. *Tourism Management*, 46, 283-298.
Crainic, T.G., Gendreau, M., & Potvin, J.Y. (2009). Intelligent freight-transportation systems: Assessment and the contribution of operations research. *Transportation Research Part C: Emerging Technologies*, 17(6), 541-557.
Dawson, D., Fountain, J., & Cohen, D.A. (2011). Seasonality and the lifestyle "conundrum": An analysis of lifestyle entrepreneurship in wine tourism regions. *Asia Pacific Journal of Tourism Research*, 16(5), 551-572.
Dronamraj, R. (2010). *Tools and Versioning for GUI text in SDP3*.
Elnaga, A., & Imran, A. (2013). The effect of training on employee performance. *European Journal of Business and Management*, 5(4), 137-147.
Erengüç, Ş.S., Simpson, N.C., & Vakharia, A.J. (1999). Integrated production/distribution planning in supply chains: An invited review. *European Journal of Operational Research*, 115(2), 219-236.
Frazelle, E. (2020). *Supply chain strategy: the logistics of supply chain management*. McGraw-Hill.
Glasgow, H.B., Burkholder, J.M., Reed, R.E., Lewitus, A.J., & Kleinman, J.E. (2004). Real-time remote monitoring of water quality: a review of current applications, and advancements in sensor, telemetry, and computing technologies. *Journal of Experimental Marine Biology and Ecology*, 300(1-2), 409-448.
Greeff, G., & Ghoshal, R. (2004). *Practical E-manufacturing and supply chain management*. Elsevier.
Grets, N.P., & Kasarda, J.D. (1997). Enterprise logistics in the information era. *California Management Review*, 39(4), 55-78.
Habeeb, R.A.A., Nasaruddin, F., Gani, A., Hashem, I.A.T., Ahmed, E., & Imran, M. (2019). Real-time big data processing for anomaly detection: A survey. *International Journal of Information Management*, 45, 289-307.
Harmon, R.L. (1993). *Reinventing the warehouse: world class distribution logistics*. Simon and Schuster.
Holweg, M., & Helo, P. (2014). Defining value chain architectures: Linking strategic value creation to operational supply chain design. *International Journal of Production Economics*, 147, 230-238.
Jain, A.K., & Lad, B.K. (2017). Dynamic optimization of process quality control and maintenance planning. *IEEE Transactions on Reliability*, 66(2), 502-517.
Jain, V., & Benyoucef, L. (2008). Managing long supply chain networks: some emerging issues and challenges. *Journal of Manufacturing Technology Management*, 19(4), pp.469-496.
Kunnath, S.N., Pride, D., Herrmannova, D., & Knoth, P. (2021). *Overview of the 2021 SDP 3C citation context classification shared task*. Association for Computational Linguistics.

Lasserre, J.B., & Magron, V. (2019). In SDP relaxations, inaccurate solvers do robust optimization. *SIAM Journal on Optimization*, 29(3), 2128-2145.
Li, G., Wang, S., Li, J., Wang, R., Liu, F., Peng, X., ..., & Xu, C. (2023). Integrated sensing and communication from learning perspective: An SDP3 approach. *IEEE Internet of Things Journal*.
Macharia, S.M., & Mukulu, E. (2016). Role of just-in-time in realization of an efficient supply chain management: A case study of Bidco Oil Refineries Limited, Thika. *The Strategic Journal of Business & Change Management*, 3(6), 123-152.
Marlow, P.B., & Casaca, A.C.P. (2003). Measuring lean ports performance. *International Journal of Transport Management*, 1(4), 189-202.
Mentzer, J.T., Stank, T.P., & Esper, T.L. (2008). Supply chain management and its relationship to logistics, marketing, production, and operations management. *Journal of Business Logistics*, 29(1), 31-46.
Pandey, D., Kulkarni, M.S., & Vrat, P. (2011). A methodology for joint optimization for maintenance planning, process quality and production scheduling. *Computers & Industrial Engineering*, 61(4), 1098-1106.
Pinto, J.L.Q., Matias, J.C.O., Pimentel, C., Azevedo, S.G., & Govindan, K. (2018). *Just in time factory. Implementation through lean manufacturing tools*. Cham: Springer International Publishing AG.
Porter, M.E., & Heppelmann, J.E. (2015). How smart, connected products are transforming companies. *Harvard Business Review*, 93(10), 96-114.
Richards, G. (2017). *Warehouse management: a complete guide to improving efficiency and minimizing costs in the modern warehouse*. Kogan Page Publishers.
Ríos-Mercado, R.Z., & Borraz-Sánchez, C. (2015). Optimization problems in natural gas transportation systems: A state-of-the-art review. *Applied Energy*, 147, 536-555.
Romano, P. (2003). Co-ordination and integration mechanisms to manage logistics processes across supply networks. *Journal of Purchasing and Supply Management*, 9(3), 119-134.
Rüßmann, M., Lorenz, M., Gerbert, P., Waldner, M., Justus, J., Engel, P., & Harnisch, M. (2015). *Industry 4.0: The future of productivity and growth in manufacturing industries*. Boston Consulting Group, 9(1), 54-89.
Sabbaghi, A., & Vaidyanathan, G. (2008). Effectiveness and efficiency of RFID technology in supply chain management: strategic values and challenges. *Journal of Theoretical and Applied Electronic Commerce Research*, 3(2), 71-81.
Sahay, S., Nicholson, B., & Krishna, S. (2003). *Global IT outsourcing: software development across borders*. Cambridge University Press.
Scallan, P. (2003). *Process planning: the design/manufacture interface*. Elsevier.
Serdarasan, S. (2013). A review of supply chain complexity drivers. *Computers & Industrial Engineering*, 66(3), 533-540.
Sheffi, Y. (2012). *Logistics clusters: delivering value and driving growth*. MIT Press.
Stankovic, J.A., Abdelzaher, T.E., Lu, C., Sha, L., & Hou, J.C. (2003). Real-time communication and coordination in embedded sensor networks. *Proceedings of the IEEE*, 91(7), 1002-1022.
Sturgeon, T., & Lester, R.K. (2004). The new global supply base: new challenges for local suppliers in East Asia. *Global Production Networking and Technological Change in East Asia*, 476, 35-87.
Sugathadasa, R., Wakkumbura, D., Perera, H.N., & Thibbotuwawa, A. (2021). Analysis of risk factors for temperature-controlled warehouses. *Operations and Supply Chain Management: An International Journal*, 14(3), 320-337.
Swaminathan, J.M., Smith, S.F., & Sadeh, N.M. (1998). Modeling supply chain dynamics: A multiagent approach. *Decision Sciences*, 29(3), 607-632.
Tabassi, A.A., Ramli, M., & Bakar, A.H.A. (2012). Effects of training and motivation practices on teamwork improvement and task efficiency: The case of construction firms. *International Journal of Project Management*, 30(2), 213-224.
Taylor, J., & Raden, N. (2007). *Smart Enough Systems: How to Deliver Competitive Advantage by Automating Hidden Decisions*. Pearson Education.
Van Apeldoorn, J., Gilyén, A., Gribling, S., & de Wolf, R. (2017, October). Quantum SDP-solvers: Better upper and lower bounds. In 2017 IEEE 58th Annual Symposium on Foundations of Computer Science (FOCS) (pp. 403-414). IEEE.

Westerman, G., Bonnet, D., & McAfee, A. (2014). *Leading digital: Turning technology into business transformation*. Harvard Business Press.

Wu, S.P., & Boyd, S. (1996, September). Design and implementation of a parser/solver for SDPs with matrix structure. In Proceedings of Joint Conference on Control Applications Intelligent Control and Computer Aided Control System Design (pp. 240-245). IEEE.

Chapter 3

INNOVATION IN LOGISTICS CLUSTERS IN POLAND

Anna Horzela-Miś[1], Jakub Semrau[2]

[1] Silesian University of Technology, Faculty of Management, Poland
Anna.Horzela-Mis@polsl.pl ORCID 0000-0003-2345-9861
[2] Silesian University of Technology, Faculty of Logistics, Poland
Jakub.Semrau@polsl.pl ORCID 0000-0002-4894-7792

Abstract: In today's market, innovation is a critical factor in determining competitive advantage, especially in the logistics sector, where it is the basis for operational efficiency and customer satisfaction. This chapter examines the role of logistics clusters in Poland as facilitators of innovation, examining their contribution to the evolution of the logistics industry against the backdrop of technological progress and growing market demands. The methods discussed in the methodological part of the work are critical analysis of the literature, inductive-deductive reasoning and case study analysis. By conducting a case study of Polish logistics cluster, the research highlights how integrated networks of companies can leverage modern technologies – such as IoT, AI, and automation – to optimize supply chain processes and streamline service delivery. The results indicate that the research cluster effectively supports innovation through collaborative partnerships, technological integration, and a focus on sustainable development, thereby increasing the competitiveness of member companies. Furthermore, challenges such as regulatory complexity, infrastructure constraints, and shortages of skilled labor are identified as barriers to further development of logistics clusters in Poland. The chapter concludes with recommendations for policymakers and industry leaders to create an environment conducive to innovation, ultimately positioning Poland as a leading logistics hub in Europe and contributing to broader economic growth.

Keywords: cooperation, innovation, logistics clusters

Introduction

Nowadays, innovations are one of the key factors that determine gaining and maintaining a competitive advantage in the market (Sumantri, 2020, pp. 1-2). They are often referred to as a requirement for conducting business in a market economy, as well as the most valuable assets of a modern organization (Lozhachevska et al., 2021, p. 315). Their importance results from the role they play in enterprises. They contribute not only to improving the quality of goods and services offered, but also determine the ability to survive and develop through quick response to changes in the market and the ability to adapt to the needs and expectations of customers (Dziekoński & Chwiećko, 2013, p. 176).

It is difficult to imagine a modern organisation without a well-functioning logistics. Polish companies are joining the trend of this fourth revolution, implementing innovative projects in the field of modern production lines, robotic internal logistics, mobile applications, intelligent materials and drones (Palmen & Baron, 2016, p. 34). The use of technological means to ensure the efficiency of logistical processes is becoming a key issue. High technological requirements and changing conditions in the creation of value in logistical chains are increasingly challenging the efficiency and rationalisation of logistical processes. Information as the most important value in a rapidly changing environment has become one of the most important elements of the logistical process. It has become a challenge for modern information systems to provide up-to-date data for the effective realisation of logistical activities. The integration of state-of-the-art information technology with the existing hardware and software infrastructure poses a major challenge to both management and senior staff using the implemented technology (Sosnowski & Olczak, 2011, p. 77).

Logistics companies are under intense pressure to continuously develop and increase the profitability of their operations (Krauth et al., 2005, p. 240). As emphasised by Koźlak (2008, p. 2), their position depends primarily on the level of costs of provided services and their quality. In turn, these two parameters are strongly influenced by the innovative solutions implemented. Logistics companies are a diverse group in terms of many parameters related to their size, organisational structure, type and scope of services provided. At the same time, they have a significant innovative potential, which results from their dynamic development, increase in demand for the services offered, increase in the level of revenues, the scope of the served market, as well as the inflow of capital. However, it is mainly the large and international players who are looking for new opportunities and solutions. Innovation entails the need to incur high financial expenditures, and this is often one of the factors inhibiting innovation, especially for small and medium-sized enterprises (Koźlak, 2014, p. 138).

In the case of the logistic industry, the area of implemented innovative activities can be very large, these can be not only new products offered on the market, but also changes in the technology of service production itself, in the concept of management of a logistics enterprise, changes in the way the enterprise works and many others (Antonowicz, 2015, p. 1134). Innovations in the logistic industry concern all activities that are perceived as new and useful for stakeholders, both internal and external. In the first case, they are intended to improve operational efficiency, while in the second, they are intended to raise the level of customer service (Zailani et al., 2015, p. 108). Antonowicz emphasizes that the task of innovations in the TSL industry is both effectively fulfilling current customer needs, as well as creating new ones that take into account their requirements (Antonowicz, 2014, p. 22). On the other hand, A. Bujak emphasizes better adaptation to changes in the environment and gaining the ability to react faster to market needs (Bujak, 2011, p. 92).

Researchers have highlighted the importance of stimulating innovation within logistics clusters as a key prerequisite for advancing the transport sector (Shkoda et al., 2023, p. 365; Smoliar et al., 2022, pp. 1-7). Logistics clusters have emerged as critical nodes in global supply chains, facilitating the seamless movement of goods and services across regions (Choi & Siqin, 2022). In Poland, these clusters have gained prominence due to strategic geographical location, infrastructure development, and supportive government policies aimed at fostering industrial growth and innovation (Han, 2014, p. 1395). The aim of this paper is to examine how these clusters contribute to innovation in the logistics sector and beyond, using the example of a selected Polish logistics cluster.

Literature review

Clusters have become a very popular tool of regional policy of all provinces in Poland (Gemra, 2017, p. 30). This is the result of the intensification of regional development processes for which clusters are a basic strategic tool (Dmuchowski, 2019, p. 351; Knop, 2013, pp. 174-175). The basis of the cluster concept are cooperative, informational and interpersonal ties between companies in the entire supply chain or in horizontal connections (Kazojć, 2016, pp. 57-60; Verduzco-Garza, 2015, p. 1). Clusters themselves are geographical concentrations of interconnected institutions of a given area of economic activity (Porter, 2001, pp. 246-256). The systematically progressing internationalization of activity and dynamic technological development mean that the ongoing economic processes in many cases take on the characteristics of complex systems, in which it is increasingly difficult to determine the directions of possible changes (Trzmielak & Woźniakowski, 2015, p. 27).

Business innovation is a very important and topical area of research and analysis. Also in relation to the logistics industry, the role of, as well as the need to generate and implement new solutions due to the competitiveness in the market and the potential of these enterprises is emphasized (Budrin et al., 2019, pp. 176-181). One of the widely discussed problems in the literature is the classification of innovations, in which many different approaches are proposed. However, by far the dominant and basic one is the division in line with OECD recommendations. This manual has significantly revised the definition of business innovation by simplifying the earlier, more complex list that categorized innovations into four types: product, process, organizational, and marketing. Based on insights from cognitive testing, the definition has been streamlined to focus on two primary categories: product innovations and business process innovations (OSLO Manual, 2018).

Advanced technology clusters are an undeniable instrument for supporting the development and competitiveness of regions (Kovbatiuk & Shevchuk, 2018, pp. 114-121). The development of advanced technology clusters is one of the main instruments of pro-innovation policy in the world. International experience shows that effective support for cluster initiatives by the public sector leads to an increase in the competitiveness of enterprises gathered in clusters, contributes to the diffusion and transfer of knowledge and to closer cooperation between business and the research and development sector (Sheffi, 2014). The main goal of supporting clusters is to permanently increase the level of competitiveness of the economy at the local, regional and national level, by increasing the innovativeness of enterprises and improving their competitive position (Domański & Marciniak, 2003, p. 152). Therefore, support for the creation and development of clusters, including advanced technology clusters, is one of the key aspects of regional policy, both in its pro-investment and pro-innovation dimension. Support for the creation and development of clusters is also often considered as an element of the cohesion policy implemented in Poland (Parysek, 2003, p. 45). Innovation clusters are a form of closed partnership. In this model, a network of intensive cooperation is created between the operator and a selectively selected external partner (Frankowska, 2016, pp. 325-340).

One specific type of cluster is the logistics cluster. According to Elsner (2010), a logistics cluster is a group of companies from either the manufacturing or service sectors, united by the common characteristic that their employees perform logistics-related functions. This group typically includes producers, suppliers, service companies, as well as public and private organizations involved in logistics services (Liu et al., 2022). These services are usually provided by entities such as logistics and warehouse centers, specialized and intermediary carriers, freight forwarders, freight brokers, intermodal marketing companies, and back-office firms related to the transport, shipping, and logistics (TSL) sector. Examples of such back-office firms include equipment and machinery suppliers, leasing companies, and transportation fleet service providers. These companies are often concentrated around logistics infrastructure such as ports, airports, and rail hubs (Elsner, 2010, pp. 1-33). This definition implies that a logistics cluster requires both the execution of logistics functions by employees within these companies and the geographical concentration of these firms around key logistical infrastructure. Key logistics functions typically include transportation and warehousing, along with activities such as ordering, inventory management, loading, and material handling.

In turn, Sheffi (2010, pp. 11-17) is the author of a simple definition that a logistics cluster is a set of companies offering logistics services, such as transport, storage and distribution. Later, Sheffi complicated his definition, indicating that a logistics cluster is a set of companies performing operations that intensively use logistics. He indicated three types of these companies at the same time. First, these are logistics service providers, such as carriers, warehouses, specialized consultants and IT suppliers, 3PL, freight forwarders and customs brokers. Second, these are industrial companies performing logistics operations for distribution or spare parts supply. Third, these are industrial companies in which logistics operations are a source of significant costs (Sheffi, 2013, p. 468).

Witkowski and Kiba-Janiak (2012, pp. 397-414) present a similar way of reasoning to Sheffi's. According to them, a logistics cluster is a geographical concentration of interconnected companies, competing with each other, but also cooperating, providing logistics services, such as transport, storage, packaging, reloading, forwarding, as well as companies providing services supporting logistics processes, such as service, financial, insurance, etc. services, and other institutions (scientific, standardizing, industry associations) in order to carry out specific tasks: educational, scientific, business and training.

Logistics clusters occupy a key place in regional policy, especially in regions focusing on logistics services as a source of competitive advantage (Xiu, 2013, p. 401). However, the development of logistics clusters encounters many barriers that make it difficult to fully use this concept (Bergmansson, 2005). The main infrastructural constraints include poorly developed ICT and transport infrastructure, a shortage of industrial areas and inadequate technological support, especially in the area of research and development. Investment problems result from the lack of suitable areas and high land costs (Kowalski, 2013, pp. 183-184). Economic and financial constraints include a low level of industrial development, limited innovation and difficulties in obtaining investment capital, including high-risk funds. Territorial and structural and organizational constraints concern, among others, difficult access to international markets and the lack of qualified staff and business self-organization. Environmental and cultural problems include increased emissions, lack of trust and cooperation in the cluster, and low public awareness of the role of clusters in innovation and competitiveness (Chyba, 2008). Legal constraints result from the lack of a clear legal definition of a cluster and the instability of legal regulations. These complex problems require coordinated actions at the regional and national levels to support the development of logistics clusters as a key element of regional development strategies (Oziębło, 2016, pp. 144-145).

In the coming years, Polish regions are unlikely to gain a comparative advantage in the field of innovation, mainly due to delays in the development of clusters and the high-tech sector (Skoczylas, 2014, pp. 178-179). Nevertheless, the modernization of regional economies and structural reform, especially in the area of competition regulation and cooperation between business and R&D institutions, are crucial for further growth of competitiveness (Pyka & Kruppers, 2002, p. 7; Schumpeter, 2007, p. 27). Current regulations hinder the development of the advanced technology sector, and Polish companies cooperate less often with each other in the field of innovation than companies in other EU countries (Rochefort, 2009, p. 25; Świstalski, 2004, pp. 89-98). Moreover, there is a discrepancy between the structure of research expenditures and market needs, which limits the transfer of research results to Polish companies.

The logistics industry, a key component of global supply chains, is evolving rapidly through the use of modern technology. Innovations in this sector are helping to improve efficiency, optimise processes and increase customer satisfaction. Below are the key innovations that have revolutionised logistics in recent years (Abdirad & Krishnan, 2020, pp. 1-15; Anthony et al., 2024, p. 53; Barreto et al., 2017, p. 1245; Jirsak, 2018, pp. 121-146; Mahdavisharif et al., 2022, p. 386):

1. Automated warehouses and robotization. The use of automated warehouses and barcode scanning robots significantly streamlines warehouse processes. The use of RFID technology and product packaging programmes minimises errors and reduces lead times. Automation allows logistics companies to increase competitiveness and optimise their work.
2. IoT and blockchain technologies. the Internet of Things (IoT) and blockchain are becoming increasingly popular in the logistics industry. With IoT, it is possible to monitor the location, temperature and other parameters of shipments in real time, which increases security and transport efficiency. Blockchain, on the other hand, enables transparency in the supply chain, especially in terms of tracking shipments, which helps logistics operators to manage the so-called ‘last mile’.
3. Artificial intelligence (AI). AI finds applications in warehouse management and demand forecasting. AI supports logistics in optimising delivery routes, analysing data and predicting operational problems. By automating decisions, it is possible to manage resources more efficiently and reduce operational risks.
4. Data analytics and Big Data. Modern logistics increasingly relies on the analysis of large data sets. Big Data makes it possible to predict trends, optimise processes and make more precise business decisions. It also acts as a tool for demand forecasting and risk management.

5. Sustainable logistics. logistics companies are increasingly emphasising environmentally friendly measures, which allows them not only to build a positive image, but also to meet customers' growing expectations in terms of social responsibility. Implementing green solutions, such as supporting local suppliers, is an important part of building competitiveness.

Development of AR and VR technologies. Augmented reality (AR) and virtual reality (VR) are finding their way into goods picking and warehouse space management. These technologies make it possible to eliminate human error and increase operational efficiency.

Research methodology

In order to achieve the aim of the paper, a critical analysis of the literature was first conducted in relation to the definition of logistics clusters and their innovativeness. A logistics cluster is a new organizational form functioning in economic realities, which requires better understanding. The innovativeness of logistics clusters was presented based on a case study of a selected Polish cluster – Kilog based on materials available in the cluster reports, website and other publicly available materials.

Research results and discussion

Poland's strategic location at the crossroads of major European trade routes has positioned it as a key logistics hub. The development of logistics clusters in cities like Warsaw, Łódź, and Wrocław has been driven by investments in modern infrastructure, including airports, seaports, and road networks. These clusters integrate various elements of the supply chain, from warehousing to distribution, leveraging economies of scale and scope to enhance operational efficiencies. Innovation within logistics clusters in Poland is propelled by several factors. Firstly, advancements in technology, such as IoT (Internet of Things), AI (Artificial Intelligence), and automation, are revolutionizing warehouse management, transportation planning, and last-mile delivery. Secondly, collaborative networks between industry players, academic institutions, and government bodies foster knowledge sharing and R&D initiatives, leading to the development of cutting-edge solutions. Thirdly, sustainability concerns are prompting innovations in eco-friendly logistics practices, including green transportation and packaging solutions.

This section presents case study of notable logistics cluster in Poland: Cluster Innovative Logistics -Kilog cluster, highlighting their unique approaches to innovation.

The main objective of the Kilog cluster is to increase the competitiveness and innovation of the logistics sector. Table 3.1 presents the main goals and their implementation of Kilog cluster.

Examples of the realization of innovative challenges in the field of logistics show the excellent solutions applied by the Kilog cluster. Table 3.2 shows examples of companies for which the studied cluster has contributed to further development.

Table 3.1. Goals and their implementation

Goals	Implementation
- achieving a high level of innovation and competitiveness of enterprises associated in the Cluster, - ensuring high economic and financial efficiency of enterprises associated in the Cluster and initiatives conducted by them, - diagnosing and developing concepts for solving problems in the field of logistics management, especially sales and distribution networks, - implementing activities aimed at ensuring comprehensive and full logistics services for enterprises, especially sales and distribution networks, - carrying out activities that will serve the development of associated companies and institutions and creating favourable conditions for conducting business activities, - animating cooperation between enterprises, public administration, industry associations, educational and research and development institutions and other interested entities, and as a result stimulating socio-economic growth and development of entrepreneurship, especially in the region of Eastern Poland.	- using the synergy effect, - using the available organizational, technological, scientific and personal resources, - exchanging knowledge and experience of the Cluster members, - monitoring, analyzing and creating recommendations in the field of economic and financial efficiency, - disseminating the idea of innovation among entrepreneurs and scientific institutions, including universities, - supporting technological and business initiatives related to the development of the Cluster, - obtaining sources of financing, including EU funds for economic, scientific, research projects and other initiatives, - cooperating with the scientific and educational community, - developing smart specialization strategies and creating knowledge and innovation databases, - conducting information, advisory and educational activities, including: in the scope of innovation, technology transfer, cooperative links between companies and cluster creation methodology, - associating and supporting pro-innovation activities of companies, universities and scientific and research institutions and institutes, - conducting own and handling commissioned development and research projects, - promoting the Cluster's offer, - participating in national and regional programmes concerning the implementation of the Cluster's objectives, - organising training courses and classes, symposia, lectures, discussion meetings, exhibitions, competitions, shows and other activities promoting innovation in logistics, - publishing and publishing activities, - initiating and undertaking, in compliance with applicable regulations, other activities aimed at implementing the statutory objectives and tasks of the Cluster.

Source: Own study based on ERPwincash Commit Polska Sp. z o.o., www.commit.pl (access on 26.09.2024).

Table 3.2. Case studies of Kilog cluster

Company	Challenge	Solution	Benefits
Recman	Replacement of the existing POS system. Communication of the show-rooms with the head office in real time. Enhanced management of price and promotions. Integration with web shop and other online shop and other external systems.	ERPwincash Back Office ERPwincash Logistics ERP-wincash POS Oracle Business Intelligence	Omnichannel. Intuitive creation of diverse promotional campaigns. Increased efficiency and accelerated sales processes. Central management of all sales channels.
Inglot	Communication of the salons with the head office in real time. Optimisation of logistics processes optimisation of logistics processes within the network. Enhanced management of pricing and promotions. Introduction of a loyalty programme. Integration into an operational production system, financial and accounting system and web shop.	NTSwincash Back Office NTSwincash Logistics NTSwincash POS	A rich tool for creating promotional activities. Launch of the loyalty programme. Increased efficiency of logistics processes Stock control of shops from the head office position. Effective integration with external systems.
Vodafone Qatar	Short implementation time Emphasis on management logistics.	NTSwincash Retail Suite § Retail Manage-ment § Retail Store Point § Retail Logistics	Management system Logistics Integration with payment terminal Payment terminal (EFT) Replication to protect against Fail-safe replication Mobile points of sale Equipped with NTSwincash
EGR	Replace the existing system Standard interface for financial and accounting system.	NTSwincash in SaaS model	Support for shops offering prod-ucts and services of various trading partners Central data management No costs associated with setting up an IT facility on the customer's side Saving time and money management, on IT infrastructure, support operation and IT

Source: Own study based on ERPwincash Commit Polska Sp. z o.o., www.commit.pl (access on 26.09.2024).

Table 3.2 shows the challenges, solutions and benefits achieved by four selected companies through the implementation of modern ERP and POS systems. In each case, the main objectives were to improve communication with head office, optimise logistics, manage pricing and promotions, and integrate with other internal and external systems. The implemented solutions brought a number of benefits, such as improved sales efficiency, central data management, and the introduction of innovative tools such as mobile POS and loyalty programmes. Summarize the data presented in Table 3.2 it is possible to indicate few key findings:

– Centralisation of management. All companies benefited from the centralisation of sales channel management and logistics processes, resulting in significant operational improvements.
– Omnichannel. By integrating different sales systems, both stationary and online, companies gained the ability to conduct omnichannel activities, which increased product availability and improved customer experience.
– Logistics efficiency. Optimisation of logistics processes has been a key aspect in improving inventory and delivery management, resulting in better control over the flow of goods and reduced operating costs.

Supporting companies in implementing these changes, the KILOG cluster has implemented a number of innovative logistics solutions. Here are the most important of these:

– Advanced automation of logistics processes. The KILOG cluster introduced systems to automate inventory management, allowing for more precise planning and a reduction in human error.
– Integration with ERP systems. By integrating logistics systems with ERP, companies can control warehouse and logistics processes in real time, ensuring better coordination of activities.
– Optimisation of delivery routes. Advanced route planning tools allow delivery processes to be optimised, reducing transport costs and lead times.
– Cloud-based warehouse management (SaaS). The implementation of cloud-based systems (SaaS) in logistics enables companies to flexibly manage their inventory without investing in costly IT infrastructure.

The innovative solutions introduced by the KILOG cluster have allowed companies to make significant improvements in the area of logistics, resulting in operational efficiency, lower costs and greater flexibility in managing sales and warehouse processes.

Conclusion

The issue of clusters is one of the most complex and still insufficiently researched issues. The interest in a logistics cluster is an important economic and social issue, confirmed by the European Union in the implementation of joint investments. The existence of appropriate infrastructure is recommended for the implementation of logistics cluster tasks, the places where clusters occur are primarily industrialized regions and metropolises. Entities operating in clusters in Poland are aware of the need to cooperate with public authorities in order to consolidate their position in the region and to make a certain level of their competitiveness. Determinants influencing the creation of logistics clusters are sought among internal and external factors. Key factors should be sought in the processes of internationalization, liberalization of capital flows and capital investment in places with particularly favorable conditions, searching for new sources of competitive advantage and large disproportions between regions.

Despite their successes, logistics clusters in Poland face challenges such as regulatory complexities, infrastructure bottlenecks, and skilled labor shortages. Addressing these challenges requires coordinated efforts from policymakers, industry leaders, and academia to create an enabling environment for continuous innovation. Moreover, opportunities abound for leveraging emerging technologies like blockchain and predictive analytics to further optimize supply chain processes and enhance competitiveness on a global scale (Kumar et al., 2017, pp. 25-36).

The strategic implications of innovation in logistics clusters extend beyond operational efficiencies to broader economic impacts. Enhanced logistics capabilities attract foreign direct investment (FDI), stimulate job creation, and contribute to regional development. Policymakers can leverage these clusters to promote economic diversification and resilience, positioning Poland as a leading logistics hub in Europe. Future research should focus on longitudinal studies to track the evolution of logistics clusters in Poland, evaluate the long-term impacts of innovation on economic growth and sustainability, and explore novel strategies for overcoming existing challenges in the rapidly evolving logistics landscape.

References

Abdirad, M., & Krishnan, K. (2020). Industry 4.0 in logistics and supply chain management: A systematic literature review. *Engineering Management Journal*, 33(3), 1-15. DOI: 10.1080/10429247.2020.1783935.

Anthony, O.O., Olabanji, O.M., & Rameshwar, D. (2024). Impacts of industry 4.0 on supply chain management of logistics providers: A methodical review. *Global Journal of Engineering and Technology Advances*, 20(03).

Antonowicz, M. (2014). Logistics innovations in transport. *LogForum*, 10(1).

Antonowicz, M. (2015). O innowacjach produktowych i marketingowych w usługach transportowo-logistycznych. *Logistyka*, 2 (CD).

Barreto, L., Amaral, A., & Pereira, T. (2017). Industry 4.0 implications in logistics: an overview. *Procedia Manufacturing*, 13(1), 1245-1252. DOI: 10.1016/j.promfg.2017.09.045.

Bergmansson, E.M. Johansson, B., & Stought, R. (eds.) (2005). *Industrial clusters an inter – film network.* Northampton, Edward Elgar Publishing.

Budner, W.W. (2022). *Klastry logistyczne. Podstawy teoretyczne i praktyka w Polsce*. Poznań: Bogucki Wydawnictwo Naukowe. DOI:10.12657/978-83-7986-418-8.

Budrin, A.G., Budrina, E.V., Lebedeva, A.S., Rogavichene, L.I., & Kvitko, K.B., (2019). Intelligent Transport Systems as an Integration Platform for Creating a Network of Regional Transport and Logistics Complexes, 2019 International Conference Quality Management, Transport and Information Security, Information Technologies (IT&QM&IS), Sochi, Russia, DOI: 10.1109/ITQMIS.2019.8928343.

Bujak, A. (2011). Innowacyjność i innowacyjne rozwiązania w logistyce. *Logistyka,* 2.

Choi Tsan-Ming, & Siqin, T., (2022). Blockchain in logistics and production from Blockchain 1.0 to Blockchain 5.0: An intra-inter-organizational framework. *Transportation Research Part E: Logistics and Transportation Review*, 160, 102653, DOI: 10.1016/j.tre.2022.102653.

Chyba, Z. (2008). Klastry przemysłowe a przedsiębiorstwa spin-off. *Ekonomika i Organizacja Przedsiębiorstw*, 3.

Dmuchowski, R. (2019). The concept of logistics clusters and efficiency of economic enterprises. *Journal of European Economy*, 18, 3, DOI: 10.35774/jee2019.03.351.

Domański, R., & Marciniak, A. (2003). Sieciowe koncepcje gospodarki miast i regionów. *Studia KPZK PAN*, t. CXIII.

Dziekoński, K., & Chwiećko, J. (2013). Innowacyjność przedsiębiorstw z branży TSL. *Ekonomia i Zarządzanie*, 2.

Elsner W. (2010). Regional service clusters and networks. Two approaches to empirical identification and development: the case of logistics in the German port city-states Hamburg and Bremen. *International Review of Applied Economics*, 24, 1.

Frankowska, M. (2016). Innowacyjna obsługa logistyczna na przykładzie klastra logistycznego „Logistics in Wallonia" w segmencie biologistics. *Zeszyty Naukowe Uniwersytetu Gdańskiego. Ekonomika Transportu i Logistyka*, (58), 325-340.

Gemra, S. (2017). Istota i znaczenie klastrów w zarządzaniu przedsiębiorstwami transportowymi. *Autobusy*, 11.

Han, M., Han, Y.H., & Chen, C. (2014). Study on the measurement of logistics industry cluster. *Applied Mechanics and Materials*, 488-489, DOI: 10.4028/www.scientific.net/amm.488-489.1395.

Jirsak, P. (2018). *Analyzing an impact of industry 4.0 on logistics and supply chain,* In *Analyzing the impacts of Industry 4.0 in modern business environments*, eds. R. Brunet-Thornton & F. Martinez. IGI Global, DOI: 10.4018/978-1-5225-3468-6.ch007.

Kazojć, K. (2016). *Model transferu technologii w klastrach morskich w Polsce*. Warszawa: Wyd. CeDeWu pl.

Knop, L. (2013). *Zarządzanie klastrem. Koncepcje. Strategie. Modele*, Gliwice: Wyd. Politechniki Śląskiej.

Kovbatiuk, M., & Shevchuk, V. (2018). Efficiency evaluation of cooperation between transport enterprises and higher education institutions in the transport and logistics cluster. *Baltic Journal of Economic Studies*, 4(5). DOI: 10.30525/2256-0742/2018-4-5-114-121.

Kowalski, A.M. (2013), *Znaczenie klastrów dla innowacyjności gospodarki w Polsce*. Warszawa: Oficyna Wydawnicza Szkoła Główna Handlowa.

Koźlak, A. (2008). Innowacyjność w podaży usług jako czynnik konkurencyjności przedsiębiorstw sektora TSL. Referat z konferencji Eurotrans, Warszawa.

Koźlak, A. (2014). Wspieranie innowacyjności przedsiębiorstw sektora TSL w Polsce z funduszy Unii Europejskiej. *Logistyka*, 2.

Krauth, E., Moonen, H., Popova, V., & Schut, M.C. (2015). Performance measurement and control in logistics service providing. Conference paper: ICEIS 2005, USA.

Kumar, I., Zhalnin, A., Kim, A., & Beaulieu, L.J. (2017). Transportation and logistics cluster competitive advantages in the U.S. regions: A cross-sectional and spatio-temporal analysis, *Research in Transportation Economics*, 61, 2017, DOI: 10.1016/j.retrec.2016.07.028.

Liu, S., He, N., Cao, X., Li, G., & Jian, M. (2022). Logistics cluster and its future development: A comprehensive research review. *Transportation Research Part E: Logistics and Transportation Review*, 168, 102974, DOI: 10.1016/j.tre.2022.102974.

Lozhachevska, O., Navrotska, T., Melnyk, O., Kapinus, L., Zos-Kior, M., & Hnatenko, I. (2021). Management of logistics and marketing behavior of innovation clusters in territorial communities in the context of digitalization of society and the online market. *Laplage em Revista*, 7(3).

Mahdavisharif, M., Cagliano, A.C., & Rafele, C. (2022). Investigating the integration of Industry 4.0 and leanprinciples on supply chain: A multi-perspective systematic literature review. *Applied Sciences*, 12(2). doi DOI: 10.3390/app12020586.

OECD/Eurostat (2018), Oslo Manual 2018: Guidelines for Collecting, Reporting and Using Data on Innovation, 4th Edition, The Measurement of Scientific, Technological and Innovation Activities, Paris/Eurostat, Luxembourg: OECD Publishing, DOI: 10.1787/9789264304604-en.

Oziębło, M. (2016). *Klastry logistyczne – koncepcja.* In *Logistyka w XXI wieku – wybrane zagadnienia.* eds. Z. Kurasiński & M. Pawlisiak. Wydawnictwo Społecznej Akademii Nauk, Przedsiębiorczość i Zarządzanie, T. XVII, z. 3, cz. 3.

Palmen, L., & Baron, M. (2016). Przewodnik dla animatorów inicjatyw klastrowych w Polsce. Warszawa: Polska Agencja Rozwoju Przedsiębiorczości.

Parysek, J.J. (2003). *Metropolie: metropolitalne funkcje i struktury przestrzenne*, In: *Funkcje metropolitalne i ich rola w organizacji przestrzeni*, red. I. Jażdżewska, Łódź: WSE.
Porter, M.E. (2001). *Porter o konkurencji*. Warszawa: PWE.
Pyka, A., & Kuppers, G. (2002). *Innovation Networks Theory and Practice*. Edward Elgar, Cheltenham, UK, Northampton, USA.
Rochefort, M. (2009). Métropoles et fragmentation des espaces, *Metropole*, 5.
Schumpeter, J.A. (2007). *Teoria rozwoju gospodarczego*, Warszawa: PWE.
Sheffi, Y. (2010). *Logistics intensive clusters*. *Época/Epoch*, 20, 1-2.
Sheffi, Y. (2013). *Logistics-intensive clusters: global competitiveness and regional growth. Handbook of Global Logistics*. New York: Springer.
Sheffi, Y. (2014), Logistics Clusters: Delivering value and Driving Growth. MIT Press.
Shkoda, M., Marova, S., Gorobets, N., Tokuieva, N., Zvonovskyi, R., Babaiev, V., & Tereshchenko, S. (2023). Technological management of cluster innovations in the education system, personnel development and logistics in realising the potential in post-war renewal. *Management Theory and Studies for Rural Business and Infrastructure Development*, *45*(4), 364-378. DOI: 10.15544/mts.2023.36.
Skoczylas, A. (2014). Polskie i brytyjskie innowacyjne klastry na drodze kreowania konkurencyjności regionu. *Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu Research Papers of Wrocław University of Economics*, 369.
Smoliar, L., Koba, N., & Koba, M. (2022, October). Clusterization as a Factor of Business Development in TransportLogistic Sphere. In 2022 IEEE 3rd International Conference on System Analysis & Intelligent Computing (SAIC). IEEE.
Sosnowski, J., & Olczak, P. (2011). Systemy bezprzewodowych transmisji danych w logistyce. *Acta Universitatis Lodziensis Folia Oeconomica* 251.
Sumantri, Y. (2020). Drivers of logistics service innovation in Third Party Logistics business. IOP Conference Series: Materials Science and Engineering, 732, 012068.
Świstalski, W. (2004). Nauka, zasoby wiedzy, teoria innowacyjności a wzrost gospodarczy, *Ekonomista*, 1.
Trzmielak, D.M., & Woźniakowski, M. (2015). Innowacje w transporcie – na przykładzie badań w sektorze transportowym. *Zeszyty Naukowe Uniwersytetu Szczecińskiego, Ekonomiczne Problemy Usług* 121, 891, DOI: 10.18276/epu.2015.121-02.
Verduzco-Garza, T. (2015) A logistics and transportation Cluster Initiative: A theoretical framework. Conference: 18th TCI Global Conference At: Daegu, South Korea, 18.
Witkowski, J., & Kiba-Janiak, M. (2012). Rozwój europejskich centrów i klastrów logistycznych na podstawie doświadczeń hiszpańskich. *Ekonomiczne Problemy Usług*, 94.
Xiu, X.F. (2013). The study of the regional logistics cooperation system based on the industrial cluster. Applied Mechanics and Materials, 2183-2186. DOI: 10.4028/www.scientific.net/amm.401-403.2183.
Zailani, S., Amran, A., & Jumadi, H. (2011). Green Innovation adopting among logistics service providers in Malaysia: an exploratory study on the manager's perceptions. *International Business Management*, 5(3).

Chapter 4

TRENDS IN GREEN INNOVATION RESEARCH DEVELOPMENT

Anuphat Thirakulwanich

WSB University, Faculty of Applied Sciences, Poland
anuphat.thirakulwanich@student.wsb.edu.pl ORCID 0000-0002-8462-8561

Abstract: Studies in Green Innovation Management (GIM) have gained considerable attention in the last decade, demonstrating widespread progress in addressing ecological problems through green innovative practices. This investigation reflects the dynamic nature of GIM research, examining its interdisciplinary origins and scholarly value through an extensive bibliometric analysis based on studies extracted from the Scopus database. This deconstruction employs a bibliometric analysis to explore the evolution and impact of GIM across global research studies from 2019 to 2023 by examining annual publication volumes, citation data, and scholarly contributors through a three-field plot. It highlights the increasing annual output of GIM articles, significant citation rates indicating the growing importance of the field, and how the authors, affiliations, and keywords are interconnected. The research identifies the top journals and authors in green innovation management research, showcasing the field's influential entities and the global shift towards sustainable innovation practices. A crucial limitation of the study is that while the Scopus database is the benchmark for researchers, future studies should diversify and incorporate other data sources other than Scopus for future analyses and foster interdisciplinary collaboration to address GIM challenges. The findings aim to guide policymakers, researchers, and practitioners toward effective strategies for sustainable innovation.

Keywords: bibliometric analysis, citation analysis, green innovation management, green innovation, sustainability, sustainable practices

Introduction

There has been a significant increase in attention towards green innovation research in recent years as evidenced by scholarly contributions (Alsmadi et al., 2023; Kumar et al., 2021; Silintowe & Sukresna, 2023). These reflections have largely been driven by the pressing need to address environmental green challenges societies worldwide face (Shuwaikh et al., 2023; Wang et al., 2021; Zameer & Yasmeen, 2022) and incorporate management perspectives (Ahmed et al., 2023; Gao et al., 2022; Wang et al., 2022) to coin the research phrase "green innovation management" (GIM) (Abadzhiev et al., 2022; Bigliardi & Bertolini, 2012; Schiederig et al., 2011). Researchers have turned to bibliometric analysis to understand developments and trends within this field better (Alsmadi et al., 2023; Kumar et al., 2021; Silintowe & Sukresna, 2023). The growing recognition of the importance of green business practices has propelled a global focus on green innovation, creating the need for a better understanding of the trends shaping GIM and the institutions, authors, and journals influencing this emergence (Baeshen et al., 2021; Ge et al., 2018; Hasan et al., 2019; Li et al., 2020; Shahzad et al., 2022). This paradigm shift involves aligning innovative approaches with ecological consciousness, effectively tackling current environmental challenges, and providing solutions for future issues while pursuing developmental goals in the present. As a result, the academic research landscape has seen many studies that aim to dissect, elucidate, and promote green innovation in various contexts and regions (Barbieri et al., 2023; Obobisa et al., 2023; Rahman et al., 2023; Ramzan et al., 2023; Tariq et al., 2019; Xu, 2022; Wysocki, 2021). Researchers can solve green innovation's complexities by systematically analyzing the existing literature and clarifying its significance in our societal and environmental geographies. Such investigations are vital for informing policymakers, researchers, and practitioners as they seek to develop innovative solutions to address pressing environmental concerns (Ahmed et al., 2023; Khan et al., 2021; Rodrigues & Franco, 2023; Wang et al., 2021). This quantitative method examines scientific publications, citations, and collaboration patterns, providing data into critical topics, influential authors, high-impact journals, and emerging developments related to green innovation.

The concept of bibliometric analysis was first developed by Pritchard in 1969 to describe a new field that utilizes quantitative approaches to study the scientific communication process by measuring and analyzing different elements of written materials, and it greatly enhances the clarity of a particular research field (Pritchard, 1969; Stork & Astrin, 2014). Bibliometrics is a burgeoning field of study that includes various disciplines of organized human learning (Jones, 2015; Mhando et al., 2023; Thanuskodi, 2017). As scholars have acknowledged, bibliometrics, in recent decades, has emerged as a widely accepted instrument for research policy and management, including data such as publication titles and citation statistics, along with advanced bibliometric methodologies, which play a crucial role in the development of major scholarly indicators when studies are being evaluated.

Bibliometrics is a systematic assessment of the publication trends and authorship of both large-scale and small-scale communication through mathematical and statistical calculations. Broadus (1987) aptly defines bibliometric research as a quantitative study of bibliographic material with the goal of providing an extensive overview of a research subject. The prioritization of content in this form of analysis is mostly determined by the aggregate count of articles or the cumulative count of citations. Bibliometrics is the examination of the correlation between numerical values and trends in bibliographical statistics, such as the number of publications, the emergence of literature, and the usage patterns of institutional libraries and research databases in analysis.

Bibliometric approaches are valuable tools for conducting literature evaluations. Even prior to reading, researchers can identify the most influential publications and create an exhaustive map of the research topic, in this instance, green innovation management, free from personal prejudices (Anlesinya & Dadzie, 2023; Linnenlueck et al., 2019; Patience et al., 2018; Perpetuo et al., 2022; Rosado & Souza, 2021). Extensive documentation exists regarding the expansion of bibliometrics beyond literature studies (Ellegaard & Wallin, 2015; González-Alcaide, 2021; Larivière et al., 2012). Several authors express concerns about the uncontrolled use and widespread adoption of this strategy, especially when authors in distant domains lack an understanding of effective procedures (Sánchez et al., 2022; Sweileh, 2020; Rosado & Souza, 2021). However, when implemented in the right manner, bibliometric approaches provide several advantages to other fields and cannot be anticipated to be limited. In this context, bibliometricians are charged with the responsibility of documenting the progression of the area and elucidating its attributes as it undergoes expansion.

This analysis aims to map the research publications in this field and identify the most influential themes and contributors. The author aim to provide a systematic overview of the research efforts thus far, emphasizing existing lacunas and potential avenues for future studies by exploring the body of knowledge generated by scholars in this area. Additionally, the analysis will be a valuable resource for future researchers, empowering them to understand seminal works, research collaborations, and the evolving trajectories of green innovation research. Exploring green innovation research through bibliometric analysis provides a robust framework for understanding its trends, advancements, and key contributors (Aboelmaged et al., 2023; Albort-Morant et al., 2017; Chàfer et al., 2021; Fatma & Haleem, 2023; Punj et al., 2023). By assessing the volume, dispersion, and impact of scholarly works, this study endeavors to map the trajectory of green innovation research, highlighting its pivotal contributions, emerging niches, and potential future directions. This knowledge accelerates further research, encourages collaboration, and ultimately contributes to developing sustainable solutions for a greener future.

To achieve this, the author employ a rigorous methodology to collect a vast corpus of scholarly publications on green innovation. Bibliometric techniques analyze critical bibliographic data, such as publication volume, three-field plots, citation counts, thematic map, thematic evolution, most influential authors, country influence, co-authorship networks, and keyword co-occurrence. The analysis incorporates a range of bibliometric indicators, including citation-based metrics, journal publications data, three-field plot, top journals, and authors in the field of green innovation (Albort-Morant et al., 2017; Alsmadi et al., 2023; Kumar et al., 2021; Silintowe & Sukresna, 2023).

Green innovation studies are considered the cornerstone of sustainable development and are instrumental in enhancing economic growth, environmental protection, and quality of life. This concept integrates innovative technologies and practices that reduce environmental impacts, promote energy efficiency, and utilize renewable resources (Akbari et al., 2022; Albort-Morant, 2017; Pérez et al., 2024; Rupasinghe et al., 2024; Silintowe & Sukresna, 2023). Green innovation supports the transition towards a green economy by opening new markets and reducing costs through efficient resource application (Pattinson et al., 2023; Sun et al., 2023). Scholars have also acknowledged its importance in mitigating climate change and conserving biodiversity (Muluneh & Worku, 2022; Schlaepfer & Lawler, 2022). Green innovation encourages the development of sustainable products and services, contributing to a circular economy where waste is minimized and resources are reused and recycled. The Thai economy is transitioning towards a circular economy, with the government encouraging citizens and corporate organizations to become key to this important government initiative (Agrawal et al., 2023; Herrador & Van, 2024; Melati, Nikam & Nguyen, 2021; Samitthiwetcharong et al., 2023; Thongplew et al., 2022; Wang & Liu, 2022).

The role of green innovation has also been recognized to positively impact public health by mitigating pollution and improving air and water quality. Increasing the prevailing quality of life by encouraging surroundings that prioritize sustainability and green innovation leads to healthier and more habitable communities, thus improving the overall quality of life. In addition, it provides prospects for employment development in new green sectors, which boosts economic growth while ensuring responsible environmental management by all stakeholders involved in the circular economy business (Kumar et al., 2019; Shabir et al., 2023; Shan et al., 2021; Thongplew et al., 2022; Yoelao et al., 2021).

The adoption of green innovation practices requires a multidisciplinary approach involving collaboration among scholars, regulators, policymakers, businesses, communities, and other stakeholders involved. It requires the implementation of supportive policies, incentives for green business practices, and investment in research and development of green technologies. Educating the public about the benefits of green innovation and sustainability practices is equally important to ensure widespread adoption and behavioral change, which are key requirements in adopting the circular economic model (Alraja et al., 2022; Cheng et al., 2023; Lima et al., 2023; Thuyen & Bich, 2024).

As Thailand joins the world in bracing for the increasing environmental challenges due to climate change and other physical activities of humans, the application of green innovation in bibliometric studies provides:

- Valuable insights into the evolution of this field.
- Identifying key trends.
- Influential research.
- Emerging areas of interest.

These types of analysis have the potential to provide helpful recommendations for future research initiatives, formulation of policies, and investment distributions, demonstrating the crucial significance of green innovation in the attainment of sustainable development objectives.

By synthesizing and interpreting the findings of our bibliometric analysis, we expect to reveal the emerging trends and research hotspots within the field of green innovation. As the urgency to adopt sustainable practices continues to rise, this study contributes to the growing body of knowledge that can inform entrepreneurs, innovators, researchers, and practitioners about innovative resolutions to environmental concerns. Furthermore, the analysis offers a valuable resource for future researchers by providing an overview of the seminal works, collaborations, and evolving research trajectories within green innovation. This study aims to contribute to the existing understanding of green innovation research by employing an exhaustive bibliometric analysis approach covering recent publications. This section provides valuable insights into the key subjects, influential researchers, and predominant research patterns within this area through quantitative approaches. The findings will accelerate further research, foster collaboration, and ultimately contribute to developing sustainable solutions for a greener future.

Methodology

The primary objective of conducting a systematic literature review is to identify significant scientific contributions pertaining to the specific field of inquiry. This process mitigates bias or systematic errors, enhances the credibility and influence of ensuing evidence, and yields more dependable conclusions for determining trends and informed decision-making. The Scopus database, a widely recognized global scholarly resource, was used to conduct an in-depth search for academic literature on green innovation (Agrawal et al., 2023). The search for publications on "Green Innovation" was conducted and limited to between January 1, 2019, and March 31, 2023, to understand the recent trends in green innovation publications. The search criteria for "green innovation" was limited to aspects such as: "article title, abstract, and keywords". The search documents box for "green innovation" produced a total of 2,627 documents. These were then filtered to cover only the years from 2019 to 2023. The results were further filtered and restricted to include the document type "article", language "English", giving a total of 1,887 documents. These 1,887 documents are used to perform the bibliometric analysis.

The utilization of the bibliometric technique allows academics to assess and analyze data. The repository in question is a scholarly resource that collects scientific data and various quantitative methodologies to do research. This approach facilitates identifying and evaluating the underlying pattern that applies to a specific subject matter, such as the country of publication, most influential authors, journals, or research field. Bibliometric analysis is a widely employed method in literary studies for assessing the significance of concepts and subjects. Furthermore, it recognizes the valuable contributions of many scholarly periodicals, educational establishments, and other geographical regions (Donthu et al., 2021; Ninkove et al., 2022). The analysis utilized the VOS viewer software and biblioshiny to analyze the results of the bibliometric search (van Eck & Waltman, 2010). They produce intelligible results, including visuals that range from graphic images and tables that condense the complex search results (Bukar et al., 2023). The software packages facilitate co-citations and bibliographic coupling during presentations and preparatory activities. Bibliographic coupling refers to the association established between two cited works through their shared reference to a third work within their respective bibliographies (García-Lillo et al., 2023; Ma et al., 2022). In contrast, co-citation pertains to the frequency with which a specific document is cited alongside two other articles. This action suggests that the two articles possess a shared topic (Wang et al., 2018; Zhao et al., 2020).

Results and discussion

Systematic review

Drawing on the analysis of articles sourced from the Scopus database, the information is divided into sections under the following headings; main information about the data, document content, authors, author collaboration and document types. It is evident that the primary data reveals an average yearly publication count of 377.4 between 2019 and 2023. Furthermore, this data set exhibits a notable annual growth rate of 45.28%. The mean citation count for each document is 15.32, while the average age of each document is 1.25. A total of 112,853 references were utilized in the studies. The research included a cohort of 3363 authors, among whom 92 were identified as single authors. These single authors collectively contributed to a total of 105 publications. There were 3.47 co-authors per document, while the analysis of international co-authorship indicated that 30.47% of the published outcomes resulted from collaboration between authors from different countries. Table 4.1 provides an in-depth summary of the general information.

Table 4.1. Overview of general bibliometric information

Description	Results
Main Information About Data	
Timespan	2019-2023
Sources (Journals, Books, etc.)	404
Documents	1887
Annual Growth Rate, %	45.28
Document Average Age	1.25
Average citations per doc	15.32
References	112853
Document Contents	
Keywords Plus (ID)	4268
Author's Keywords (DE)	4281
Authors	
Authors	3363
Authors of single-authored docs	92
Authors Collaboration	
Single-authored docs	105
Co-Authors per Doc	3.47
International co-authorships %	30.47
Document Types	
Article	1887

Source: Author compilations.

Annual journal publications

The green innovation landscape has witnessed a remarkable evolution over recent years, as evidenced by the data sourced from the Scopus database. Between 2019 and 2023, 1887 publications were published in this field, underscoring its emerging significance in academic research. A closer examination of the year-by-year distribution, as illustrated in Table 4.2, reveals interesting patterns. There was a pronounced growth in the number of publications each year from 2019. 2020 saw an increment of 67 articles compared to the preceding year. This momentum sustained into 2021, registering an even more notable increase with an additional 104 articles. The zenith of this growth trajectory was achieved in 2022, which witnessed a surge of 531 more articles than its predecessor. However, 2023 marked a departure from this trend (see Fig. 4.1), with the number of publications contracting by 315 articles. Despite this dip, the overarching trend over the five years signals a burgeoning interest and growing commitment to green innovation research. One plausible catalyst for this heightened interest could be global events. The post-Covid-19 era, for instance, witnessed an unprecedented global emphasis on health, conservation, and climate change. The pandemic, having fore-grounded the vulnerabilities in our global systems, sparked a collective realization about the importance of sustainability. As societies grappled with the pandemic's fall-out, there was a palpable shift in priorities. People globally began to envision a future characterized by enhanced environmental resilience.

Table 4.2. Annual publications of green innovation articles

Year	Number of Articles
2019	112
2020	179
2021	283
2022	814
2023	499
Total	1887

Source: Author compilations.

The surging academic interest in green innovation reflects this more significant societal pivot. This collective drive towards a more sustainable future highlights the necessity and timeliness of research on green innovation.

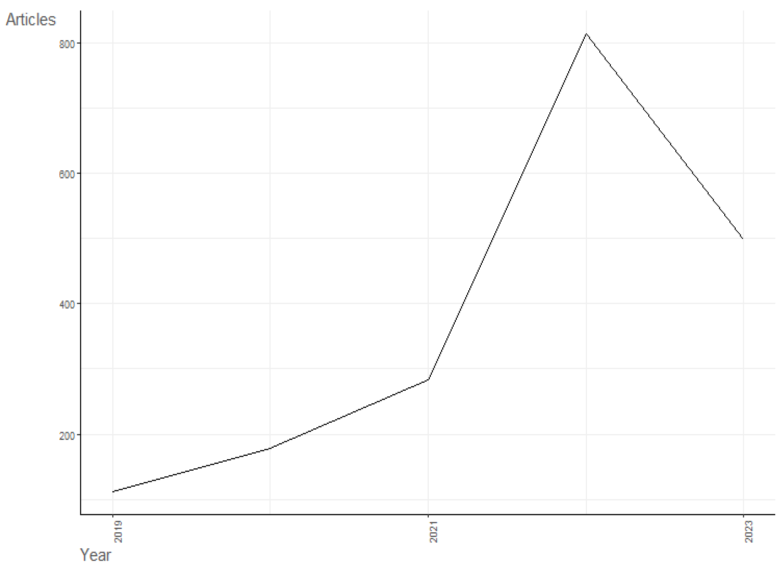


Figure 4.1. Annual scientific productions of green innovation articles

Source: Author compilations.

The observed data trend, as represented in Table 4.2 and illustrated in Figure 4.1, might need to be more accurate, especially considering the sudden drop in 2023. It is vital to understand that the data for 2023 was only collected up until March, indicating that the 499 articles were the cumulative output for the first quarter of the year.

We estimate a monthly production of about 166 articles by extrapolating this on a linear projection model. Over an entire 12-month span, this would sum up to approximately 1,992 articles. Such a projection significantly alters the perceived trend in Figure 4.1, making it more consistent with the trajectory observed in Figure 4.2. This aligns with the view that there is an increasing annual pattern of green innovation articles.

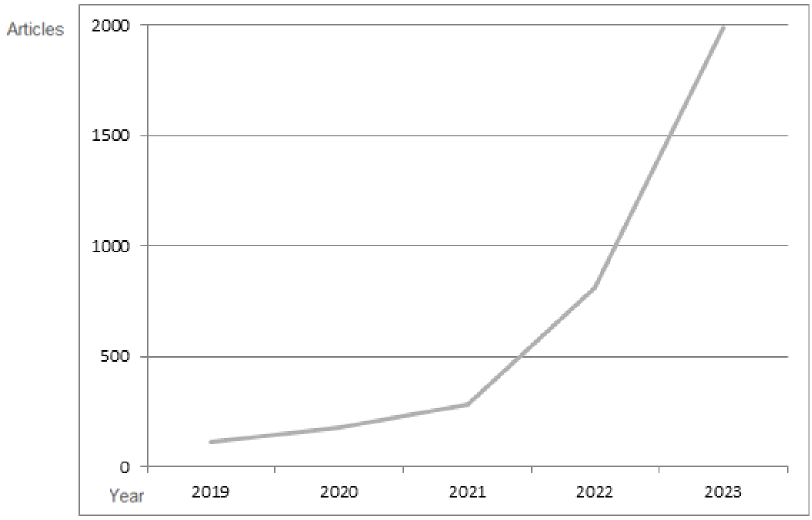


Figure 4.2. Projected annual productions of green innovation articles

Source: Author compilations.

Annual citations of journal publications

Table 4.3 provides an overview of the academic impact of articles on green innovation over the course of five years, from 2019 to 2023. The data presents the trends in research relevance, dissemination, and recognition, as inferred from the number of citations per article and year. 2019 stands out as the peak regarding the mean total citations per article, recording 54.34 citations. Given that there were 112 articles published, each article received an average of 10.87 citations annually over the course of five citable years. This high citation rate highlights the novelty and significance of the research in this period, suggesting that the studies were particularly influential and laid foundational insights for subsequent works in the field. 2020 saw a decline in the mean total citations per article to 38.88. However, these articles have garnered an average of 9.72 citations annually over four citable years. The relatively high number suggests that the work in 2020 continued to be of substantive relevance, though less impactful on a per-article basis than the preceding year. The year 2021 saw a decline in the mean total citations per article to 28.1. The annual average citations per article also saw a slight dip, settling at 9.37 over three citable years. For 2022, however, the mean total citations per article dropped to 8.69, with an annual mean of 4.34 over two citable years. The increase in research output coupled with a decline in citations might be attributed to the nascent nature of the studies, which need more time to accrue citations than in previous years. 2023 saw a stark drop in the mean total citations per article to 1.68. These articles have had just a year to accumulate citations, so the annual average remains the same.

Table 4.3. Annual citations

Year	Mean Total Citations per Article	N	Mean Total Citations/Year	Citable Years
2019	54.34	112	10.87	5
2020	38.88	179	9.72	4
2021	28.1	283	9.37	3
2022	8.69	814	4.34	2
2023	1.68	499	1.68	1

Source: Author compilations.

It is crucial to note that newer publications generally take time to gain traction and recognition in academic circles, and thus, the citation rate is expected to be lower. The data showcases a dynamic landscape of green innovation research over the examined period. While 2019 and 2020 demonstrated robust citation rates, suggesting high-impact research, the subsequent years, particularly 2022 and 2023 highlight the burgeoning volume of research in the domain. It will be intriguing to monitor how the citations for recent years evolve as they age, offering further insights into their long-term academic influence.

Three-field plot

Figure 4.3 depicts a three-field plot that visually represents three distinct components, namely the authors' affiliations, the authors' names, and the keywords associated with the study. Gray links visually represent the interrelation between these three components. The linkages depict the connection between the affiliation name, author, and the respective keyword associated with each author's publication. The dimensions of each rectangle inside the separate lists correspond to the number of papers linked to that aspect.

The first component, situated on the left-hand side, represents the affiliation. It is worth noting that the top 20 institutions were identified in the three-field plot as having authors affiliated with them who have published papers on green innovation and interacted with the other elements on the plot. Shandong University exhibited the highest level of interaction with other variables on the plot, followed by Wuhan University, Shandong University of Finance and Economics, Jilin University, and Northwestern Polytechnical University. The remaining associations exhibit a somewhat uniform composition but with varying sizes. The second element, located in the plot's middle section, comprises the authors' names. Authors affiliated with the different institutions outlined, including Zhang Y, who is affiliated with various institutions such as Shandong University, Wuhan University, and Northwestern Polytechnical University. Wang Y. and Zhang J. are also notable authors linked to several universities. The 20 top authors are listed in this plot. The size of the rectangle shows the number of papers written by each author. In this plot, Zhang Y., Wang Y., Zhang J., Li Y., Liu X., etc., had the largest rectangles, followed by the other listed authors on the plot. All the authors listed had Chinese names.

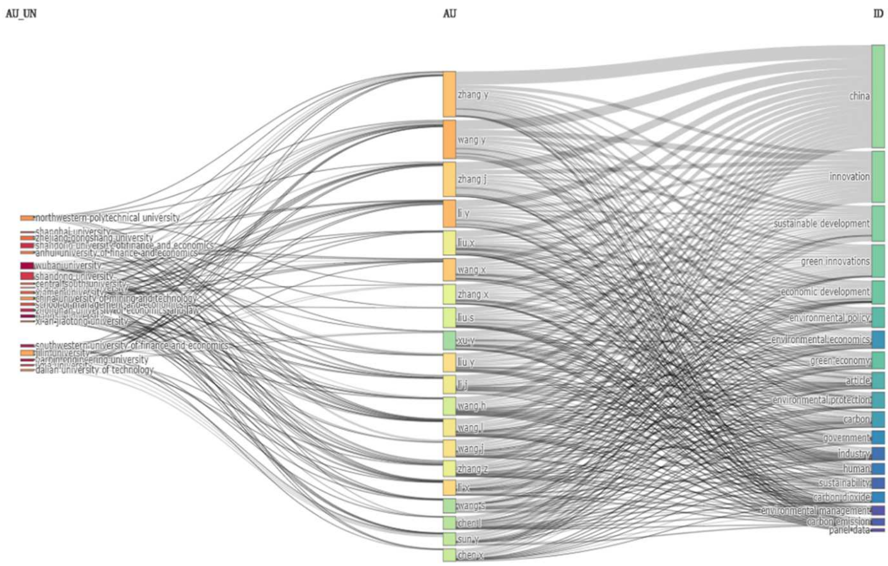


Figure 4.3. Three-field plot showing affiliation, authors and keywords

Source: Author compilations.

The third aspect comprises the keywords most commonly observed in the published articles and relevant to the topic. Every subject matter is linked to scholars who have substantially published works. A total of 19 keyword themes have been enumerated, with the keyword "China" being the most common occurrence, as evidenced by the larger size of the red rectangle, which significantly surpasses the dimensions of the other rectangles. The prominence of China as a keyword stems from the dominance of Chinese institutions within the represented affiliations, as evidenced by their positioning on the left-hand side of the plot. Additionally, the prevalence of Chinese authors is apparent, as all authors mentioned in the center of the plot had Chinese names. Furthermore, alongside China, this plot exhibits other prominent terms extensively employed, including "innovation" and "sustainable development".

Top journals

The bibliometric analysis also yielded findings regarding the publishers with the highest number of relevant journals and local citations related to green innovation. A citation serves as a scholarly acknowledgment by a researcher to attribute credit to the previous scholars for their work. The quantity of citations inside a journal indicates its quality, with more citations suggesting a superior publication (Divecha et al., 2023). Table 4.4 displays the 20 most relevant journals. The highest number of relevant journal articles was published in Sustainability, with a total of 225 articles, followed by Environmental Science Research (133) and Journal of Cleaner Production (127).

Table 4.4. Most relevant journals

S/No	Sources	Articles
1	*Sustainability*	225
2	*Environmental Science and Pollution Research*	133
3	*Journal of Cleaner Production*	127
4	*International Journal of Environmental Research And Public Health*	90
5	*Frontiers in Environmental Science*	83
6	*Business Strategy and the Environment*	69
7	*Technological Forecasting and Social Change*	43
8	*Frontiers in Psychology*	38
9	*Journal of Environmental Management*	32
10	*Energy Economics*	31
11	*Economic Research-Ekonomska Istrazivanja*	27
12	*Resources Policy*	24
13	*Energies*	19
14	*European Journal of Innovation Management*	19
15	*Technology Analysis and Strategic Management*	19
16	*Environment, Development and Sustainability*	17
17	*Sustainable Development*	17
18	*Science of the Total Environment*	15
19	*Corporate Social Responsibility and Environmental Management*	14
20	*Finance Research Letters*	14

Source: Author compilations.

To further understand the top relevant journals, their research was analyzed over five years (2019-2023) to understand their publication pattern. The journals in focus were the top five identified in Table 4.4. The data reveals specific trends, growth patterns, and shifts in publication volumes. The common occurrence among all the journals was the consistent growth in publication volume from 2019 to 2022, while they all experienced a drop in 2023, which we have attributed to the data covering only the first three months of the year. On projection, the 2023 (696) output will more than double the overall production of 310 in 2022 (see Table 4.5). *Environmental Science and Pollution Research* and *International Journal of Environmental Research* and *Public Health* had no entries in 2019; the latter also did not record any publication about green innovation in 2020. Its first entries were in 2021. On the other hand, the *International Journal of Environmental Research and Public Health* recorded six publications each in 2019 and 2020 and then doubled its publication rates over the following years.

Table 4.5. Top 5 journals over time

Journals	2019	2020	2021	2022	2023	Total
Sustainability	11	23	37	101	53	225
Environmental Science and Pollution Research	0	2	12	53	66	133
Journal of Cleaner Production	11	19	32	44	21	127
International Journal of Environmental Research and Public Health	6	6	12	49	17	90
Frontiers in Environmental Science	0	0	3	63	17	83
Total	28	50	96	310	174	658

Source: Author compilations.

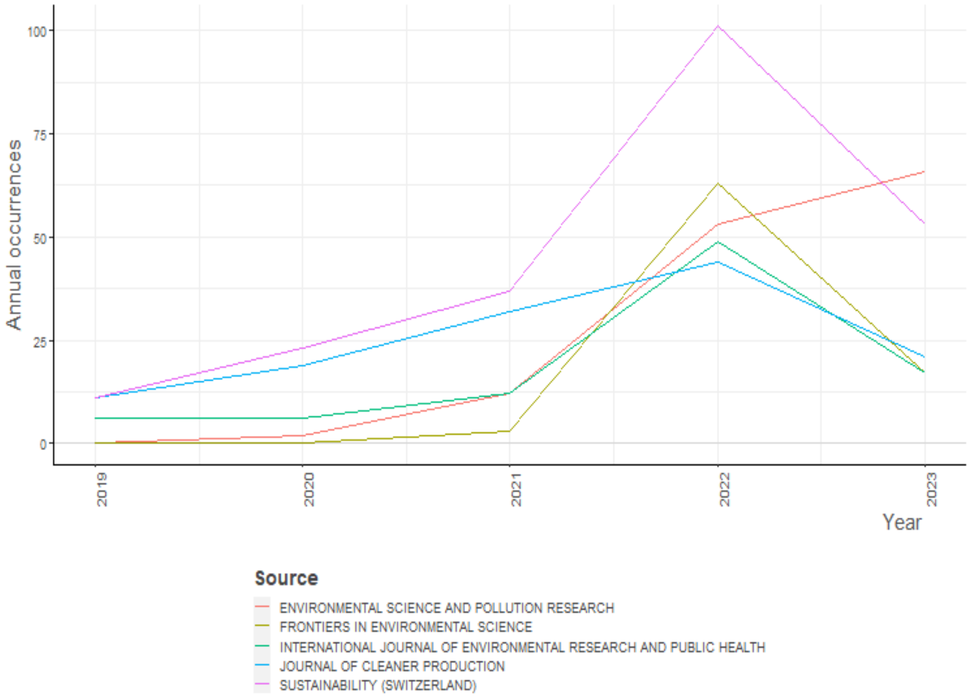


Figure 4.4. Top 5 journals over time

Source: Author compilations.

Table 4.6. Top 5 journals over time with projected 2023 data

Journals	2019	2020	2021	2022	2023	Total
Sustainability	11	23	37	101	212	384
Environmental Science and Pollution Research	0	2	12	53	264	331
Journal of Cleaner Production	11	19	32	44	84	190
International Journal of Environmental Research and Public Health	6	6	12	49	68	141
Frontiers in Environmental Science	0	0	3	63	68	134
Total	28	50	96	310	696	1180

Source: Author compilations.

The *Journal of Cleaner Production* had the highest scholarly influence, evidenced by a citation count of 8722. *Journal of Business Ethics* publications on green innovation received the second highest citation count with 2601 citations. *Sustainability* followed them with a citation count totaling 2413, while *Technological Forecasting and Social Change* received the next most citations, amounting to 1699.

Table 4.7 presents a compilation of prominent academic publications that garnered the highest number of sources, reflecting their significant effect within the scholarly community. The data utilized for this ranking is derived from the Scopus database.

Table 4.7. Journals with the most citations

S/No	Sources	Articles
1	*Journal of Cleaner Production*	8722
2	*Journal of Business Ethics*	2601
3	*Sustainability*	2413
4	*Technological Forecasting and Social Change*	1699
5	*Business Strategy and the Environment*	1662
6	*Environmental Science and Pollution Research*	1473
7	*Energy Policy*	1438
8	*Research Policy*	1407
9	*Journal of Business Research*	1399
10	*Ecological Economics*	1293
11	*Energy Economics*	1021
12	*Strategic Management Journal*	840
13	*Journal of Environmental Economics and Management*	581
14	*Business Strategy and the Environment*	552
15	*Journal of Environmental Management*	538
16	*Corporate Social Responsibility and Environmental Management*	538
17	*Academy of Management Journal*	501
18	*Energy*	470
19	*International Journal of Production Economics*	467
20	*Science of the Total Environment*	456

Source: Author compilations.

Table 4.8 provides a comparative view of the impact of the top 20 journals that have published articles on green innovation. Based on the data in Table 4.8, we can infer that the journal with the highest h_index is the *Journal of Cleaner Production* with an h_index of 42, while the journal with the lowest h_index is *Resources, Conservation and Recycling*, with an h_index of 3.

For g_index, the *Journal of Cleaner Production* leads in g_index as well, with a score of 68, while the lowest g_index is again recorded by *Resources, Conservation and Recycling* at 3. The *Journal of Cleaner Production* again had the highest m_index of 8.4, while the lowest m_index was again recorded by *Resources, Conservation and Recycling* at 0.6. Regarding net production, *Sustainability* had the highest net output with a value of 225. In contrast, *Resources, Conservation and Recycling* and *Sustainable Cities and Society* had the lowest net production value, at 5. Most of the journals in the list started production in 2019. The most recent journal in terms of starting its production is *Renewable Energy* in 2022. We can deduce that the *Journal of Cleaner Production* stands out as a leading journal in the given list regarding h_index, g_index, and m_index.

The journal *Sustainability* produces a significant content volume, as indicated by its highest net production. While *Resources, Conservation, and Recycling* scored the lowest in most metrics, it is worth noting that the importance of a journal is not only based on these metrics but also on the quality, impact, and relevance of its publications.

It is critical to acknowledge that the h_index, g_index, and m_index are bibliometric indices that measure the productivity and impact of the publications of a scientist or scholar, or in this case, an entire journal. The h_index represents the number of articles that have received at least that many citations, the g_index focuses on the top-ranked publications, and the m_index is the h_index divided by the number of years the journal has been active (Keshavarz-Fathi et al., 2023; Shah & Jawaid, 2023).

Table 4.8. Comparative view of the top 20 journals in green innovation

Journal	h_index	g_index	m_index	Net Production	Production Year Start
Journal of Cleaner Production	42	68	8.4	127	2019
Technological Forecasting and Social Change	19	43	3.8	43	2019
Business Strategy and the Environment	31	47	6.2	69	2019
Sustainability	23	30	4.6	225	2019
Environmental Science and Pollution Research	20	31	5	133	2020
Energy Economics	11	30	2.75	31	2020
Journal of Environmental Management	16	30	3.2	32	2019
Energy Policy	10	13	2	13	2019
Int. J. Environ. Res. Public Health.	16	25	3.2	90	2019
Science of the Total Environment	10	15	2	15	2019
Technology in Society	10	12	2	12	2019
Sustainable Production and Consumption	10	14	2	14	2019
Resources, Conservation and Recycling	3	3	0.6	3	2019
Sustainable Development	8	17	2	17	2020
Resources Policy	7	18	2.33333333	24	2021
European Journal of Innovation Management	7	16	1.4	19	2019
Renewable Energy	9	14	4.5	14	2022
Economic Analysis and Policy	7	12	2.33333333	12	2021
Sustainable Cities and Society	3	5	0.75	5	2020
Frontiers in Environmental Science	7	10	2.33333333	83	2021

Source: Author compilations.

Top authors on green innovation

The contributions of scholars in any field, and in this instance, green innovation research, serve to advance knowledge in the area. The top authors can be assessed by their output and the impact of their research. An analysis of authors and their respective outputs presents an opportunity to appreciate their efforts and assess the breadth and depth of their contributions. Table 4.9 presents the top 20 authors in green innovation research; some interesting observations can be deduced from the data. Wang Y emerges as the most prominent member of this group, boasting an impressive count of 61 publications. This chart highlights the extensive productivity of Wang Y and emphasizes his significant standing when taking into account fractionalized contributions, which amount to around 19.961. Fractionalized counts frequently serve as a metric for quantifying the number of co-authored articles, providing insights into collaboration patterns within the academic community. In the instance of Wang Y, it is seen that while he has the highest number of papers, the fractionalized count indicates that a significant amount of his contributions may have been collaborative efforts with other scholars.

Table 4.9. Top 20 productive authors in green innovation

S/No	Authors	Articles	Articles fractionalized
1	Wang Y	61	19.9611111
2	Li Y	41	12.175
3	Zhang Y	40	12.1027778
4	Wang X	38	11.9666667
5	Zhang J	38	10.2095238
6	Li X	27	8.45119048
7	Liu Y	27	7.48452381
8	Wang J	27	8.71666667
9	Wang L	27	7.45
10	Li J	26	8.70238095
11	Liu X	26	7.90952381
12	Zhang Z	26	6.625
13	Zhang X	23	7.31666667
14	Liu S	22	6.74285714
15	Wang H	20	7.00952381
16	Chen X	19	5.46666667
17	Sun Y	19	6.43333333
18	Chen L	18	5.7
19	Wang S	18	5.01666667
20	Xu Y	18	5.53333333

Source: Author compilations.

Wang Y is followed by Li Y and Zhang Y, who have authored 41 and 40 papers, respectively. The fractionalized numbers of 12.175 for Li Y and 12.103 for Zhang Y suggest a comparable level of collaboration but slightly lower than that of Wang Y. It is striking that Wang X and Zhang J have both authored 38 papers; nevertheless, their fractionalized counts exhibit variation. Based on the fractionalized count, Zhang J exhibits a collaboration level of roughly 10.21, slightly lower than that of Wang X, who demonstrates a count of around 11.97. The mid-section of the table, populated by the likes of Li X, Liu Y, Wang J, and Wang L, illustrates a tighter clustering in terms of article counts, ranging from 27 to 26. However, even within this close-knit group, the variation in fractionalized counts, spanning from Liu Y's 7.484 to Li X's 8.451, indicates varying collaboration among these authors.

In the latter sections of the table, there is a noticeable decline in the number of articles, indicating the involvement of authors who have contributed between 18 and 23 articles. Despite this decrease, the fractionalized counts continue to indicate the presence of collaborative research efforts. As an illustration, the scholarly output of Chen L and Xu Y comprises 18 articles. However, upon examining their fractionalized counts of 5.7 and 5.533, respectively, it becomes apparent that subtle variations exist in their collaborative tendencies. Table 4.9 provides insight into the academic contributions of the top 20 authors in the field of green innovation. While absolute article counts offer a preliminary glimpse into their productivity, the fractionalized figures enrich the narrative by hinting at the collaborative nature of their endeavors. The academia thrives on collaborative spirits, and Table 4.9 is a testament to the collective quest for knowledge that these researchers embody.

Table 4.10 offers an overview of the most influential authors in green innovation research based on local citations. First, Li Y and Wang Y emerge as the leading scholars in green innovation. At the top, Li Y has been cited 247 times, making him the most influential author. He is followed by Wang Y, with 239 citations, marking a mere eight-citation difference between the top two contributors. Their significant citations underline their crucial role in shaping discussions and advancing knowledge in green innovation. Following the pacesetters is a tight cluster of authors: Li W and Wang X. Their citations, 196 and 195, respectively, showcase their substantial contributions and influence in green innovation. Notably, the one-citation difference mirrors the close contention between them. Another observation is the proximity in citation numbers from the eighth to the twelfth position, from Zhang X's 165 citations to Liu K's 131. This narrow range highlights the competitive and dynamic nature of the field, where numerous contributors make significant impacts. Towards the table's end, the density of citation counts further tightens. Venkatesh VG, Liboni LB, Li X, and Chiappetta Jabbour CJ all share a citation count 120. Such clustering suggests that despite being at the lower end of this list, these authors have made comparably influential contributions to the discourse on green innovation.

Table 4.10. Top 20 most cited authors

S/No	Author	Local citations
1	Li Y	247
2	Wang Y	239
3	Li W	196
4	Wang X	195
5	Zhang J	180
6	Tang Y	171
7	Chen SX	170
8	Zhang X	165
9	Yang S	150
10	Liu X	150
11	Liu S	137
12	Liu K	131
13	Xue Y	130
14	Hossain MR	129
15	Jahanger A	126
16	Wang C	124
17	Venkatesh VG	120
18	Liboni LB	120
19	Li X	120
20	Chiappetta Jabbour CJ	120

Source: Author compilations.

Conclusion

This research investigated the research publications on green innovation management using bibliometric analysis from publications on the Scopus database. The study was to analyze publication trends, author collaborations, and influential keywords within the field of green innovation management. The findings reveal a rapidly growing field, evidenced by the significant increase in research publications about green innovation between 2019 and 2023. While a slight decrease is observed in 2023 data (likely due to the limited timeframe), the overall trend indicates an increasing focus on green innovation research.

The analysis identified China as a prominent contributor, with numerous publications emanating from Chinese institutions and authors. Additionally, it identified key journals in the field, such as *Sustainability, Environmental Science and Pollution Research*, and *Journal of Cleaner Production* for publishing, as well as *Journal of Cleaner Production, Journal of Business Ethics*, and *Sustainability* as citation aggregators with many of their publications cited in numerous publications. This study highlights the increasing significance of GIM research. Additional investigation into developing trends within this particular subject has the potential to provide valuable guidance for future research initiatives and make significant contributions to the progress of sustainable innovation methods. When considering the future implications, a number of potential outcomes arise from the findings of this study.

1. **Policy and Strategy Development**: The empirical evidence of the growing reach and influence of GIM research can provide helpful knowledge for policymakers and entrepreneurs, enabling them to make informed strategic choices that prioritize and promote sustainable practices. This phenomenon has the potential to result in the development of more robust environmental regulations and corporate strategies that prioritize innovation.
2. **Research and Collaboration Expansion**: To foster multidisciplinary cooperation and new solutions to difficult environmental concerns, it is beneficial to identify major themes, influential authors, and leading journals. This approach allows for the integration of ideas from different subject areas.
3. **Educational and Training Programs**: The results highlight the significance of integrating GIM principles into academic curricula and professional development initiatives. Providing the necessary information and abilities will equip the upcoming cohort of scholars and professionals to make valuable contributions to sustainability and innovation.

This study has identified several areas that show potential for future research in order to expand upon the existing knowledge base. Nevertheless, it is critical to recognize the inherent limitations associated with this research. The main constraint relates to the exclusive reliance on Scopus as the sole source for data collecting. The inclusion of supplementary databases, such as Web of Science or Google Scholar, could enhance the depth of the research landscape, in addition to the wide coverage provided by Scopus. In addition, it is important to note that bibliometric studies primarily concentrate on publishing data, which may only sometimes represent the entirety of the research effort. To achieve an all-encompassing understanding, future studies should include the use of qualitative methodologies, such as expert interviews. Despite these constraints, the study provides significant perspectives on the existing condition and prospective avenues of investigation of green innovation management. Through the recognition of these constraints and the contemplation of potential avenues for future investigation, this study establishes a foundation for a more elaborate knowledge of the dynamic research environment within this field.

References

Abadzhiev, A., Sukhov, A., Sihvonen, A., & Johnson, M. (2022). Managing the complexity of green innovation. *European Journal of Innovation Management*, 25(6), 850-866. DOI: 10.1108/EJIM-02-2022-0098.

Aboelmaged, M., Bani-Melhem, S., Al-Hawari, M.A., & Ali, I. (2023). Product innovation research over the past 60 years: a bibliometric analysis of intellectual structure and emergent trends. *Benchmarking: An International Journal*. DOI: 10.1108/BIJ-09-2022-0595.

Agrawal, R., Agrawal, S., Samadhiya, A., Kumar, A., Luthra, S., & Jain, V. (2023). Adoption of green finance and green innovation for achieving circularity: An exploratory review and future directions. *Geoscience Frontiers*, 101669. DOI: 10.1016/j.gsf.2023.101669.

Ahmed, R.R., Akbar, W., Aijaz, M., Channar, Z.A., Ahmed, F., & Parmar, V. (2023). The role of green innovation on environmental and organizational performance: Moderation of human resource practices and management commitment. *Heliyon*, 9(1), e12679. DOI: 10.1016/j.heliyon.2022.e12679.

Akbari, M., Padash, H., Shahabaldini Parizi, Z., Rezael, H., Shariari, E., & Khosravani, A. (2022). A bibliometric review of green innovation research: identifying knowledge domain and network. *Quality & Quantity*, 56, 3993-4023. DOI: 10.1007/s11135-021-01295-4.

Albort-Morant, G., Henseler, J., Leal-Millian, A., & Cepeda-Carrión, G. (2017). Mapping the field: A bibliometric analysis of green innovation. *Sustainability*, 9(6), 1011. DOI: 10.3390/su9061011.

Alraja, M.N., Imran, R., Khashab, B.M., & Shah, M. (2022). Technological innovation, sustainable green practices and SMEs sustainable performance in times of crisis (COVID-19 pandemic). *Information Systems Frontiers*, 24, 1081-1105. DOI: 10.1007/s10796-022-10250-z.

Alsmadi, A.A., Al-Okaily, M., Alrawashdeh, N., Al-Gasaymeh, A., Moh'd Al-hazimeh, A., & Zakari, A. (2023). A bibliometric analysis of green bonds and sustainable green energy: Evidence from the last fifteen years (2007-2022). *Sustainability*, 15, 5778. DOI: 10.3390/su15075778.

Anlesinya, A., & Dadzie, S.A. (2023). Technology and the conduct of bibliometric literature reviews in management: The software tools, benefits, and challenges. Rana, S., Singh, J. and Kathuria, S. (Ed.) Advancing methodologies of conducting literature review in management domain. *Review of Management Literature*, 2, Emerald Publishing Limited, Leeds, 57-78. DOI: 10.1108/S2754-586520230000002004

Baeshen, Y., Soomro, Y.A., & Bhutto, M.Y. (2021). Determinants of green innovation to achieve sustainable business performance: Evidence from SMEs. *Frontiers in Psychology*, 12. DOI: 10.3389/fpsyg.2021.767968.

Barbieri, N., Consoli, D., Napolitano, L., Perruchas, F., Pugliese, E., & Sbardella, A. (2023). Regional technological capabilities and green opportunities in Europe. *Journal of Technology Transfer*, 48, 749-778. DOI: 10.1007/s10961-022-09952-y.

Bigliardi, B., & Bertolini, M. (2012). Green innovation management: theory and practice. *European Journal of Innovation Management*, 15(4). DOI: 10.1108/ejim.2012.22015daa.001.

Bukar, U.A., Sayeed, M. S., Abdul Razak, S.F., Yogarayan, S., Amodu, O.A., & Raja Mahmood, R.A. (2023). A method for analyzing text using VOSviewer. *MethodsX*, 11. DOI: 10.1016/j.mex.2023.102339.

Chàfer, M., Cabeza, L.F., Pisello, A.L., Tan, C.L., & Wong, N.H. (2021). Trends and gaps in global research of greenery systems through a bibliometric analysis. *Sustainable Cities and Society*, 65, 102608. DOI: 10.1016/j.scs.2020.102608.

Cheng, C., Ahmad, S.F., Irshad, M., Alsanie, G., Khan, Y., A. Bani, A.Y., & Aleemi, A.R. (2023). Impact of green process innovation and productivity on sustainability: The moderating role of environmental awareness. *Sustainability*, 15(17), 12945. DOI: 10.3390/su151712945.

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N., & Lim, W.M. (2021). How to conduct a bibliometric analysis: An overview and guidelines. *Journal of Business Research*, 133, 285-296. DOI: 10.1016/j.jbusres.2021.04.070.

Ellegaard, O., & Wallin, J.A. (2015). The bibliometric analysis of scholarly production: How great is the impact?. *Scientometrics*, 105, 1809-1831. DOI: 10.1007/s11192-015-1645-z.

Fatma, N., & Haleem, A. (2023). Exploring the nexus of eco-innovation and sustainable development: A bibliometric review and analysis. *Sustainability*, 15(16), 12281. https://doi.org/10.3390/su151612281.

Gao, K., Wang, L., Liu, T., & Zhao, H. (2022). Management executive power and corporate green innovation – Empirical evidence from China's state-owned manufacturing sector. *Technology in Society*, 70, 102043. DOI: 10.1016/j.techsoc.2022.102043.

García-Lillo, F., Seva-Larrosa, P., & Sánchez-García, E. (2023). What is going on in entrepreneurship research? A bibliometric and SNA analysis. *Journal of Business Research*, 158, 113624. DOI: 10.1016/j.jbusres.2022.113624.

Ge, B., Yang, Y., Jiang, D., Gao, Y., Du, X., & Zhou, T. (2018). An empirical study on green innovation strategy and sustainable competitive advantages: Path and boundary. *Sustainability*, 10(10), 3631. DOI: 10.3390/su10103631.

González-Alcaide, G. (2021). Bibliometric studies outside the information science and library science field: uncontainable or uncontrollable? *Scientometrics* 126, 6837-6870. DOI: 10.1007/s11192-021-04061-3.

Hasan, M.M., Nekmahmud, M., Yajuan, L., & Patwary, M.A. (2019). Green business value chain: A systematic review. *Sustainable Production and Consumption*, 20, 326-339. DOI: 10.1016/j.spc.2019.08.003.

Herrador, M., & Van, M.L. (2024). Circular economy strategies in the ASEAN region: A comparative study. *Science of the Total Environment*, 908, 168280. DOI: 10.1016/j.scitotenv.2023.168280.

Jones, A. (2015). Forensic journals: Bibliometrics and journal impact factors. *Encyclopedia of Forensic and Legal Medicine (Second Edition)*, 528-538. DOI: 10.1016/B978-0-12-800034-2.00181-6.

Khan, S.J., Kaur, P., Jabeen, F., & Dhir, A. (2021). Green process innovation: Where we are and where we are going. *Business Strategy and the Environment*, 30(7), 3273-3296. DOI: 10.1002/bse.2802.

Kumar, N., Shahzeb Hasan, S., Srivastava, K., Akhtar, R., Kumar Yadav, R., & Choubey, V.K. (2021). Lean manufacturing techniques and its implementation: A review. *Materials Today: Proceedings*, 64, 1188-1192. DOI: 10.1016/j.matpr.2022.03.481.

Kumar, P., Druckman, A., Gallagher, J., Gatersleben, B., Allison, S., Eisenman, T.S., Hoang, U., Hama, S., Tiwari, A., Sharma, A., Abhijith, K., Adlakha, D., McNabola, A., Astell-Burt, T., Feng, X., Skeldon, A.C., De Lusignan, S., & Morawska, L. (2019). The nexus between air pollution, green infrastructure and human health. *Environment International*, 133, 105181. DOI: 10.1016/j.envint.2019.105181.

Larivière, V., Sugimoto, C.R., & Cronin, B. (2012). A bibliometric chronicling of library and information science's first hundred years. *Journal of the American Society for Information Science and Technology*, 63(5), 997-1016. DOI: 10.1002/asi.22645.

Li, L., Msaad, H., Sun, H., Tan, M. X., Lu, Y., & Lau, K.W. (2020). green innovation and business sustainability: New evidence from energy intensive industry in China. *International Journal of Environmental Research and Public Health*, 17(21). DOI: 10.3390/ijerph17217826.

Lima, O., Fernandes, G., & Tereso, A. (2023). Benefits of adopting innovation and sustainability practices in project management within the SME context. *Sustainability*, 15(18), 13411. DOI: 10.3390/su151813411.

Linnenluecke, M.K., Marrone, M., & Singh, A.K. (2020). Conducting systematic literature reviews and bibliometric analyses. *Australian Journal of Management*, 45(2), 175-194. DOI: 10.1177/0312896219877678.

Ma, T-J., Lee, G-G., Liu, J.S., Lan, R., & Weng, J-H. (2022). Bibliographic coupling: a main path analysis from 1963 to 2020. *Information Research*, 27(1). DOI: 10.47989/irpaper918.

Melati, K., Nikam, J., & Nguyen, P. (2021). Barriers and drivers for enterprises to transition to circular economy. Stockholm Environment Institute. http://www.jstor.org/stable/resrep38152.

Mhando, F., Dhamir, M., Qadri, S., Seidel, S., Ackermann, K., Anderson, C., Sanga, E., & Juma, O. (2023) Community advisory boards: A bibliometrics analysis and future research directions. *Voice of the Publisher*, 9, 129-149. DOI: 10.4236/vp.2023.93013.

Muluneh, M.G., & Worku, B.B. (2022). Contributions of urban green spaces for climate change mitigation and biodiversity conservation in Dessie city, Northeastern Ethiopia. *Urban Climate*, 46, 101294. DOI: 10.1016/j.uclim.2022.101294.

Ninkov, A., Frank, J.R., & Maggio, L.A. (2022). Bibliometrics: Methods for studying academic publishing. *Perspectives on Medical Education*, 11(3), 173-176. DOI: 10.1007/s40037-021-00695-4.

Obobisa, E.S., Chen, H., & Mensah, I.A. (2022). The impact of green technological innovation and institutional quality on CO_2 emissions in African countries. *Technological Forecasting and Social Change*, 180, 121670. DOI: 10.1016/j.techfore.2022.121670.

Patience, G.S., Pounis, G., Patience, P.A., & Boffito, D.C. (2018). Principles of research publication. *Analysis in Nutrition Research*, 197-230. DOI: 10.1016/B978-0-12-814556-2.00008-7.

Pattinson, S., Damij, N., El Maalouf, N., Bazi, S., Elsahn, Z., Hilliard, R., & Cunningham, J.A. (2023). Building green innovation networks for people, planet, and profit: A multi-level, multi-value approach. *Industrial Marketing Management*, 115, 408-420. DOI: 10.1016/j.indmarman.2023.10.016.

Pérez, G.L., García Sánchez, I.M., & Zafra Gómez, J.L. (2024). A systematic literature review and bibliometric analysis of eco-innovation on financial performance: Identifying barriers and drivers. *Business Strategy and the Environment*, 33(2), 1321-1340. DOI: 10.1002/bse.3550.

Perpetuo, L., Ferreira, R., Thongboonkerd, V., Guedes, S., Amado, F., & Vitorino, R. (2021). Urinary exosomes: Diagnostic impact with a bioinformatic approach. *Advances in Clinical Chemistry*, 111, 69-99. DOI: 10.1016/bs.acc.2022.07.002.

Pritchard, A. (1969) Statistical bibliography or bibliometrics. *Journal of Documentation*, 25, 348-349.

Punj, N., Ahmi, A., Tanwar, A., & Abdul Rahim, S. (2023). Mapping the field of green manufacturing: A bibliometric review of the literature and research frontiers. *Journal of Cleaner Production*, 423, 138729. DOI: 10.1016/j.jclepro.2023.138729.

Rahman, M.A., Ahmad, R., & Ismail, I. (2023). Does the US regional greenhouse gas initiative affect green innovation? *Environmental Science and Pollution Research*, 30, 15689-15707. DOI: 10.1007/s11356-022-23189-0.

Ramzan, M., Razi, U., Quddoos, M.U., & Adebayo, T.S. (2023). Do green innovation and financial globalization contribute to the ecological sustainability and energy transition in the United Kingdom? Policy insights from a bootstrap rolling window approach. *Sustainable Development*, 31(1), 393-414. DOI: 10.1002/sd.2399.

Rodrigues, M., & Franco, M. (2022b). Role of human resources for sme sustainability: what the literature says and what we can expect for the future. *Revista de Administração de Empresas (Journal of Business Management),* 62(5), 1-7. DOI: 10.1590/S0034-759020220512x.

Rosado, C.A.G., & Souza, M.C. (2021). A bibliometric study on the use of games in the Production Engineering area. *Gestão & Produção*, 28(3), e5171. DOI: 10.1590/1806-9649-2021v28e5171.

Rupasinghe, L.R., Pushpakumari, M.D., & Perera, G.D.N. (2024). Mapping the knowledge of green innovation: A systematic literature review. *Journal of Humanities and Applied Social Sciences*, 6(3). DOI: 10.1108/JHASS-10-2023-0148.

Samitthiwetcharong, S., Kullavanijaya, P., Suwanteep, K., & Chavalparit, O. (2023). Towards sustainability through the circular economy of plastic packaging waste management in Rayong Province, Thailand. *Journal of Material Cycles and Waste Management*, 25, 1824-1840. DOI: 10.1007/s10163-023-01657-0.

Sánchez, J.M., Rodríguez, J.P., & Espitia, H.E. (2022). Bibliometric analysis of publications discussing the use of the artificial intelligence technique agent-based models in sustainable agriculture. *Heliyon*, 8(12). DOI: 10.1016/j.heliyon.2022.e12005.

Schiederig, T., Tieze, F., & Herstatt, C. (2011). What is green innovation? A quantitative literature review, Working Paper, No. 63, Hamburg University of Technology (TUHH), Hamburg: Institute for Technology and Innovation Management (TIM), http://hdl.handle.net/10419/55449.

Schlaepfer, M.A., & Lawler, J.J. (2022). Conserving biodiversity in the face of rapid climate change requires a shift in priorities. *Wiley Interdisciplinary Reviews: Climate Change*, 14(1), e798. DOI: 10.1002/wcc.798.

Shabir, M., Hussain, I., Işık, Ö., Razzaq, K., & Mehroush, I. (2023). The role of innovation in environmental-related technologies and institutional quality to drive environmental sustainability. *Frontiers in Environmental Science*, 11, 1174827. DOI: 10.3389/fenvs.2023.1174827.

Shahzad, M., Qu, Y., Rehman, S.U., & Zafar, A.U. (2022). Adoption of green innovation technology to accelerate sustainable development among manufacturing industry. *Journal of Innovation & Knowledge*, 7(4), 100231. DOI: 10.1016/j.jik.2022.100231.

Shan, S., Genç, S.Y., Kamran, H.W., & Dinca, G. (2021). Role of green technology innovation and renewable energy in carbon neutrality: A sustainable investigation from Turkey. *Journal of Environmental Management*, 294, 113004. DOI: 10.1016/j.jenvman.2021.113004.

Shuwaikh, F., Benkraiem, R., & Dubocage, E. (2023). Investment in green innovation: How does it contribute to environmental and financial performance? *Journal of Innovation Economics & Management*, 41, 107-149. DOI: 10.3917/jie.pr1.0137.

Silintowe, Y.B.R., & Sukresna, I.M. (2023). Green innovation in marketing research: A systematic literature review and bibliometric analysis. *AEBMR*, 221, 4-22. DOI: 10.2991/978-94-6463-076-3_2.

Stork, H., & Astrin, J. (2014) Trends in biodiversity research – A bibliometric assessment. *Open Journal of Ecology*, 4, 354-370. DOI: 10.4236/oje.2014.47033.

Sun, Y., Gao, P., Tian, W., & Guan, W. (2023). Green innovation for resource efficiency and sustainability: Empirical analysis and policy. *Resources Policy*, 81, 103369. DOI: 10.1016/j.resourpol.2023.103369.

Sweileh, W.M. (2020). Bibliometric analysis of peer-reviewed literature on climate change and human health with an emphasis on infectious diseases. *Globalization and Health*, 16(44). DOI: 10.1186/s12992-020-00576-1.

Tariq, A., Badir, Y., & Chonglerttham, S. (2019). Green innovation and performance: moderation analyses from Thailand. *European Journal of Innovation Management*, 22(3), 446-467. DOI: 10.1108/EJIM-07-2018-0148.

Thanuskodi, S. (2017). Journal of social sciences: A bibliometric study. *Journal of Social Sciences*, 24(2), 77-80. DOI: 10.1080/09718923.2010.11892847.

Thongplew, N., Onwong, J., Kotlakome, R., & Suttipanta, N. (2022). Approaching circular economy in an emerging economy: A solid-waste reutilization initiative in a small fresh market in Thailand. *Sustainability: Science, Practice and Policy*, 18(1), 665-678. DOI: 10.1080/15487733.2022.2110677.

van Eck, N.J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, 84, 523-538 (2010). DOI: 10.1007/s11192-009-0146-3.

Wang, B., Bu, Y., & Huang, W. (2018). Document- and keyword-based author co-citation analysis. *Data and Information Management*, 2(2), 70-82. DOI: 10.2478/dim-2018-0009.

Wang, C., Chen, P., Hao, Y., & Dagestani, A. A. (2022). Tax incentives and green innovation – The mediating role of financing constraints and the moderating role of subsidies. *Frontiers in Environmental Science*, 10, 1067534. DOI: 10.3389/fenvs.2022.1067534.

Wang, H., Khan, M.A.S., Anwar, F., Shahzad, F., Adu, D., & Murad, M. (2021). Green innovation practices and its impacts on environmental and organizational performance. *Frontiers in Psychology*, 11, 553625. DOI: 10.3389/fpsyg.2020.553625.

Wang, M., & Liu, Z. (2022). How do green innovation strategies contribute to firm performance under supply chain risk? Evidence from China's manufacturing sector. *Frontiers in Psychology*, 13. DOI: 10.3389/fpsyg.2022.894766.

Wysocki, J. (2021). Innovative green initiatives in the manufacturing SME sector in Poland. *Sustainability*, 13(4), 2386. DOI: 10.3390/su13042386.

Xu, L. (2022). Towards green innovation by China's industrial policy: Evidence from made in China 2025. *Frontiers in Environmental Science*, 10, 924250. DOI: 10.3389/fenvs.2022. 924250.

Zemtsov, S., Barinova, V., Semenova, R., & Mikhailov, A. (2022). Entrepreneurship policy and SME development during pandemic crisis in Russia. *Regional Research of Russia*, 12, 321-334. DOI: 10.1134/S2079970522700071.

Zhao, W., Korobskiy, D., & Chacko, G. (2020). Delayed recognition: a co-citation perspective. *Frontiers in Research Metrics and Analytics*, 5. DOI: 10.3389/frma.2020.577131.

Thuyen, T.T.N., & Bich, L.N. (2024). Barriers perceived by companies and potential solutions to foster green innovation in Vietnam. *Thailand and the World Economy*, 42(1), 91-109. https://so05.tci-thaijo.org/index.php/TER/article/view/270073.

Yoelao, D., Sombatwattana, P., & Priya Mohan, K. (2021). Development and validation of the sufficiency living wage scale for workers in Thailand. *Thailand and the World Economy*, 39(1), 23-38. https://so05.tci-thaijo.org/index.php/TER/article/view/242467.

Chapter 5

THE SYMBIOSIS OF WEB 2.0, WEB 4.0 TECHNOLOGIES AND SUPPLY CHAIN MANAGEMENT: INSIGHTS FROM BIBLIOGRAPHIC ANALYSIS AND TOPIC MODELING

Gabrielė Radavičiūtė

Vilnius Gediminas Technical University, Faculty of Business Management, Lithuania
gabriele.radaviciute@vilniustech.lt ORCID 0009-0005-0887-1681

Abstract: Digitization is the application of novel technologies and a shift in how the organization manages its processes, increasing its resilience. Moreover, digitization is one of the main trends anticipated to impact supply chains highly by 2025. However, the impact of digital technologies such as Web 2.0, including social networks, and Web 4.0, including artificial intelligence, blockchain, the Internet of things, and metaverse, is still underexplored in the field of supply chain management. Thus, the main goal of this study is to theoretically determine the effect of web-based digitization on supply chain management. The bibliographic analysis and topic modeling were conducted to analyze 940 Web of Science Core Collection publications from 1997 to 2024. The aim was to uncover selected publications' characteristics, main keywords, and research methods. Moreover, to analyze how social networks such as "Facebook", "YouTube", and "X" (previously "Twitter") and Web 4.0 technologies are connected to supply chain management. Also, the topic modeling was used to provide three possible research directions. However, this research also had limitations, such as concentrating only on the "Web of Science Core Collection". Another limitation is that only bibliographic analysis was conducted, suggesting potential future systematic literature reviews or empirical studies.

Keywords: bibliographic analysis, digitization, social network, supply chain management (SCM), topic modeling, Web 2.0, Web 4.0

Introduction

Global phenomena have emerged in the current millennium due to the increased popularity of internet technologies. Over the past twenty-five years, the popularity of second-fourth-generation internet technologies (Web 2.0-4.0) has grown. Social networks have reached five billion users, with individuals dedicating approximately one-tenth of their daily time to these platforms. The main trends anticipated to impact supply chains by 2025 are related to digitization, including big data, business analytics, and digitalization. Moreover, a quarter of logistics professionals believe that enhancing supply chain resilience could be achieved by transitioning to digital or direct sales and applying advanced fourth-generation internet technologies. However, the symbiosis of web technology and supply chain management has yet to be thoroughly explored. This study analyzes the impact of web-based digitization on supply chain management based on other author's publications. The main goal is to determine web digitization's existing or potential impact on supply chain management (Statista, 2024a; Statista, 2024b; APQC, 2022; Statista, 2021).

Moreover, such research tasks are planned:

- To conduct a bibliographic analysis of the Web of Science database publications and assess the interconnectedness of web technologies and supply chain management;
- To highlight the main characteristics of selected publications;
- To provide insights on web technologies within supply chain management as presented in the works of other authors;
- To develop proposals for future research based on topic modeling.

This study employs research methods such as content analysis and literature review. These are followed by a bibliographic analysis and topic modeling of literature sources (Web of Science Core Collection). For graphical data visualization, "VOSviewer" and "orange data mining" computer software are used.

Literature review

Digitization is not merely the application of digital technologies within an organization or replacing analog systems with digital ones. It extends beyond combining supply chain planning and execution with Industry 4.0 and 5.0 technologies. These technologies include cloud computing, artificial intelligence, big data, predictive business analytics, and distributed ledger technologies (DLT) such as blockchain. Also, such industrial technologies as 3-D printing, the Internet of Things (IoT), radio-frequency identification (RFID), and geographic information systems (GIS). Moreover, simulations, including building information modeling (BIM) or cloud-based digital twins (DT) and additive manufacturing, can be categorized within Industry 4.0-5.0 technologies. Digitization is also oriented toward the organization itself – it represents a shift in how an organization manages and organizes its activities to fully leverage the benefits offered by digital technologies (Andersen & Jæger, 2021; Naz et al., 2022; Tiwari et al., 2024; Yu, 2022).

First-generation internet technologies (Web 1.0) are considered passive tools for gathering and sharing information from HTML pages among users. Second-generation internet technologies (Web 2.0), termed by Darcy DiNucci, introduced the capability for users to create content themselves and interact collaboratively within virtual communities. Consequently, the emergence of social networks is closely associated with Web 2.0 technology and the beginning of the new millennium. The first decade of this millennium saw the creation of various social networking platforms; however, some failed (e.g., "Sixdegrees", "Friendster"), while others lost users and popularity (e.g., "Myspace"). A part remains actively utilized to this day (e.g., "LinkedIn", "Facebook", "YouTube", "Twitter/X", "Instagram") (Makridakis et al., 2010; Tambe & Vora, 2016; Zhong et al., 2021).

Third-generation internet technologies (Web 3.0) distinguish themselves through personalized search and deeper integration with social networks. The use and accessibility of Internet and mobile technologies are closely linked to the number of social network users, with 94% of Internet users utilizing social networks. With the increasing popularity of Web 2.0-4.0 technologies, particularly as affordable mobile devices become more accessible in developing and less technologically advanced countries, it is projected that there will be approximately 5.85 billion social network users by 2027. Meanwhile, fourth-generation internet technologies (Web 4.0) continue to evolve, combining a symbiosis between human and smart technologies, including, for instance, artificial intelligence (AI), Internet of Things (IoT), blockchain, and metaverse (Statista, 2024; Statista, 2024a; Tambe & Vora, 2016).

This study focuses exclusively on Web 2.0-4.0 technologies and supply chain management, as addressed in other authors' works. First-generation internet technologies (Web 1.0), which lack relevance to social networks and are characterized by their "read-only" function, are not examined. Fifth-generation internet technologies (Web 5.0) are also not extensively discussed because they have yet to be widely applied and are more conceptual. Additionally, within this study, the supply chain is understood as a cohesive system whose elements (procurement, production, warehouse, and sales management) are interconnected to meet consumer needs. Supply chain management is also the supplier-manufacturer-distributor triad (Carter et al., 2015; Hopkins et al., 2022; Tambe & Vora, 2016).

Research methodology

An analysis of bibliographic literature sources was conducted within the Web of Science Core Collection database to identify key publications. Keywords related to internet technologies such as "web 2", "web 3", or "web 4" were utilized during the analysis. Additionally, keywords about supply chain management were employed, including "supply chain*" or "supply chain manage*" or "logistic*" or "operation*" or "production*" or "procurement*" or "sales" or "warehouse*". Based on Web of Science database results, 940 relevant publications were filtered.

Bibliographic visualization utilized a software tool called "VOSviewer" (https://www.vosviewer.com), designed by van Eck and Waltman. This software examines data by measuring similarity and generating interconnected bibliographic maps for exploration and visualization. These maps depict co-occurrences, indicating how frequently terms appear together in publications (Silva et al., 2023).

Topic modeling was employed to identify thematic categories within the selected publications, which can guide future research. The "Orange Data Mining" (https://orangedatamining.com) tool's topic modeling feature facilitated this analysis. Essential textual components, including authors, article titles, abstracts, and author keywords, were compiled into a text corpus. Subsequently, text preprocessing procedures were applied: converting all text to lowercase, removing URLs, and tokenizing words while filtering out stopwords and regular expressions to enhance data cleanliness. The objective was to derive three key topics using the "Latent Dirichlet Allocation" criteria (Naz et al., 2022).

Research results and discussion

In order to understand the interconnectivity between web technology and supply chain management, subsequent sections provide an analysis of the main characteristics of these publications. Firstly, the publications' main statistics are evaluated.

Secondly, the other authors' main keywords and research methodologies are analyzed. Thirdly, the leading social networking platforms mentioned by other authors and their connections to supply chain management are being identified. Then, the analysis explores Web 4.0 technologies and their interfaces with supply chain management processes. Finally, three new topics based on topic modeling results suggest new directions for future studies.

The main statistics of selected publications

"Orange data mining" software was used to understand the main statistics of publications: the document types and the publishing timeline, the average number of times these publications were cited, which publication was the most cited, and the number of cited references.

As given in Figure 5.1, most publications were articles (525 publications), followed by 387 proceeding papers and 58 book chapters. Meanwhile, the publication period ranges from 1997 to 2024. Furthermore, the beginning of the topic is associated with the emergence of second-generation internet technologies and the first social networks at the beginning of this millennium. From 1997 to 2004, there were only a few publications, but the number of publications significantly increased from 2007 to 2010, peaking in 2011 with ninety-three publications.

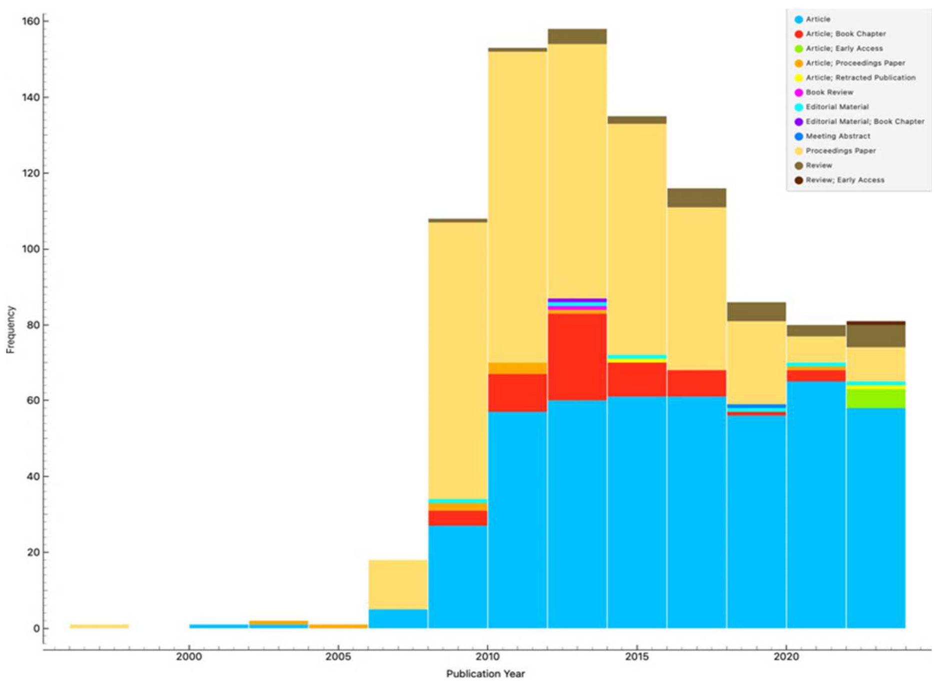


Figure 5.1. The distribution of supply chain management and web technologies publications (based on document type and publication year)

Source: Web of Science Core Collection, data of 24th June 2024, created by author using "Orange data mining" software.

Subsequently, the number of publications slightly decreased, reaching about seventy-nine in 2012. Furthermore, scholarly interest in this topic consistently declined, with thirty-two publications on supply chains and internet technology in 2023. Although it is no longer as popular as it was in the 2010s, this topic remains relevant and attracts interest in the academic community. On the other hand, other concepts and terminology may now be more actively used than “internet technologies” or “web technologies”. This could be analyzed in future research.

The publications were cited on average twenty-three times within the Web of Science Core Collection (WOS) or twenty-six times in all databases. The most cited publication from WOS and all databases was Kietzmann et al.'s (2011) publication on functional building blocks of social media, with 2089 citations in all databases and 2043 citations in WOS. The median number of cited references was thirty, while Dhaigude and Mohan (2023) reached a maximum with 287 references cited in their customer experience and social commerce review paper.

Main keywords and research methods within selected publications

A bibliographic analysis of Web of Science database sources was conducted to gain deeper insights into the research methods employed by other authors (see Fig. 5.2). The most popular keywords were: “web 2.0”, “social media”, “internet”, “information”, “technology”, “impact”, and “sales”.

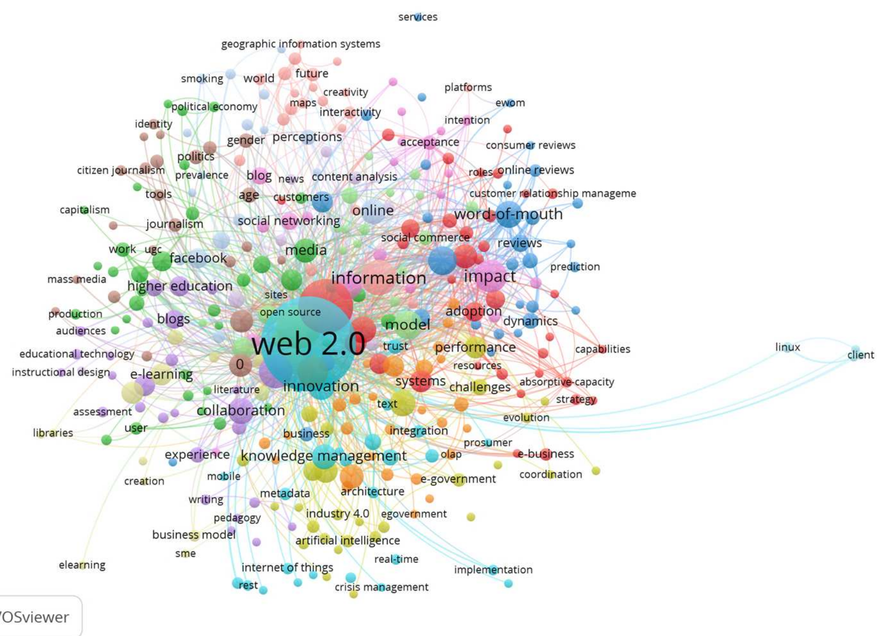


Figure 5.2. The bibliographical results of supply chain management and web technologies (co-occurrence of all keywords)

Source: Web of Science Core Collection, data of 24th June 2024, created by author using “VOSviewer” software.

Even though various qualitative and quantitative research methods could be found within the keywords, it was not possible to identify a single dominant research method. Nevertheless, the following methods are discussed in more detail:

- **Qualitative research methods.** The authors employed semi-structured interviews to explore how small businesses utilize social media for consumer communication, creating additional value. For instance, creators (performers and recording companies) seek to connect with their music consumers (fans) and disseminate information about their product (music) (Choi & Burnes, 2017).
- **Survey.** Through a survey, the authors determined that top management support is crucial when implementing web technologies in supply chain management systems. Especially in manufacturing and service industries where Internet technologies are less frequently used (Tarofder et al., 2019).
- **Sentiment analysis.** This research method helps to evaluate differences between external and intrinsic characteristics and identify emotional states and subjective information (Ghorbanloo & Shokouhyar, 2023). For instance, product sellers utilize it when tracking customer feedback to forecast future sales outcomes and make related decisions. When comparing different product features, sellers primarily focus on improving less popular product attributes (Singh et al., 2015).
- **Text mining.** Text extraction using topic modeling is applied to analyze topics discussed in online communities and their changes over time. This also assists in discovering future trends that could lead to further discussion (Zeng, 2018).
- **Big data analytics.** Other authors discuss integrating big data analytics into blockchain-based food traceability and supply chain systems. Integrating these technologies assists in restructuring the food supply chain, monitoring the flow of food products, identifying waste generation points, and enhancing food safety measures (Ellahi et al., 2023).

In summary, a sole and specific research method has not been identified to analyze the impact of web technologies and supply chain management. However, various research methods were applied in the publications, including semi-structured interviews, surveys, sentiment analysis, text mining, and big data analytics.

Social networks and supply chain management

The further study provides a detailed analysis of the most frequently mentioned social networks by other authors: “YouTube”, “X” (previously known as “Twitter”), and “Facebook”. Other social media platform names were not identified in the bibliographic analysis.

The social network platform “YouTube” was associated with the following concepts: “Web 2.0” technology, “social media”, “information”, “knowledge”, “videos”, “Facebook”, “Twitter”, and “smoking” (see Fig. 5.3). However, other keywords suitable for supply chain management were not identified. The analysis of “YouTube” was most popular between 2016 and 2018, possibly because it was and still is the second largest social network in the world by user base (Statista, 2024c).

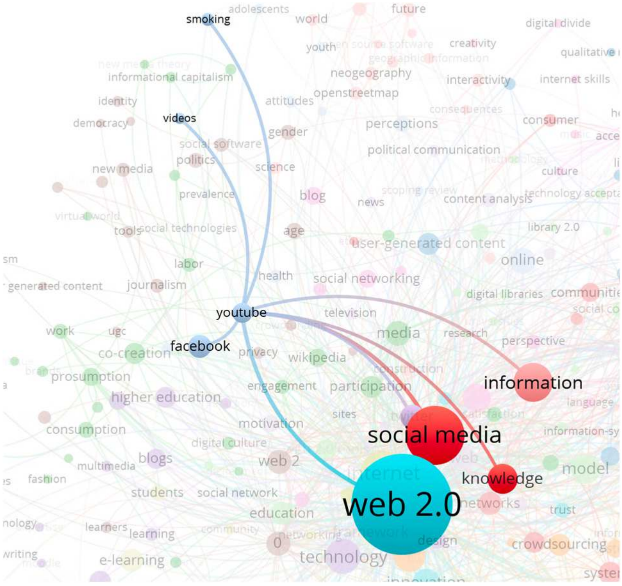


Figure 5.3. "YouTube" and supply chain management results

Source: Web of Science Core Collection, data of 24th June 2024, created by author using "VOSviewer" software.

While evaluating the social media platform "Twitter" ("X") and its connections to the supply chain processes, some inconsistencies were noted. "Twitter" is the most commonly associated with "Web 2.0", "social media", "information", "YouTube", and "Facebook" (Fig. 5.4). On the other hand, new concepts have been identified: "motivation", "television", and "sentiment analysis", which were not identified in the analysis of the "YouTube" platform. The analysis of "Twitter", among other authors' works, was also most prevalent from 2016-2018. The popularity of "Twitter" among researchers can be explained by its convenient API data access function (Chae, 2015).

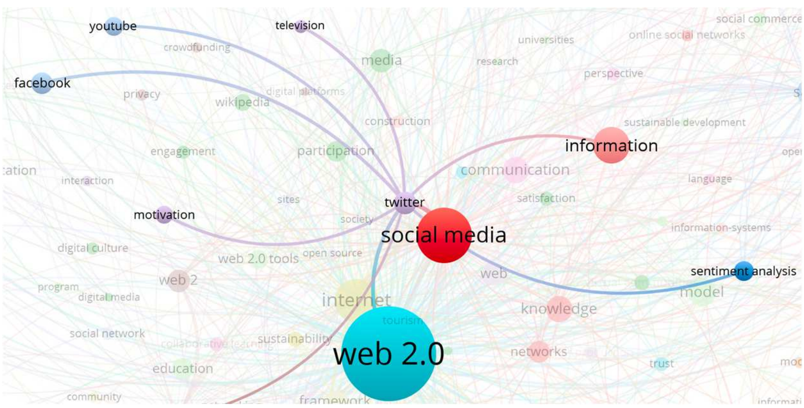


Figure 5.4. "Twitter" and supply chain management results

Source: Web of Science Core Collection, data of 24th June 2024, created by author using "VOSviewer" software.

The last frequently mentioned social network was “Facebook”. This social media platform was associated with “Web 2.0”, “social media”, “motivation”, “YouTube”, “Facebook”, and “knowledge” (as given in Fig. 5.5). Additionally, the bibliographic analysis reveals these new keywords: “social network”, “students”, “internet”, “technology”, “media”, “communication”. These concepts were not analyzed in the context of the “YouTube” and “Twitter” platforms. The popularity of “Facebook” among researchers can be explained by its status as the social network with the highest number of users worldwide (Statista, 2024c). Furthermore, “Facebook” is also the most popular among marketing specialists, holding 45% of the market share (Statista, 2023).

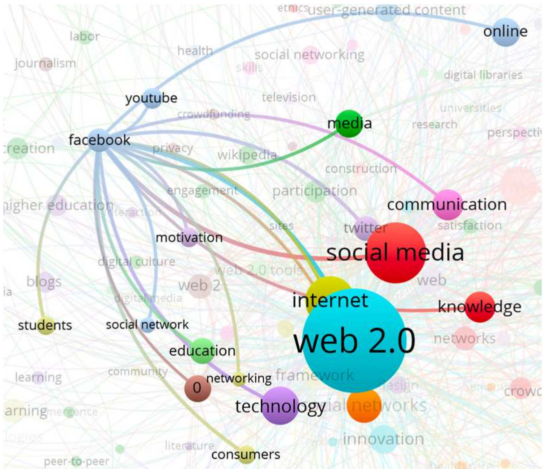


Figure 5.5. “Facebook” and supply chain management results

Source: Web of Science Core Collection, data of 24th June 2024, created by author using “VOSviewer” software.

However, the keyword “consumers” was suitable for supply chain management. The authors mentioned the “Facebook” platform and consumers while discussing crowdfunding. They believed crowdfunding could increase sales, profits, satisfaction, and organizational competitiveness (Zolkepli, 2017). Other authors emphasized the importance of company websites and “Facebook” pages in activities involving producing consumers (referred to as “prosumers”). For example, companies can adapt products to individual needs and obtain user advice on new product ideas and changes (Bartosik-Purgat & Bednarz, 2021).

Zhang and Moe (2021) noted that data from “Facebook” and other social network users helps to measure brand popularity and user favorability. They analyzed “Facebook” data on over 3,300 brands and about 205 million unique users who interacted with these brands through their “Facebook” pages, encompassing 6.68 billion likes and 1.01 billion user comments. The authors developed a model that measures consumer opinions about a brand more accurately than traditional methods.

To sum up, bibliographic analysis only partially assisted in the identification of comprehensive connections between social network platforms and supply chain-related keywords. Only three social network platforms – “YouTube”, “Twitter”, and "Facebook" – were identified. Bibliographic analysis of the "Facebook" platform allowed the identification of one concept related to the supply chain – "consumers". Therefore, future research should aim to improve search strategies and further examine this topic in detail, as the results are insignificant.

Web 4.0 technologies and supply chain management

A supplementary keyword search assessed the prevalence of Web 4.0 technologies: artificial intelligence, Internet of Things, blockchain, and virtual reality. Analysis using VOSviewer revealed that artificial intelligence has been prominently featured in the works of other authors since 2018. However, no suitable concepts were found for supply chain management (Fig. 5.6).

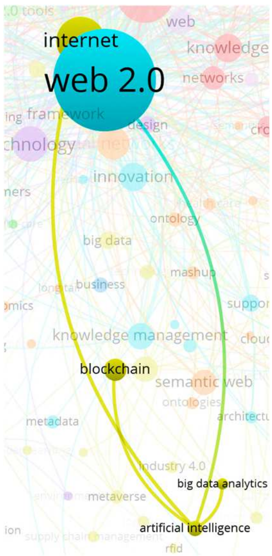


Figure 5.6. Artificial intelligence and supply chain management results

Source: Web of Science Core Collection, data of 24th June 2024, created by author using "VOSviewer" software.

The popularity of the Internet of Things was noticed earlier than that of artificial intelligence, especially during the years 2016-2018. However, suitable keywords specifically for supply chain management were also not identified (Fig. 5.7).

In keyword analysis of blockchain and supply chain management, the singular appropriate term identified was "supply chain management" (Fig. 5.8). Furthermore, the analysis of these topics was relatively recent, as it has been pertinent among scholars since 2018. Dey et al. (2022) explored blockchain and machine learning in the food supply chain and smart cities, addressing waste issues. The authors also discussed the "SmartNoshWaste" system, based on blockchain, cloud computing, and QR codes. It promotes continuous learning to reduce food waste in smart cities. Moreover, this system successfully reduced potato waste by approximately 10% compared to traditional methods.

Figure 5.7. Internet of Things and supply chain management results

Source: Web of Science Core Collection, data of 24th June 2024, created by author using "VOSviewer" software.

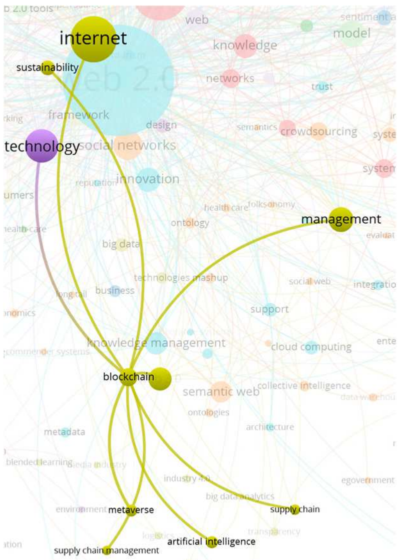


Figure 5.8. Blockchain and supply chain management results

Source: Web of Science Core Collection, data of 24th June 2024, created by author using "VOSviewer" software.

Virtual reality or metaverse topics have remained relevant since 2017 (as per Fig. 5.9). Furthermore, a connection between virtual reality and supply chain management keywords was also observed. Dolgui and Ivanov (2023, p. 8179) introduced the concept of "metaverse" for the first time in 1992 in Stephenson's book "Snow Crash", describing it as a black spherical planet accessible to users through virtual reality terminals. Its fundamental significance lies in the "digital twin" of human, product, or organization. The synergies among metaverse, supply chain, and operations management areas can lead to new domains related to novel processes, decision-making, and performance metrics. For instance, joint demand forecasting for virtual and physical products, digital inventory allocation, and integrated production planning. Also, for digital product pricing and contract formation, virtual customer experience level, digital product accessibility and resilience, and sustainability (Dolgui & Ivanov, 2023, p. 8187).

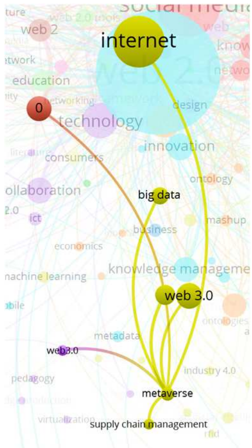


Figure 5.9. Metaverse and supply chain management results

Source: Web of Science Core Collection, data of 24th June 2024, created by author using "VOSviewer" software.

The keywords analysis showed that the authors mentioned Web 4.0 technologies such as blockchain, virtual reality, and supply chain management concepts. Moreover, the Internet of Things and artificial intelligence were less frequently associated with the supply chain or its elements. This could be a potential gap for future research.

Topic modeling for future research

According to the topic modeling conducted with "Orange data mining software", there were three main topics, as given in Table 5.1. These topics could be used and analyzed in depth within further research. The author subjectively provides several future research recommendations, indicating possible themes that could incorporate the findings of the researched topics, as well as supply chain management, operations, and logistics.

The first topic could investigate social media trends and the negative consequences on production, for example, within the fast fashion and apparel industries. The sustainability and environmental aspects could be taken into account as well. Additionally, the Web of Science Core Collection (WOS) database was searched for such keywords as "fast fashion", AND "social media", social networks", AND "supply chain", OR "production" to understand if the topic is novel. As a result, only 21 similar publications were found, which could indicate that the topic is still nascent. Also, the publication timeline was checked – it ranged from 2016 to 2024, with a peak in 2023.

Table 5.1. Topic modeling for further research

Number	Words with the highest probability	Topic label for further research
1.	web, social, knowledge, media, data, learning, based, information, production, new	The Negative Impact of Social Media Real-Time Data on Fast Fashion Production
2.	web, social, research, media, data, information, based, business, content, knowledge	The Impact of Web-Based Knowledge Sharing on Global Supply Chain Innovations
3.	web, social, information, media, online, data, e-learning, new, use	Utilizing Social Media Web Scraping for Predictive Analytics in Supply Chain Risk Management

Source: Web of Science Core Collection, data of 24th June 2024, topics extracted by the author using “Orange data mining” software.

The second topic of future research could concentrate on web-based knowledge sharing (for example, using platforms such as “YouTube”) and global supply chain-related innovations. Furthermore, the WOS database was searched for such topic keywords as “knowledge sharing” AND “web” OR “internet” OR “social media” OR “social network” AND “supply chain” AND “innovation” OR “industry 4” OR “industry 5” OR “artificial intelligence” OR “internet of things” OR “digital twins”. Consequently, 15 similar publications were found, indicating a potential research gap.

For the last topic, possible research could investigate online data and social media analytics based on application programming interface (API) and web scraping technologies. The goal could be to enhance predictive capabilities in supply chain risk management, improving proactive disruption identification and resilience. As previously, the WOS database was searched for such topic keywords as “web scraping” OR “API” AND “supply chain” AND “risk” OR “resilience”. Only 19 similar publications were found, indicating another potential research topic.

Conclusion

While some of the popular social networking platforms created at the beginning of this millennium have failed or lost popularity, others remain actively used to this day (e.g., “Facebook”, “YouTube”, “Twitter”, “Instagram”). Meanwhile, the popularity of Web 4.0 technologies, which combine human and smart technologies such as artificial intelligence, Internet of Things, blockchain, and metaverse, is growing. Therefore, this study analyzed the symbiosis of supply chain and web technologies. A bibliographic analysis was performed, identifying:

- key characteristics from 940 publications,
- main keywords and research methods,
- associations of social network-related keywords, and supply chain management,
- associations of Web 4.0 technology keywords and supply chain management.

Moreover, the three topics were suggested for further research direction based on topic modeling results. First, future research could concentrate on social media trends and their negative consequences on production. Second, web-based knowledge sharing and global supply chain-related innovations could be further analyzed. Third, the analysis could provide insights into online data and social media analytics based on application programming interfaces and web scraping technologies.

However, publications on Web technologies in supply chain management have waned in popularity (with a peak in 2011). Therefore, it is recommended that alternative keywords be evaluated in future studies to reveal the latest trends in scholarly work. Future research could empirically apply the earlier research to explore digitization's impact on supply chain management. Another limitation of this study is that only the "Web of Science Core Collection" was analyzed; therefore, it is suggested that other databases such as "Scopus" be included in future research. This work contributes to understanding how digital web advancements influence the management of supply chains and suggests future research to explore these dynamics further.

References

Andersen, T., & Jæger, B. (2021). Circularity for electric and electronic equipment (Eee), the edge and distributed ledger (edge&dl) model. *Sustainability (Switzerland)*, 13(17). DOI: 10.3390/su13179924.

APQC (2022). 2022 Supply Chain Challenges and Priorities Survey Report | APQC. https://www.apqc.org/resource-library/resource-listing/2022-supply-chain-challenges-and-priorities-survey-reporT.

Bartosik-Purgat, M., & Bednarz, J. (2021). The usage of new media tools in prosumer activities – a corporate perspective. *Technology Analysis and Strategic Management*, 33(4), 453-464. DOI: 10.1080/09537325.2020.1820475.

Chae, B. (2015). Insights from hashtag #supplychain and Twitter analytics: Considering Twitter and Twitter data for supply chain practice and research. *International Journal of Production Economics*, 165, 247-259. DOI: 10.1016/j.ijpe.2014.12.037.

Choi, H., & Burnes, B. (2017). Bonding and spreading: Co-creative relationships and interaction with consumers in South Korea's indie music industry. *Management Decision*, 55(9), 1905-1923. DOI: 10.1108/MD-10-2016-0691.

Dey, S., Saha, S., Singh, A.K., & McDonald-Maier, K. (2022). SmartNoshWaste: Using Blockchain, Machine Learning, Cloud Computing and QR Code to Reduce Food Waste in Decentralized Web 3.0 Enabled Smart Cities. *Smart Cities*, 5, 5(1), 162-176. DOI: 10.3390/SMARTCITIES5010011.

Dhaigude, S.A., & Mohan, B.C. (2023). Customer experience in social commerce: A systematic literature review and research agenda. *International Journal of Consumer Studies*, 47(5), 1629-1668. DOI: 10.1111/IJCS.12954.

Dolgui, A., & Ivanov, D. (2023). Metaverse supply chain and operations management. *International Journal of Production Research*, *61*(23), 8179-8191. DOI: 10.1080/00207543.2023.2240900.

Ellahi, R.M., Wood, L.C., & Bekhit, A.E.D.A. (2023). Blockchain-based frameworks for food traceability: A systematic review. *Foods*, 12(16). DOI: 10.3390/FOODS12163026.

Ghorbanloo, S., & Shokouhyar, S. (2023). Consumers' attitude footprint on sustainable development in developed and developing countries: a case study in the electronic industry. *Operations Management Research* 16(3), 1444-1475. DOI: 10.1007/S12063-023-00357-0.

Kietzmann, J.H., Hermkens, K., McCarthy, I.P., & Silvestre, B.S. (2011). Social media? Get serious! Understanding the functional building blocks of social media. *Business Horizons*, 54(3), 241-251. DOI: 10.1016/J.BUSHOR.2011.01.005.

Naz, F., Kumar, A., Majumdar, A., & Agrawal, R. (2022). Is artificial intelligence an enabler of supply chain resiliency post COVID-19? An exploratory state-of-the-art review for future research. *Operations Management Research*, 15(1-2), 378-398. DOI: 10.1007/S12063-021-00208-W/FIGURES/10.

Silva, L.B. da, Silva, L.L. da, & Almeida, L. de A. (2023). Análise das capacidades estatais municipais na literatura acadêmica: Construção e visualização de mapas bibliométricos com VOSviewer e CitNetExplorer. *Cadernos Gestão Pública e Cidadania*, 28, e88046. DOI: 10.12660/CGPC.V28.88046.

Statista (2021). *Which of the following are you likely to implement in order to create more resilience within your supply chains? Statista.* Retrieved April 28, 2024, from https://www.statista.com/statistics/1225546/suggested-changes-to-strengthen-supply-chains/.

Statista (2023). *Most important social media platforms for marketers worldwide as of January 2023. Statista.* Retrieved April 28, 2024, from https://www.statista.com/statistics/259390/most-important-social-media-platforms-for-marketers-worldwide/.

Statista (2024a). *Number of internet and social media users worldwide as of January 2024. Statista.* Retrieved April 28, 2024, from https://www.statista.com/statistics/617136/digital-population-worldwide/.

Statista (2024b). *Global social media usage reasons 2024. Statista.* Retrieved April 28, 2024, from https://www.statista.com/statistics/433871/daily-social-media-usage-worldwide/.

Statista (2024c). *Most popular social networks worldwide as of January 2024, ranked by number of monthly active users. Statista.* Retrieved April 28, 2024, from https://www.statista.com/statistics/272014/global-social-networks-ranked-by-number-of-users/.

Tarofder, A.K., Jawabri, A., Haque, A., & Sherief, S.R. (2019). Validating technology-organization-environment (TOE) framework in web 2.0 adoption in supply chain management. *Industrial Engineering and Management Systems*, 18(3), 482-494. DOI: 10.7232/IEMS.2019.18.3.482.

Tiwari, S., Sharma, P., & Jha, A.K. (2024). Digitalization & Covid-19: An institutional-contingency theoretic analysis of supply chain digitalization. *International Journal of Production Economics*, 267, 109063. DOI: 10.1016/J.IJPE.2023.109063.

Yu, H. (2022). Modeling a remanufacturing reverse logistics planning problem: some insights into disruptive technology adoption. *The International Journal of Advanced Manufacturing Technology*, 1, 3. DOI: 10.1007/s00170-022-10387-w.

Zeng, M.A. (2018). Foresight by online communities – The case of renewable energies. *Technological Forecasting and Social Change*, 129, 27-42. DOI: 10.1016/J.TECHFORE.2018.01.016.

Zhang, K., & Moe, W. (2021). Measuring Brand Favorability Using Large-Scale Social Media Data. *Information Systems Research*, 32(4), 1128-1139. DOI: 10.1287/ISRE.2021.1030.

Zolkepli, Izzal Asnira (2016). Changing Consumer Culture in The Wake of 3.0: Mobilizing Online Crowd Competency and Expertise Through Crowdsourcing, *Proceedings of 3rd European Conference on Social Media (ECSM),* 12-13th July, Caen, France.

PART II.

Sustainable Development and Logistics Process Optimization

Chapter 6

CSR CONCEPT IN MANAGEMENT OF LOGISTICS ENTERPRISES – ANALYSIS OF IMPLEMENTATION OF SUSTAINABLE DEVELOPMENT GOALS

Julia Wieczorek[1], Marta Kadłubek[2]

[1,2] Czestochowa University of Technology, Faculty of Management, Poland
marta.kadlubek@wz.pcz.pl ORCID 0000-0002-0424-8316

Abstract: The chapter's aim was to analyse the implementation of corporate social responsibility (CSR) activities in enterprises from the logistics industry, with particular emphasis on the implementation of sustainable development goals. The study was conducted based on data obtained from the Responsible Business Forum, in the field of good ESG (Environmental, Social and Governance) practices in Poland, covering the period from 2021 to 2023. Information was collected on the number of sustainable development goals met by companies from the logistics industry and the coefficient of variation of these goals was estimated. The results of the study indicated which sustainable development goals were priority areas of involvement of enterprises from the logistics sector and identified the goals that were implemented to the least extent. The analysis provided conclusions on the priorities in this industry, at the same time indicating contribution within guidelines for companies wishing to direct their activities towards sustainable development.

Keywords: sustainable development goals, good practices, logistics companies, corporate social responsibility, sustainable development of enterprises

Introduction

In the context of a rapidly evolving societal and regulatory landscape, companies within the logistics industry are confronted with the imperative of integrating sustainable business practices into their core operations. The principles of Corporate Social Responsibility (CSR), which were previously regarded as a means of enhancing a company's public image, have now become an integral component of many organisations' long-term growth strategies. The field of CSR in logistics encompasses a vast array of activities, including the reduction of adverse environmental impacts, the promotion of responsible consumption practices, and the creation of value for local communities (Younis, 2016). The integration of CSR principles in the logistics sector can respond to increasing customer demands and also bring economic and operational benefits, thereby contributing to the efficiency and market stability of companies (Uyar et al., 2020).

The challenge of meeting the Sustainable Development Goals (SDGs) formulated by the United Nations in 2015 represents a significant undertaking for businesses around the world, with the logistics industry in particular being called upon to play a pivotal role in achieving the chosen goals (Govindan & Hasanagic, 2021). However, the sector encounters technological challenges and costly investments that may restrict its capacity to comprehensively implement sustainable practices (Theeraworawit et al., 2022). Despite the increasing acknowledgement of the necessity to curtail greenhouse gas emissions and implement green solutions (Singh et al., 2020), logistics companies frequently find themselves under pressure to reconcile expenditure on innovation with economic imperatives, resulting in a variable level of commitment to specific goals (Novitasari & Agusia, 2022).

According to above-mentioned, the introduction of sustainable practices and CSR principles in the logistics sector is not only a market requirement, but also a potential source of competitive advantage. Companies that effectively implement sustainability principles are able to effectively manage risks, build a positive image and engage in innovative solutions to support environmental protection. This chapter aims to analyze the implementation of the CSR concept in logistics companies, with particular emphasis on meeting sustainable development goals. The implementation of this defined goal of the study requires answers to the following research questions:

Q1: What are the benefits of implementing CSR principles in the logistics companies?

Q2: How has the implementation of sustainable development goals in the logistics industry changed between 2021 and 2023?

Q3: Which SDGs are the dominant areas of engagement for the logistics companies, and which are the least implemented?

The chapter consists of two parts: theoretical and empirical. The theoretical part discusses key aspects of the concept of corporate social responsibility, its benefits and activities resulting from its implementation in enterprises. The importance of sustainable logistics is presented in detail, focusing on its main areas and potential benefits resulting from the implementation of sustainable development principles in various aspects of logistics. The empirical part focuses on the analysis of the implementation of sustainable development goals by enterprises from the logistics sector. A study was conducted to determine the variability of the goals implemented using the coefficient of variation and the identification of the most intensively implemented goals in this industry and the least involved. The study was carried out based on data obtained from the Responsible Business Forum, in the field of good ESG (Environmental, Social and Governance) practices in Poland, covering the period from 2021 to 2023 (Forum Odpowiedzialnego Biznesu, 2024).

The results provide important information on the practical aspects of implementing sustainable development in the logistics sector. This research allows for a more detailed understanding of the challenges and successes related to implementing the SDGs. Further analysis can help identify areas for improvement and optimize sustainable development strategies in the context of the specific needs of the logistics sector.

The concept of corporate social responsibility

The concept of corporate social responsibility is essential in building a long-term business strategy based on the cooperation of the economic, ecological and social spheres. It describes responsible, entrepreneurial actions that voluntarily integrate social and ecological issues in business activities and interactions with interest groups and stakeholders (Euramco, 2024). The ambiguity around the meaning of corporate social responsibility results not only from the multitude of definitions but also from the existence of concepts that can be interpreted as close or separate in meaning in relation to CSR. These concepts include business ethics, stakeholder management and sustainable development (Zaborek, 2021). The concept of corporate social responsibility has many definitions, but they share a common element. Companies implementing CSR principles in their strategy take into account social interests, environmental protection, sustainable development and appropriate relations with various stakeholder groups (Sikora, 2022). The International Organization for Standardization, on the occasion of the inauguration of the first standard for managing aspects of business ethics – ISO 26000, indicates that social responsibility is the responsibility of an organization for the impact of its decisions and actions on society and the environment through transparent and ethical behaviour that: contributes to sustainable development, including the health and well-being of society, takes into account the expectations of stakeholders (people or groups who are interested in the decisions or actions of the organization), is compliant with applicable law and consistent with international standards of conduct, is implemented throughout the organization and practised in its activities within its sphere of influence (Polski Komitet Normalizacyjny, 2024). According to this definition, an enterprise implementing the CSR concept has a real opportunity to act in a socially responsible manner, which in the era of sustainable development is becoming a requirement of society around the world, and is not just a matter of choice.

The implementation of the concept of social responsibility often becomes an integral strategic element in a company, as evidenced by surveys conducted among managers, reports of the Responsible Business Forum, initiatives undertaken by institutions, and even competitions for the best social reports. Verification of corporate social responsibility disclosures has become a standard business practice and has seen significant growth in the global arena. This expansion is caused by the need to convey to the company's stakeholders the message that environmental and social risks are constantly under control (Karama et al., 2021). The concept of CSR presented as a modern model for increasing the value of an organization and achieving a competitive advantage promotes the social inclusion of fair and profitable markets in which sustainable principles drive growth, generating long-term (and shared) values through the integration and balance of natural, social, human, and financial capital (Cheng et al., 2021; Solarin & Bello, 2021; Hunjra et al., 2022).

The implementation of the doctrine allows companies to shape a positive image, while from the perspective of stakeholders, the company gains trust. This results in an exchange of benefits, which have a basis both within the organization and in its micro- and macro-environment. The specificity of activities and benefits resulting from the implementation of the CSR concept in the company is presented in Table 6.1.

The implementation of the concept of corporate social responsibility brings a number of benefits to the company's stakeholders, however, for the benefits to be really noticeable, each of these groups should take specific actions to support the implementation of the strategy. The CSR concept requires commitment, adherence to the principles of sustainable development, transparency and innovation to achieve positive results and long-term profits for a given organization.

Table 6.1. Activities and benefits resulting from the implementation of the CSR concept in the enterprise

Stakeholder group	Activities	Benefits
Owner	Development and implementation of CSR strategy Regular monitoring and transparent reporting	Increasing the market value of the company Making it easier to obtain funds for further development
Employees	Involvement in CSR initiatives Compliance with CSR principles, policies and culture	Increased productivity and ethical employee behaviour A safe, healthy work environment
Consumers	Conscious consumption and ethical choices Feedback and engagement in dialogue	Evaluation of consciousness towards ethical consumption Recognition of the company's quality
Strategic partners	Promoting transparency of social reporting Integration of CSR objectives in contracts and policies	Strengthened partnership Transparent terms of cooperation
Suppliers	Compliance with ethical standards and sustainable development principles	Better control of the quality of deliveries Reducing harmful effects in the supply chain
Country	Introducing Sustainable Development Policy Regulations Support for innovation and research	Stable and sustainable economic growth Improving the living conditions of society

Source: Own study based on (Wysokińska & Witkowska, 2016).

Sustainable logistics

Sustainable logistics is a key area that is increasingly appearing in the dictionaries of companies in the context of global ecological, social and economic challenges. Currently, customers expect sellers, producers and entrepreneurs to conduct business in a manner consistent with the principles of sustainable development and with care for the natural environment (Walczyński & Kanciak, 2023). Consequently, the implementation of sustainable development practices has become a key factor in competitiveness, affecting not only the reputation but also the financial results of enterprises. The conceptual approach to sustainable logistics based on a comparison of new criteria to existing logistics models and systems has allowed the creation of a universal definition of *sustainability*. This term is discussed as an efficient and flexible adaptation of an enterprise to surrounding changes through appropriate anticipation, forecasting and response to emerging market phenomena (Derdak & Misztal, 2023). Sustainable development, on the other hand, is the impact on society and the environment. Sustainable development is also becoming more and more noticeable in logistics companies thanks to automation and robotics technologies, but also thanks to the use of so-called green transport, which not only reduces exhaust emissions but also meets the expectations of society by minimizing the harmful impact on the environment, economy and urban planning (Zapałkowska, 2022). The implementation of sustainable development in enterprises includes activities to improve the financial situation, improve the quality and working conditions, develop the intellectual capital of employees, support local communities, reduce emissions of harmful substances and implement environmentally friendly technologies (Derdak & Kowalska, 2023). Sustainable logistics focuses on the integration of the principles of sustainable development in the management of logistics operations. The practical implementation of the principles of sustainable logistics is often associated with challenges, such as investments in new technologies or changes in the organization of processes, but meeting the growing requirements and social expectations is becoming more important for enterprises. Sustainable logistics is a dynamically developing area that combines ecological, economic and social aspects, striving to create more effective, responsible and resilient logistics systems.

Activities and potential benefits of implementing the sustainable development concept in individual logistics areas

Corporate social responsibility, perceived as an activity that can only be implemented by companies with high financial resources, is giving way to activity based on the principle of respecting the interests of all stakeholders operating in the company's environment. Companies have a real possibility of applying the principles of sustainable development while fulfilling its goals by implementing the CSR concept in selected logistics areas.

The implementation of the CSR concept, especially in the field of logistics, is a mutually interconnected area. Logistics, which includes processes from supply, through production and distribution to the customer, to the area of service and waste, has a significant impact on the environment, society and economy. Integrating CSR principles with logistics is not only an expression of the ethical attitude of companies but also brings specific benefits in terms of sustainable development and improving the image of the company. Figure 6.1 shows the connections between logistics and corporate social responsibility and states that these are closely related areas, and their integration brings benefits to both companies and the environment and society. Striving to optimize logistics processes while taking into account the principles of sustainable development allows companies not only to reduce the negative impact on the environment but also to strengthen their position on the market as socially responsible entities. The development of sustainable logistics is therefore an indispensable element of the CSR strategy.

In each of the processes used in logistics, both positive and negative aspects influencing the company's environment can be distinguished. Logistics mainly covers processes related to supply, production and distribution, while there are many solutions that fit into social responsibility. Companies implementing a CSR strategy can decide to optimize routes and loads, thus reducing CO_2 emissions, invest in energy-efficient warehouses in which modern technological solutions are used or switch to ecological packaging materials.

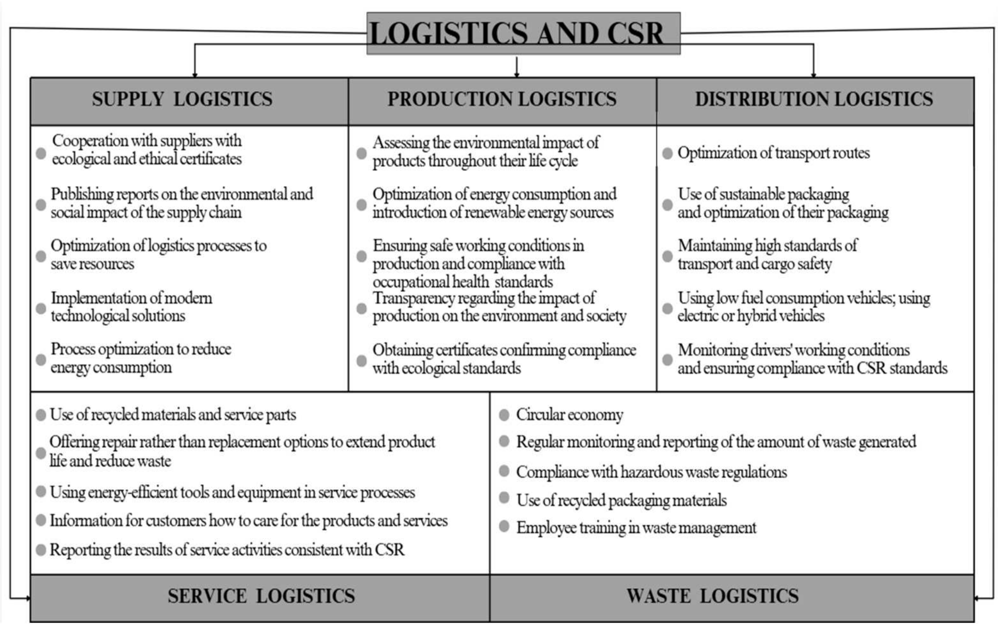


Figure 6.1. Relationship between logistics and CSR

Source: Own study.

The decision regarding the implementation of activities related to sustainable development depends on the individual capabilities of a given organization. Table 6.2 highlights selected logistics areas, their goals and selected benefits from the implementation of sustainable logistics.

The application of sustainable development in the sphere of logistics, covering the area of supply, production, distribution, service and waste, can bring measurable benefits to economic entities, both economic and environmental. Sustainable practices lead to the optimization of logistics processes, minimize the negative impact on the environment, increase the efficiency of resource reuse and build trusted relationships between the company and its stakeholders. Implementation of the CSR concept can lead to maintaining the loyalty of customers focused on social and ecological issues, gaining a competitive advantage thanks to an innovative offer, increasing efficiency by reducing energy consumption, maintaining a positive brand image, and attracting investors interested in the sustainable operation of the company. Meeting social and ecological expectations by companies therefore contributes to creating a long-term and lasting competitive advantage.

Table 6.2. Selected logistics areas, their goals and selected benefits from the implementation of sustainable logistics

Logistics area	Area goals	Selected benefits of implementing of sustainable logistics
Supply logistics	Identification of supply sources Shopping time schedule Price determination and negotiation Maintaining Material Inventories Monitoring the quality of delivered products	Sustainable order management will reduce storage costs Sustainable supplier evaluation criteria will improve the quality and stability of supplies, building trusted relationships
Production logistics	Reducing travel distances to a minimum Elimination of unnecessary material manipulation	Reducing transport distances will contribute to reducing the carbon footprint The use of ecological materials will allow for rational use of resources
Distribution logistics	Location of distribution warehouses and organization of the distribution network Selection of means of transport and optimization of transport routes	Rational organization of the distribution network will increase the efficiency of the entire supply chain Using vehicles with reduced emissions will reduce operating costs and fuel consumption
Service logistics	Supplying buyers with spare parts After-sales activities Handling of returns	Providing consumers with replacement parts will reduce excess inventory and lower storage costs Selling returnable products at a reduced price will reduce waste
Waste logistics	Transport and storage of production waste that is not suitable for use in other processes Managing waste flow to reuse sites	Disposing of waste in a non-invasive way will improve the quality of the natural environment Effective management of waste flows for recycling will increase the efficiency of resource reuse

Source: Own study.

Research methodology

An important aspect in the analysis of socially responsible actions is, above all, the fulfilment of the sustainable development goals. As the definition indicates: "the seventeen sustainable development goals are a plan of action for people, the planet and prosperity" (Organizacja Narodów Zjednoczonych, Zgromadzenie Ogólne, 2015), the intention of which is to intensify peace in conditions of freedom. All elements have been included in the 2030 Agenda for Sustainable Development (Organizacja Narodów Zjednoczonych, Zgromadzenie Ogólne, 2015) and are gradually being implemented by all stakeholders in mutual cooperation.

The implementation of the research objectives was possible as a result of the analysis of the applied good practices related to sustainable development in the logistics companies based on data from the Responsible Business Forum, covering the years 2021-2023 (Forum Odpowiedzialnego Biznesu, 2024). Information was collected on the number of Sustainable Development Goals met by companies from the logistics industry and the coefficient of variation of these goals was calculated in the analyzed period. This allowed for determining the trends of individual goals. The study also allowed for the identification of the sustainable development goals that were most intensively implemented by the logistics companies, as well as those that were least involved. The analysis provided conclusions on the priorities in this industry, at the same time indicating guidelines for companies wishing to direct their activities towards sustainable development.

Analysis of the variability of the implementation of sustainable development goals in the logistics companies in 2021-2023

Companies that are involved in the CSR concept submit their good practices related to sustainable development and social reports to the Responsible Business Forum Association. The Association, in turn, enables the analysis of these practices and the determination of which Sustainable Development Goals are being implemented as a result of assigning them to specific activities. The Sustainable Development Goals, according to the 2030 Agenda for Sustainable Development, concern the following aspects: No Poverty [C1], Zero Hunger [C2], Good Health and Well-being [C3], Quality Education [C4], Gender Equality [C5], Clean Water and Sanitation [C6], Affordable and Clean Energy [C7], Economic Growth and Decent Work [C8], Innovation, Industry and Infrastructure [C9], Reduced Inequalities [C10], Sustainable Cities and Communities [C11], Responsible Consumption and Production [C12], Climate Action [C13], Life Below Water [C14], Life on Land [C15], Peace, Justice and Strong Institutions [C16] and Partnerships for the Goals [C17] (United Nations, General Assembly, 2015). As part of the analysis of the fulfilment of the Sustainable Development Goals in the practice of the logistics companies, a summary of reported good practices from 2021-2023 was developed (Table 6.3). Table 6.3 presents the number of Sustainable Development Goals fulfilled in each year, as well as the arithmetic mean, standard deviation and coefficient of variation for each goal, based on data from three years.

Enterprises have the opportunity to submit good practices to the Responsible Business Forum Association, which acts as a coordinator and promoter of activities for sustainable development and corporate social responsibility in Poland (Forum Odpowiedzialnego Biznesu, 2024). In response to the growing interest in transparency and the need to analyze such activities, the Association has launched a dedicated website that allows you to browse reported practices according to various criteria. Users of the site can search for practices by thematic area, industry, source document, sustainable development goals or a specific company. Based on the available search tools, an analysis of good practices in the logistics industry was carried out, in particular in terms of their compliance with the sustainable development goals. As part of this analysis, it was examined which sustainable development goals were assigned to individual practices in 2021, 2022 and 2023. Based on the collected data, a table was created that contains a summary and the number of individual goals assigned to reported practices in each of these years, which allows for the identification of trends and changes in the approach of enterprises to sustainable development in the analyzed industry.

Table 6.3. Meeting the sustainable development goals in 2021-2023 through good practices by the logistics companies

Objective SD	Number of times a given sustainable development goal has been met			Arithmetic mean	Standard deviation	Coefficient of variation
	2021	2022	2023			
	xi					
C1	3	3	0	2	1,732	86,603
C2	2	1	0	1	1	100
C3	25	19	8	17,333	8,622	49.74
C4	22	5	8	11,667	9,074	77,775
C5	4	6	2	4	2	50
C6	0	0	0	0	0	-
C7	1	1	2	1,333	0.577	43,301
C8	18	12	14	14,667	3,055	20.83
C9	5	4	3	4	1	25
C10	8	9	3	6,667	3,215	48,218
C11	9	1	4	4,667	4,041	86,603
C12	10	1	12	7,667	5,859	76,428
C13	11	3	5	6,333	4,163	65,737
C14	0	0	0	0	0	-
C15	3	3	0	2	1,732	86,603
C16	2	4	1	2,333	1,528	65,465
C17	1	9	1	3,667	4,619	125,967
	Σ124	Σ81	Σ63	89,333	31,342	35,085

Source: Own study based on (Forum Odpowiedzialnego Biznesu, 2024).

Table 6.3 shows that the largest number of sustainable development goals was met by companies from the logistics sector in 2021 (124), while a systematic decrease was noted in the following years: 2022 (81) and 2023 (63). The coefficient of variation, calculated based on data from three years, is 35.085. This value indicates a moderate level of dispersion of the results of the implementation of sustainable development goals in the analyzed period. In the context of typical values for this indicator, the coefficient of variation with such a calculation suggests significant variability in the implementation of goals, which may indicate diversity in the effectiveness of actions taken by companies in the logistics sector. The lowest coefficient of variation for specific goals, indicating that the number of goals met over the three years is stable, concerns Goal 8 – Decent Work and Economic Growth (20.83), Goal 9 – Innovation, Industry and Infrastructure (25), Goal 7 – Affordable and Clean

Energy (43.301), Goal 3 – Good Health and Well-being (49.740) and Goal 5 – Gender Equality (50). This indicates that companies are consistently committed to these goals, which indicates their stable commitment. The highest coefficient of variation for Goal 17 – Partnerships for the Goals (125.967) and Goal 2 – Zero Hunger (100) indicate a significant divergence in the implementation of these goals over the period analyzed. This means that the commitment to these goals is varied, which may suggest instability or variability in the actions taken and their effectiveness. Such high variability may indicate uneven progress and various challenges related to achieving these goals.

Implementation of sustainable development goals in the logistics companies

The analysis assessed the implementation of sustainable development goals by companies in the logistics industry in the years 2021-2023. The study made it possible to identify the goal most intensively implemented in this industry, as well as to determine the goals that are least engaged. The analysis provides conclusions on priorities and areas requiring further attention and development in the context of sustainable development.

The selected tool for prioritizing factors influencing the studied phenomenon is the Pareto-Lorenz Diagram (Masiukiewicz, 2019). To perform this analysis, the fulfilled sustainable development goals were ranked from the most frequently occurring in 2021-2023 to the least implemented goal by companies from the logistics industry (Table 6.4).

Table 6.4. Fulfilment of sustainable development goals in 2021-2023 through the implementation of good practices by the logistics companies – analysis

No.	Symbol	Sustainable development goal met in 2021-2023*	Quantity	Percent
1.	C3	Good health and well-being	52	19.40299
2.	C8	Decent work and economic growth	44	16.41791
3.	C4	Quality education	35	13.05970
4.	C12	Responsible consumption and production	23	8.58209
5.	C10	Reduced inequalities	20	7.46269

6.	C13	Climate action		19	7.08955
7.	C11	Sustainable cities and communities		14	5.22288
8.	C5	Gender equality		12	4.47761
9.	C9	Industry, innovation and infrastructure		12	4.47761
10.	C17	Partnerships for the goals		11	4.10448
11.	C16	Peace, justice and strong institutions		7	2.61194
12.	C1	No poverty		6	2.23881
13.	C15	Life on land		6	2.23881
14.	C7	Affordable and clean energy		4	1.49254
15.	C2	Zero hunger		3	1.11940
16.	C6	Clean water and sanitation		0	0
17.	C14	Life below water		0	0
				= 268	**= 100%**

*Icons of sustainable development goals retrieved from (Ośrodek Informacji ONZ, 2024).

Source: Own study based on (Forum Odpowiedzialnego Biznesu, 2024).

The Pareto-Lorenz diagram created from the data taken from Table 6.4 is presented in Figure 6.2.

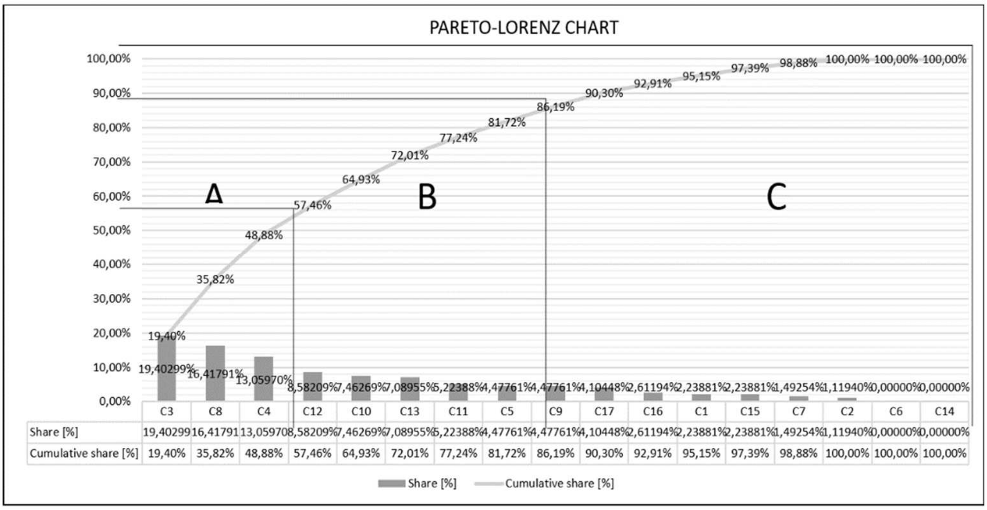


Figure 2. Pareto-Lorenz chart of sustainable development goals fulfillment by logistics companies in 2021-2023

Source: own elaboration based on Table 4 and (Forum Odpowiedzialnego Biznesu, 2024).

The analysis indicates that the goals with the highest degree of implementation and the greatest impact on the implementation of the corporate social responsibility strategy in this industry are Goal 3, Goal 8, Goal 4 and Goal 12. In the context of achieving sustainable development goals, companies in the logistics industry implement several practices related to specific goals. Goal 3 – Health and quality of life, focuses on areas related to health prevention, which includes both employee health care and consumer safety. Initiatives for the development of local communities and the integration and support of employees are also important elements. These practices include organizing training, employee volunteering and conducting dialogue with employees and stakeholders, which helps improve the overall health and safety at work. Goal 8 – Economic growth and decent work, including practices promoting fair and ethical operating standards. Companies emphasize the development of an organizational culture, providing a safe work environment and supporting employee participation. As part of this goal, companies strive to improve organizational order and effective management, as well as to maintain an open dialogue with employees. Goal 3 – Good quality education, focuses on activities supporting education and community development. Practices include support for employees and their families, involvement in the development of local communities and education of children and youth. Companies cooperate with universities, promote environmental and market education, and support cultural and artistic initiatives, which contribute to the increase in the overall quality of education. Goal 12 – Responsible consumption and production, refers to the implementation of pro-ecological practices. Companies use eco-efficient solutions, promote sustainable transport and implement pro-environmental programs such as eco-office, recycling and zero waste. These practices also include eco-construction, which contributes to reducing the negative impact of companies' activities on the environment. Analysis of the implementation of sustainable development goals by companies from the logistics industry in 2021-2023 also revealed that the goals with the least degree of implementation are Goal 7 – Clean and affordable energy and Goal 2 – Zero hunger. The low level of commitment to these goals may be related to technological and cost challenges that limit their implementation in this industry. Furthermore, goals such as Goal 6 – Clean Water and Sanitation and Goal 14 – Life Below Water were not implemented at all, suggesting their low priority in the context of the activities of the logistics industry.

The Sustainable Development Goals are a universal appeal to act to ensure peace and prosperity for people and protect the planet. Logistics companies integrate the principles of sustainable development into their business strategies and comprehensively cover both economic, ecological and social aspects. The response of companies to challenges creates a culture of social responsibility in organizations towards the company itself and its stakeholders. Companies implementing good practices invest in human resources, environmental protection and relations with their environment, and informing about these activities by creating social reports or reporting good practices to the Responsible Business Forum is a kind of driving force for innovation, which strengthens their value on the market. It is also worth paying attention to the constantly growing number of investors who take into account sustainable development criteria when making decisions about shares in companies (Grötsch, 2022). Building trust and credibility among stakeholders leads to deepening the bonds and strengthening the relationships between the company and its stakeholders. On the other hand, those interested in verifying the activities of socially responsible companies often express a desire to change their attitude to a more sustainable one.

Logistics companies are truly fulfilling the SDGs, particularly by contributing to improving the quality of life and education and playing a key role in increasing operational efficiency, which leads to economic growth. Implementing socially responsible activities therefore represents a huge opportunity to introduce positive change on a global scale. Companies are raising industry standards, but also inspiring other sectors to adopt more sustainable practices. Through these initiatives, the logistics industry is contributing to building a more just, sustainable and prosperous world for future generations.

Conclusion

The implementation of corporate social responsibility principles in logistics companies is a key element in building long-term strategies that bring benefits to the organization and its stakeholders. Companies from the logistics sector actively implement sustainable development strategies, shaping business models in line with the sustainable development goals. The organization's commitment is demonstrated by regular publication of social reports and reporting of good practices, which allows for transparent communication of pro-ecological and social activities to stakeholders and society. The implementation of sustainable development goals by these companies contributes not only to environmental protection and improvement of social conditions but also strengthens their reputation and builds trust among stakeholders. Despite existing challenges, such as high implementation costs, and lack of specific guidelines on how to conduct more sustainable business, numerous examples of good practices show that the benefits of implementing sustainable strategies are significant and real. Thanks to these initiatives, companies play a key role in striving for a more sustainable future, positively affecting the entire sector and the global economy. In the long term, a sustainable approach to business and investments in new technologies and operational processes can increase efficiency, reduce costs and open up new markets. Companies that prioritize sustainability can gain a competitive advantage by building customer loyalty and a reputation as industry leaders. In this way, sustainability efforts have broad and long-lasting effects that transcend the boundaries of individual companies, affecting the global economy and the future of our planet. Encouraging other sectors to follow similar initiatives can lead to coordinated sustainability efforts, which is essential to achieving global environmental, social and economic goals.

The survey of the implementation of CSR principles in logistics companies reveals certain data limitations. The analysis is primarily based on information reported by companies on good CSR practices, which may result in selective reporting. It is possible that the data do not reflect the full range of actual practices within the industry. Furthermore, the observed variability in the implementation of sustainability goals may be indicative of the volatility of companies' engagement in these areas.

To further advance the field of knowledge on this topic, we propose additional views for future research. It seems that expanding the evidence base, incorporating additional data sources and including the viewpoint of independent CSR audits, may provide a more objective representation of practices in the logistics sector. Concurrently, further monitoring is required to ascertain which objectives can be pursued more effectively and which strategies can enhance their sustainability. Similarly, it appears crucial to analyse the reasons for low commitment to certain objectives and to investigate methods by which companies can more effectively integrate these objectives into their strategies.

References

Cheng, F., Zhang, Y., & Wang, J. (2021). Economic policy uncertainty exposure and stock price bubbles: Evidence from China. *International Review of Financial Analysis*, 88, 201961.

Derdak, P., & Kowalska, M. (2023). *Zrównoważony rozwój przedsiębiorstw transportu wodnego w Polsce – ewaluacja*. In M. Kowalska, (ed.), *Wybrane problemy logistyki i usług turystycznych. Analiza sektorowa, zrównoważony rozwój, rachunkowość* (83-90). Wydawnictwo Rys.

Derdak, P., & Misztal, A. (2023). *Zrównoważony model biznesowy przedsiębiorstwa transportowego w dobie zmian geopolitycznych*. In M. Kowalska (ed.), *Wybrane problemy logistyki i usług turystycznych. Analiza sektorowa, zrównoważony rozwój, rachunkowość* (35-44). Wydawnictwo Rys.

Euramco (2024). *Environmental, social & governance (ESG).* https://www.euramco-asset.de/glossar/environmental-social-governance-esg/ (access: 31.07.2024).

Forum Odpowiedzialnego Biznesu (2024). *Dobre praktyki.* https://odpowiedzialnybiznes.pl/dobre-praktyki/ (access: 23.06.2024).

Govindan, K., & Hasanagic, M. (2018). A systematic review on drivers, barriers, and practices towards circular economy: a supply chain perspective. *International Journal of Production Research*, 56(1-2), 278-311.

Grötsch, A. (2022). Corporate Social Responsibility (CSR) – Status Quo und Ausblick. *Bavarian Journal of Applied Sciences*, 41-43.

Hunjra, A.I., Ali, S., & Zhang, Z. (2022). Sustainable development: The impact of political risk, macroeconomic policy uncertainty and ethnic conflict. *International Review of Financial Analysis*, 84.

Karama, A.S., Orazalin, N., Uyar, A., & Shahbaz, M. (2021). CSR achievement, reporting and assurance in the energy sector: does economic development matter? *Energy Policy*, 149, 16.

Masiukiewicz, P. (2019). Analityka predykcyjna – teoria i praktyka. *Zeszyty Naukowe Towarzystwa Naukowego Prakseologii*, 1(2019), 24.

Novitasari, M., & Agustia, D. (2022). The role of green supply chain management and green innovation in the effect of corporate social responsibility on firm performance. *Gestão & Produção*, 29, 117.

Organizacja Narodów Zjednoczonych, Zgromadzenie Ogólne (2015). *Przekształcamy nasz świat: Agenda na rzecz zrównoważonego rozwoju 2030.* Rezolucja Nr 70/1 z dnia 25 września 2015 roku (A/RES/70/1).

Ośrodek Informacji ONZ (2024). *Cele zrównoważonego rozwoju.* https://www.un.org.pl/download (access: 02.07.2024).

Polski Komitet Normalizacyjny (2013). *ISO 26000.* https://pkn.pl/informacje/2013/09/iso-26000 (access 24.08.2024).

Sikora, A. (2022), *Wykorzystanie CSR w nowoczesnej strategii przedsiębiorstw w Polsce*, In: D. Ossowska-Salamonowicz & M. Giżyńska (eds.), *Aktualne problemy badawcze – Nauki społeczne i humanistyczne* (pp. 35-43). Wydawnictwo Naukowe FNCE.

Singh, J., Singh, H., & Kumar, A. (2020). Impact of lean practices on organizational sustainability through green supply chain management–an empirical investigation. *International Journal of Lean Six Sigma*, 11(6), 1035-1068.

Solarin, S.A., & Bello, M.O. (2021). Output and Substitution Elasticity estimates between renewable and non-renewable energy: Implications for economic growth and sustainability in India. *Environmental Science and Pollution Research*, 28(46), 65313-65332.

Theeraworawit, M., Suriyankietkaew, S., & Hallinger, P. (2022). Sustainable Supply Chain Management in a Circular Economy: A Bibliometric Review. *Sustainability*, 14(15), 9304.

Uyar, A., Karaman, A.S., & Kilic, M. (2020). Is corporate social responsibility reporting a tool of signaling or greenwashing? Evidence from the worldwide logistics sector. *Journal of Cleaner Production*, 253.

Walczyński, M., & Kanciak, W. (2023). Koncepcja modelu logistyki zwrotnej w branży e-commerce jako możliwość do osiągnięcia celów zrównoważonego rozwoju. *Zeszyty Naukowe Akademii Górnośląskiej*, 6(2023), 155.

Wysokińska, Z., & Witkowska, J. (2016). *Zrównoważony rozwój, Wybrane aspekty makro- i mikroekonomiczne*. Łódź: Wydawnictwo Uniwersytetu Łódzkiego, 156-160.

Younis, H., Sundarakani, B., & Vel, P. (2016). The impact of implementing green supply chain management practices on corporate performance. *Competitiveness Review*, 26(3), 216-245.

Zaborek, P. (2021). *Społeczna odpowiedzialność biznesu a wyniki przedsiębiorstw*. SGH Oficyna Wydawnicza, 30.

Zapałkowska, A. (2022). Innowacyjne praktyki zrównoważonego rozwoju w logistyce. *Polish Journal for Sustainable Development*, 26(2), 78.

Chapter 7

Advancing Sustainable Development: Transport's Decarbonization Pathways to Carbon Neutrality in Poland

Oksana Seroka-Stolka

Czestochowa University of Technology, Faculty of Management, Poland
o.seroka-stolka@pcz.pl ORCID 0000-0003-2044-4875

Abstract: Poland, like many countries worldwide, is at a pivotal point in its pursuit of climate neutrality as an element of sustainable development. The quest for sustainable development has emerged as a key goal for nations globally, motivated by the urgent need to address climate change. Within this context, the transport sector plays a pivotal role due to its significant contribution to greenhouse gas emissions. As nations strive to achieve carbon neutrality, decarbonizing transport emerges as a crucial element of this transition. Regulation (EU) 2021/1119, enacted by the European Parliament and the Council on June 30, 2021, sets the framework for achieving climate neutrality, presenting a significant challenge in reducing GHG emissions by 2050. This landmark legislation outlines a comprehensive strategy for the EU to attain net-zero greenhouse gas emissions by 2050. It includes various measures to reduce GHG emissions, with a specific commitment to reducing emissions in the transport sector. The regulation marks a crucial step towards climate neutrality in transport by 2050, providing a detailed framework for decarbonization and setting binding targets for GHG emission reductions. It also establishes a monitoring and evaluation system to ensure these targets are achieved. To reach climate neutrality, the transport sector must significantly cut CO_2 emissions. This chapter aims to investigate CO_2 emissions from transport in Poland using available data and to present potential scenarios for reducing CO_2 emissions. The results indicate that carbon dioxide emissions from transport have increased since 1999. Scenario analyses suggest that the transport sector will be primarily responsible for meeting climate neutrality goals. Consequently, Poland must reduce transport CO_2 emissions by approximately 60% by 2050 compared to 2005 levels. Specifically, by 2050, emissions from passenger road transport should be around 6.8 Mt CO_2, and emissions from freight transport should be approximately 6.4 Mt CO_2.

Keywords: environmental sustainability, transport, decarbonization, neutrality, transport, Poland

Introduction

Advancing sustainable development through the decarbonization of transport is essential for achieving carbon neutrality and mitigating climate change. This approach not only reduces the negative impacts of climate change but also promotes economic resilience and environmental stewardship. The ambitious goal of achieving climate neutrality by 2050 requires transformative changes across various sectors. Since transport is a significant contributor to global greenhouse gas emissions, making the transition to low-carbon transport a priority.

Thus, decarbonizing the Polish transport sector is crucial to meeting these climate objectives. A climate-neutral economy is defined by attaining net-zero greenhouse gas emissions, where any emissions generated are counterbalanced by actions that extract CO_2 from the atmosphere, such as reforestation or carbon capture and storage. Reaching climate neutrality is also crucial to global initiatives aimed at combating climate change and restricting global warming to 1.5 degrees Celsius above pre-industrial levels, as specified in the Paris Agreement (Delbeke, 2024). What is more, the burning of fossil fuels still remains a significant source of global CO_2 emissions (Doan et al., 2024). Carbon dioxide, accounting for 58% of the total global energy consumption from combustion processes, is considered one of the most important greenhouse gases. Furthermore, within the EU, the transport and energy sectors are the primary sources of greenhouse gas emissions (EEA, 2023). In 2018, transport accounted for nearly 34% of total energy consumption and over 25% of total carbon dioxide (CO_2) emissions in European Union countries (European Environmental Agency Database, 2020). Transport is a significant emitter of greenhouse gases (Rehman et al., 2023), accounting for about 75% of global CO_2 emissions and 70% of CO_2 emissions in the European Union (Zhang et al., 2022). The growing demand for transport is reflected in increased traffic congestion and energy consumption, which in turn leads to higher emissions (Edenhofer et al., 2015). The Poland's emissions mainly originate from four primary sectors: transport, buildings, agriculture, and the energy industry (Brzeziński, & Kolinski, 2024). Poland's transport sector heavily dependents on coal, natural gas, and oil. Although Poland has been slow to embrace renewable energy, it has begun to implement a decarbonization strategy aimed at transitioning to a climate-neutral economy. Notably, in 2019, Poland's transport sector was responsible for 15% of global greenhouse gas emissions, highlighting the urgent need for decarbonization efforts (Pyra, 2023). However, the transport sector holds significant potential for reducing greenhouse gas emissions and energy consumption especially in urban areas.

Thus, examining the decarbonization efforts within Poland's transport sector is essential. This article examines the current state of CO_2 emissions within the transport sector, particularly in Poland, and projects future scenarios to identify effective decarbonization approaches. It also analyzes CO_2 emissions from the transport sector, both historically and prospectively, to present possible future scenarios using available data.

The structure of the paper is as follows: The first section reviews the decarbonization of transport and discusses its contribution to carbon emissions in Poland. The next section, on research methodology and data, outlines the data and methods used in the study. Then, scenarios for reducing GHG emissions in the transport sector, with a focus on achieving neutrality, are presented. The discussion section examines the findings, while the conclusion section highlights practical implications for policymakers, acknowledges the study's limitations, and suggests directions for future research.

Literature review

Reducing carbon dioxide emissions from the transport sector has become a central objective in the global fight against climate change (Beccarello, & Foggia, 2023). Currently, one of the most thought-provoking topics in climate change literature is the exploration of strategies and pathways to achieve decarbonization (Tsoi et al., 2021).

Unfortunately, decarbonization involves numerous variables and uncertainties, making it difficult to pinpoint a single path forward. By using scenario analysis, it is possible to explore various potential routes to achieve decarbonization goals (Rabiega, et al., 2019). In pursuit of these goals, the Paris Agreement has significantly driven nations to implement strong measures to prevent global temperature rise. Transitioning to renewable energy and sustainable fuels for transport is a feasible global solution, requiring active involvement from all stakeholders (Bogdanov, 2021). The transport sector plays a significant role in global CO_2 emissions. In Poland, transport accounted for 15% of the country's greenhouse gas emissions in 2021. Although there have been global reductions in pollutant emissions since 1990, the extent of these reductions varies across different modes of transport (Pyrka et al., 2022). In Poland, transport also leads to significant energy consumption. The energy requirements of transport systems vary based on the specific transport sector and the type of cargo being moved (Kierzkowski & Tubis, 2023). The transport of goods in Poland also accounts for 9% of the total freight transport in the EU. In the context of achieving climate neutrality by 2050, a significant transformation of freight transport methods is necessary.

Figure 7.1 illustrates that from 1990 to 2022 CO_2 emissions from transport have increased, highlighting a persistent upward trend in Poland's transport sector. Despite efforts to mitigate emissions, this rising trend continues. Figure 7.2 shows that CO_2 emissions in Poland in 2022 were 8.53 t/cap/yr, which remains above the global average (4.84 t/cap/yr in 2022). On a more positive note, CO_2 emissions per unit of GDP have decreased to 0.23 t CO_2/kUSD/yr, indicating some progress in reducing the carbon intensity of the economy.

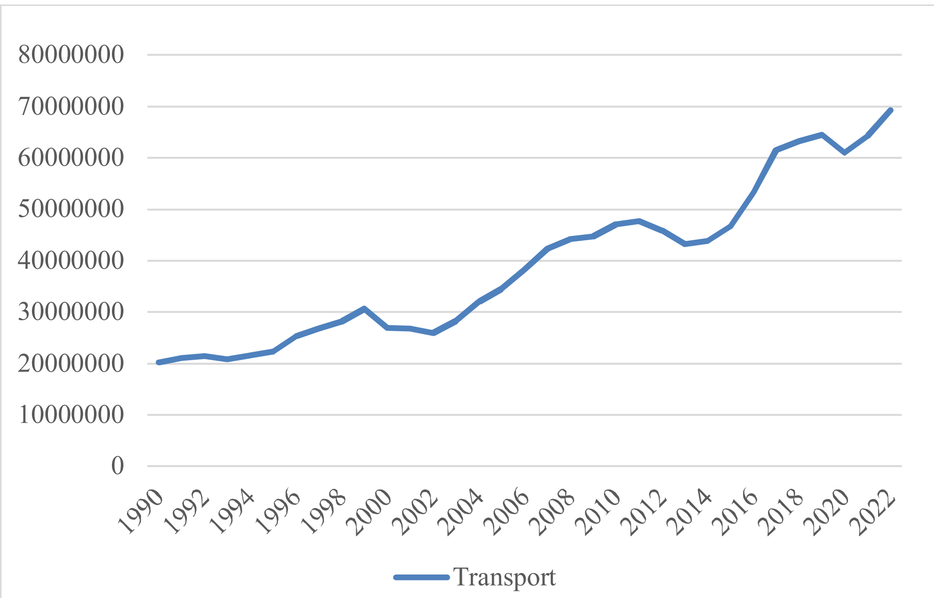


Figure 7.1. CO_2 emissions from transport in Poland in tons (1990-2022)

Source: Based on EDGAR-Emissions Database (https://edgar.jrc.ec.europa.eu/country_profile/POL).

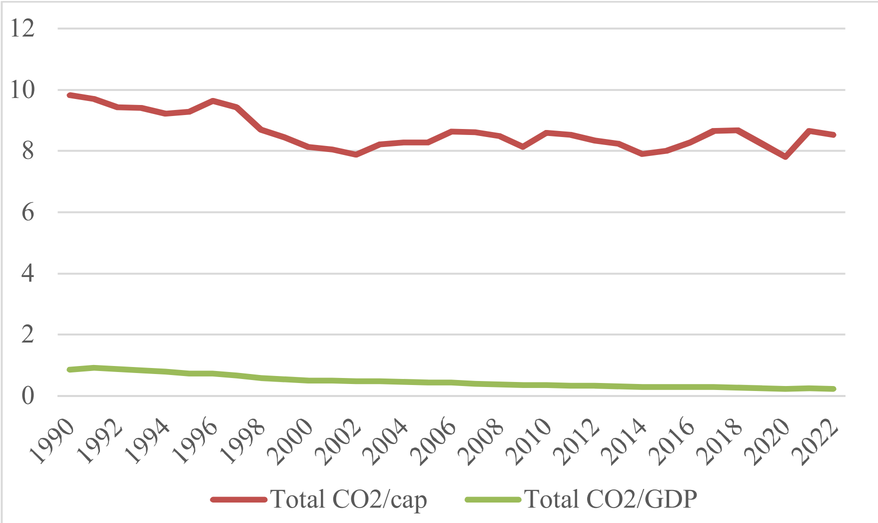


Figure 7.2. Total CO_2 emissions in Poland (1990- 2022) (total CO_2/GDP and total CO_2 /cap)

Source: Own elaboration based on EDGAR-Emissions Database (https://edgar.jrc.ec.europa.eu/climate_change).

Research methodology and data

This research primarily adopts a methodological approach that involves a literature review, focusing on national reports that describe the most realistic scenarios for transport transformation in Poland. These scenarios are quantified and compared. The study also makes use of publicly accessible secondary data sources. To examine the decarbonization process of the transport sector in Poland, data from multiple sources were utilized. The primary data set is sourced from the EDGAR-Emissions Database, which offers detailed emissions information at the country, regional, and even city levels, spanning several decades. Additionally, data from the European Environmental Agency (EEA) database were also collected. The CO_2 emissions data in the EEA database can be used to monitor progress towards the EU's emission reduction targets. EEA database provides local-level data, enabling a more detailed analysis of emissions patterns and trends. Thirdly, the study drew on national resources like the KOBIZE[1] database and publications from the National Centre for Emissions Management. This government agency, tasked with overseeing emissions data collection and management, covers a range of sectors including energy, transport, industry, and agriculture.

The study primarily focused on the period from 1990 to 2022, utilizing available data. For analyzing CO_2 emission reduction scenarios (BAU, REF, and NEU), two key timeframes were established: 2030 to 2050, with comparisons to the base years

[1] KOBIZE – the National Centre for Emissions Management in POLAND.

of 2005 and 1990. The Base Scenario (BAU) projects a 60% reduction in emissions by 2050 relative to 1990, excluding the land use and forestry sector (LULUCF). The Reference Scenario (REF) targets an 80% reduction by 2050 compared to 1990, also excluding LULUCF. The Neutrality Scenario (NEU) anticipates a 90% reduction by 2050 compared to 1990, achieving net-zero emissions through the use of carbon sequestration technologies, including contributions from LULUCF. Across all scenarios (BAU, REF, and NEU), it was assumed that the electricity and heat sectors would play a significant role in meeting emission reduction targets at both the national and EU levels. The analysis also considered a time horizon from 2015 to 2050, which is critical for evaluating the impact of energy-climate policies and achieving GHG reduction goals.

A comparison of scenarios for reducing GHG emissions in non-ETS sectors in Poland and the UE

Given the transport sector's substantial role in CO_2 emissions and the emergence of new technologies, analyzing emission reductions in this area has become increasingly critical. Numerous studies have explored different strategies and pathways for reducing carbon emissions within the sector (Meckling, & Jenner, 2016). Each country formulates its own development scenarios to identify feasible directions of development that support the formulated policy objectives (Snoek, 2003). However, it is important to mention that emissions of GHG, including CO_2 emissions from transport, fall within the so-called non-ETS area, which is not subject to a unified community reduction mechanism. Non-ETS refers to domestic greenhouse gas emissions that are not regulated by the European Union Emission Trading Scheme (EU ETS). These non-ETS emissions encompass sectors such as transport, agriculture, waste management, industrial emissions outside the EU ETS. EU member states are responsible for managing emissions in the non-ETS area, implementing national reduction targets as part of the EU's effort-sharing agreement. Consequently, GHG emission reduction strategies may differ between member states, leading to variations in the cost of reducing emissions in the non-ETS area. Furthermore, considering different GHG reduction scenarios – such as baseline, reference, and neutrality-the costs associated with reducing CO_2 emissions in ETS sectors (like energy sector) and non-ETS sectors (like transport) can vary significantly. It is also notable that in Poland, the volume of non-ETS emissions is roughly equivalent to that of EU ETS emissions, while across the EU, non-ETS emissions constitute approximately 55% of total emissions (KONIZE data base 2023).

In Table 7.1 are presented various GHG reduction scenarios both for the EU and Poland. In the baseline scenario (BAU) and the reference scenario (REF), it is assumed that the legislation introduced as part of the European Commission's package will be implemented by 2030, as well as the greenhouse gas reduction target, which is to reduce EU emissions by at least 40% by 2030 compared to 1990. The neutrality scenario (NEU) is based on the revised EU climate policy and assumes an increase in the net reduction target for 2030 to at least 55% compared to 1990 emissions and achieving net-zero emissions by 2050. According to the neutrality scenario – NEU, it was established that non-ETS sectors would reduce their emissions by 40% compared to the 2005 level. It is crucial to note that the burden-sharing between ETS and non-ETS sectors is influenced by the comparatively lower costs of emission reduction in sectors under the EU ETS, in contrast to the higher costs in non-ETS sectors such as transport, agriculture, and the residential sector. To meet the EU's community reduction target of approximately 90% by 2050, non-ETS sectors must achieve an 82% reduction in emissions by the same year, following the adoption of specific reduction levels for EU ETS sectors. Table 7.1 outlines Poland's emission reduction targets for the transport sector, which include an 18% reduction by 2030 compared to 2005 levels, and a 73% reduction by 2050 according to the neutrality scenario. The table also presents total GHG reduction scenarios for both EU ETS and non-ETS sectors for the years 2030 and 2050, relative to 1990 levels.

Table 7.1. GHG reduction scenarios for UE and Poland according to different scenarios (BAU, REF, NEU) for non-ETS sectors

Scenarios	2030 vs. 2005	2050 vs. 2005	2030 vs. 1990	2050 vs. 1990
			Total (UE, ETS and non-ETS sectors)	
BAU	UE – 30%	UE – 47%	42%	60%
	Poland – 7%	Poland – 31%		
REF	UE – 30%	UE – 75%	42%	80%
	Poland – 7%	Poland – 62%		
NEU	UE – 40%	UE – 82%	53%	90% (netto 100%)*
	Poland – 18%	Poland – 73%		

* The achieved greenhouse gas (GHG) reduction target, taking into account the absorption in the LULUCF (Land use, land use change and forestry) sector and greenhouse gas removal technologies from the atmosphere (such as biomass combustion with CCS technology).

Source: Own elaboration based on KOBIZE database. In parentheses are emission reduction figures for the non-ETS sector for Poland.

Decarbonizing the transport sector in the pursuit of carbon neutrality

Poland aims to cut carbon emissions from the transport sector by 30% by 2030 and by around 60% by 2050, relative to 2005 levels. This goal will be pursued through various strategies, including the promotion of electric vehicles, enhancement of public transport, and expansion of cycling infrastructure. To achieve climate neutrality under the NEU scenario, Poland needs to reduce CO_2 emissions in the transport sector to 16 Mt CO_2 by 2050. For 2030, the target reduction is set at 52 Mt CO_2. By 2050, emissions should be reduced by 46 Mt CO_2 in the BAU scenario and by 23 Mt CO_2 in the Reference (REF) scenario. Achieving these reduction targets necessitates focusing on cutting emissions across different types of transport (see Fig. 7.4).

Table 7.2 presents projected reductions in CO_2 emissions from the transport sector in Poland, divided between passenger and cargo transport for three different scenarios. All scenarios predict a decrease in CO_2 emissions from 2030 to 2050, with the NEU scenario showing the most significant reduction.

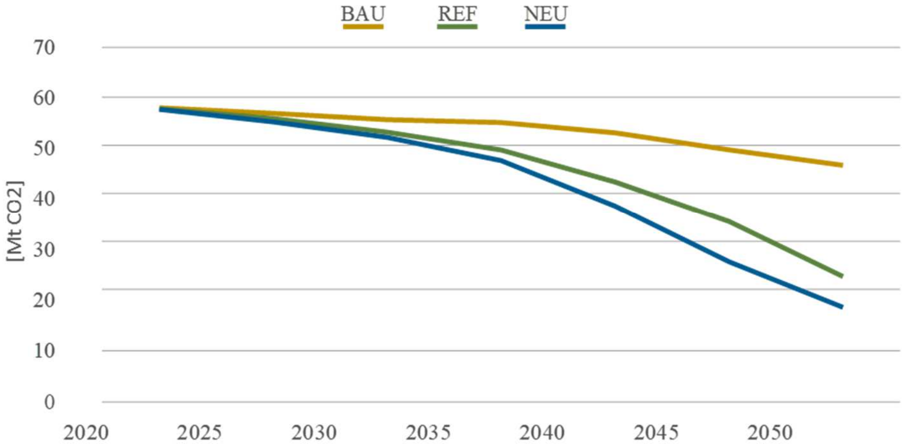


Figure 7.4. CO_2 emissions from the transport sector according to analyzed scenarios in Poland until 2050 (excluding emissions from electricity generation) [Mt CO_2]

Source: (Pyrka et al., 2022).

Table 7.2. Reduction of emissions in transport with a division between passenger and cargo transport (Mt CO_2) in Poland

Scenario	2030	2050	2030	2050	2030	2050
	Transport total including electricity demand [TWh]		Passenger transport	Cargo transport	Number of electric passenger cars [million units]	
BAU	55	46	1.7	0.2	1.0	5.2
REF	53	23	3.7	0.3	2.3	13.4
NEU	52	16	3.9	0.4	2.4	14.0

Source: Own elaboration based on (Pyrka et al., 2022).

Based on the data, it may be concluded that achieving climate neutrality will primarily depend on reducing CO_2 emissions from passenger transport. To reach climate neutrality goals, emissions from passenger road transport should be around 6.8 Mt CO_2 by 2050, and emissions from freight transport should be approximately 6.4 Mt CO_2. This suggests that newer policies (represented by NEU) could be more effective in reducing emissions compared to the NEU scenario. What is more, aviation emissions are projected to be about 2.6 Mt CO_2. Electrifying the passenger car fleet is expected to play a crucial role in achieving climate neutrality in passenger road transport, potentially reducing emissions to 5.5 Mt CO_2 by 2050. Additionally, emissions from buses are anticipated to decrease from approximately 2.5 Mt CO_2 in 2020 to around 1 Mt CO_2 by 2050 due to both electrification and a shift from road to rail public transport. However, it is important to note that international mobility growth is expected to more than double the demand for air transport between 2020 and 2050. Despite increased activity in aviation, emissions are projected to remain stable at around 2 Mt CO_2. Achieving this outcome will rely on reducing emissions intensity per passenger-kilometer, facilitated by technological advancements and the use of synthetic fuels.

Discussion

Decarbonizing transport has become a highly thought-provoking focus area to limit global warming and achieve climate policy goals. This study investigates CO_2 emissions from the transport sector using current data and aims to propose scenarios for reducing these emissions. The analysis suggests that achieving climate neutrality in Poland will largely depend on transforming the transport sector to low-emission modes. This transformation will primarily involve reducing CO_2 emissions from passenger transport, particularly from private cars, which contribute significantly to overall emissions. This transformation will be difficult due to the substantial growth in passenger and freight transport activities from 2000 to 2022, coupled with a moderate rise in their emission factors per unit of activity (Antosiewicz et al., 2022). Existing literature also supports the idea that the majority of CO_2 emissions reductions will occur within the private car road transport sector (Haasz, 2018). Multiple authors widely agree that greenhouse gas emissions from road transport pose a significant risk to urban air quality and contribute to global warming (Kok et al., 2011; Kopelias et al., 2020; Ong et al., 2011). In the case of road transport in Poland, pollutant emissions are primarily linked to the fuel combustion process, which contributes to air pollution (Mesjasz-Lech & Włodarczyk, 2022). Several authors have also explored the possibility of reducing CO_2 emissions in the private car road transport sector to achieve neutrality. Most research indicates that reducing greenhouse gas emissions in transport could be accomplished through substantial changes in markets and behaviors (Haasz, 2018; Stanley et al., 2011). Haasz (2018) suggests that the private car road transport sector accounts for the largest share of CO_2 emissions reduction. Several frequently studied policies include promoting the adoption of environmentally friendly automotive technologies, implementing standards for vehicles and fuels, and introducing tax incentives or financial support measures (Sims et al., 2014). AlSabbagh and Yusuf (2021) examined the policy environment aimed at reducing carbon emissions from road transport. They discovered that measures such as fuel taxes, vehicle taxes, and subsidies for electric vehicles can significantly decrease emissions from private cars. The authors emphasize the importance of designing policies thoughtfully to ensure fairness and avoid placing undue burden on lower-income households (AlSabbagh & Yusuf, 2021). Hall et al. (2019) analyzed how autonomous vehicles could affect cities. They concluded that while these vehicles might lower emissions by enhancing fuel efficiency and alleviating congestion, their widespread use does not guarantee an overall reduction in emissions. Therefore, a mix of policies is essential to incentivize the shift to low-emission vehicles and decrease the overall reliance on private cars (Hall et al., 2019). However, it is suggested that due to transport's ongoing reliance on fossil fuels, decarbonizing the transport sector is more challenging than decarbonizing other sectors (Pietzcker, 2014). Thus, because Poland mainly relies on fossil fuel resources, there is a need to transition from using non-renewable fossil fuels to renewable fuels (Żuk, 2023).

Conclusion

Decarbonizing Poland's transport sector poses a significant challenge, crucial for achieving the nation's goal of a climate-neutral economy by 2050. The Polish government has set ambitious targets to reduce carbon emissions by 30% by 2030, aiming for carbon neutrality by 2050. This highlights the need for greater focus on sectors like transport and agriculture in subsequent phases, which may involve more expensive measures. Achieving carbon neutrality in transport will require substantial investments in public transport, cycling infrastructure, and promotion of electric vehicles (including the development of new trams and bus lines and the improvement of existing infrastructure). Thus, a range of policies should be implemented to promote electric vehicles, including subsidies for the purchase of electric cars and the installation of charging infrastructure like quick charging stations). It is worth mentioning that the electrification of the passenger car fleet, and promotion of electromobility requires changing consumers' decisions when choosing a new car, through appropriately designed financial solutions such as subsidies for loans and low-interest loans. Investment in the development of hydrogen fuel cell technology, which has the potential to be utilized in heavy-duty vehicles such as trucks and buses, will be also required for the attainment of climate neutrality.

What is more, the transformation from using non-renewable fossil fuels to renewable and other sustainable fuels will be essential. Despite challenges, transitioning to a climate-neutral economy presents opportunities for Poland, including the growth of new industries and job creation through technologies like hydrogen fuel cells. Investments in public transport and cycling infrastructure can also enhance citizen quality of life and reduce air pollution. Overall, achieving climate neutrality by 2050 is a demanding yet vital objective for Poland and the global community.

The conducted analyses offer insights with practical implications. Policymakers must recognize that investing in new technologies is crucial to addressing the urgent issue of climate change. Reaching climate neutrality requires policies that promote the adoption of low-emission vehicles while ensuring fairness and avoiding disproportionate impacts on vulnerable populations. Moreover, the government must work closely with energy companies and local communities to ensure a smooth transition. However, the research has some limitations. The CO_2 emission analyses are confined to Poland and do not account for potential delays in political decision-making or the technical challenges of decarbonizing aviation and certain industrial sectors. Future research could explore achieving climate neutrality in other economically similar countries, such as the Visegrád Group.

References

AlSabbagh, B., & Yusuf, A. (2021). Decarbonizing road transport: A review of the policy landscape. *Journal of Cleaner Production*, 312, 127611. DOI: 10.1016/j.jclepro.2021.127611.

Antosiewicz, M., Gorzałczyński, A., & Rabiega, W. (2022). The role of public transport in Poland's efforts to achieve climate neutrality. *Climate| Society| Economy*, 57.
Beccarello, M., & Di Foggia, G. (2023). Review and perspectives of key decarbonization drivers to 2030. *Energies*, 16(3), 1345. DOI: 10.3390/en16031345.
Bogdanov, D., Ram, M., Aghahosseini, A., Gulagi, A., Oyewo, A.S., Child, M., ..., & Breyer, C. (2021). Low-cost renewable electricity as the key driver of the global energy transition towards sustainability. *Energy*, 227, 120467. DOI: 10.1016/j.energy.2021.120467.
Brzeziński, Ł., & Kolinski, A. (2024). Challenges of the green transformation of transport in Poland. *Sustainability*, 16(8), 3418.
Delbeke, J. (2024). *Delivering a Climate Neutral Europe.* New York: Routledge Taylor & Francis, 297.
Doan, N., Doan, H., Nguyen, C.P., & Nguyen, B.Q. (2024). From Kyoto to Paris and beyond: A deep dive into the green shift. *Renewable Energy*, 228, 120675.
Edenhofer, O. (ed.). (2015). *Climate Change 2014: Mitigation of Climate Change* (Vol. 3). Cambridge University Press.
European Environment Agency (EEA). (2023). Trends and projections in Europe 2023. EEA Report No 7/2023. https://www.eea.europa.eu//publications/trends-and-projections-in-europe-2023
Haasz, T., Vilchez, J.J.G., Kunze, R., Deane, P., Fraboulet, D., Fahl, U., & Mulholland, E. (2018). Perspectives on decarbonizing the transport sector in the EU-28. *Energy Strategy Reviews*, 20, 124-132.
Hall, J.W., Dawson, R.J., Barr, S.L., Batty, M., Bristow, A.L., Carney, S., ..., & Tight, M.R. (2019). The impact of autonomous vehicles on cities: A review. *Journal of Transport Geography*, 81, 102571. DOI: 10.1016/j.jtrangeo.2019.102571
Kierzkowski, A., & Tubis, A.A. (2023). Transportation systems modeling, simulation and analysis with reference to energy supplying. *Energies*, 16(8), 3586.
Kok, R., Annema, J.A., & van Wee, B. (2011). Cost-effectiveness of greenhouse gas mitigation in transport: A review of methodological approaches and their impact. *Energy Policy*, 39(12), 7776-7793.
Kopelias, P., Demiridi, E., Vogiatzis, K., Skabardonis, A., & Zafiropoulou, V. (2020). Connected & autonomous vehicles – Environmental impacts – A review. *Science of the Total Environment*, 712, 135237.
Meckling, J., & Jenner, S. (2016). Varieties of market-based policy: Instrument choice in climate policy. *Environmental Politics*, 25(5), 853-874. DOI: 10.1080/09644016.2016.1168062.
Mesjasz-Lech, A., & Włodarczyk, A. (2022). The role of logistics infrastructure in development of sustainable road transport in Poland. *Research in Transportation Business & Management*, 44, 100841. DOI: 10.1016/j.rtbm.2022.100841.
Ong, H.C., Mahlia, T.M.I., & Masjuki, H.H. (2011). A review on emissions and mitigation strategies for road transport in Malaysia. *Renewable and Sustainable Energy Reviews*, 15(8), 3516-3522.
Pietzcker, R.C., Longden, T., Chen, W., Fu, S., Kriegler, E., Kyle, P., & Luderer, G. (2014). Long-term transport energy demand and climate policy: Alternative visions on transport decarbonization in energy-economy models. *Energy*, 64, 95-108.
Pyra, M. (2023). A Scenario Analysis for the decarbonisation process in Poland's road transport sector. *European Research Studies Journal*, 26(1), 411-432.
Pyrka, M. i Aukcji, Z.S.A., Jeszke, R., & Tobiasz, I. (2022). Koszty i wyzwania w osiągnięciu celów polityki klimatycznej dla polskiej gospodarki do 2050 roku. *Klimat| Społeczeństwo| Gospodarka*, 33.
Rabiega, W., Sikora, P., & Gąska, J. (2019). CO_2 emissions reduction potential in Transport sector in Poland and the EU until 2050. Warsaw: The National Centre for Emissions Management (KOBiZE).

Rahman, N.A.A., Melewar, T.C., Foroudi, P., & Gupta, S. (2024). Conception, challenges, and commendation in logistics and transport sector. *Corporate Branding in Logistics and Transportation: Recent Developments and Emerging Issues*, 2.

Sims, R., Schaeffer, R., Creutzig, F., Cruz-Nunez, X., D'agosto, M., Dimitriu, D., ..., & Tiwari, G. (2014). Transport. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Stanley, J.K., Hensher, D.A., & Loader, C. (2011). Road transport and climate change: Stepping off the greenhouse gas. *Transportation Research* Part A: *Policy and Practice*, 45(10), 1020-1030.

Tsoi, K.H., Loo, B.P., & Banister, D. (2021). Mind the (policy-implementation) gap: Transport decarbonisation policies and performances of leading global economies (1990-2018). *Global Environmental Change*, 68, 102250. DOI: 10.1016/j.gloenvcha.2021.102250.

Zhang, H., Mu, J.E., McCarl, B.A., & Yu, J. (2022). The impact of climate change on global energy use. *Mitigation and Adaptation Strategies for Global Change*, 27, 1-19. DOI: 10.1007/s11027-021-09986-x.

Żuk, P. (2023). Soft power and the media management of energy transition: Analysis of the media narrative about the construction of nuclear power plants in Poland. *Energy Reports*, 9, 568-583. DOI: 10.1016/j.egyr.2022.11.192.

Websites

https://www.kobize.pl/en/article/non-ets/id/337/general-information. Date of publication: 25.07.2023

Chapter 8

OPTIMISATION OF MILKRUN-BASED MATERIAL SUPPLY THROUGH PROCESS INTEGRATION

Tamás Bányai

University of Miskolc, Institute of Logistics, Hungary
tamas.banyai@uni-miskolc.hu ORCID 0000-0002-0229-4781

Abstract: Milkrun processes are becoming a crucial aspect of modern manufacturing. These processes are structured into different sub-processes that optimize the transportation of goods within the production or assembly systems. Typically, milkrun processes are divided into two main sub-processes: the distribution of raw materials, components, and tools from a warehouse to manufacturing and assembly cells, and the collection of finished products, packaging materials, and tools from these cells back to the warehouse. In this chapter, the author describes a comprehensive analysis of how integrating these two sub-processes. By combining the separate sub-processes into an integrated approach, the paper argues, manufacturers can achieve significant gains in both time management and resource utilization. The author introduces a novel mathematical model that can be used to make a direct comparison between conventional milkrun processes, where distribution and collection operations are handled independently, and the integrated approach, where both sub-processes are combined into a seamless operation. The chapter presents the results of the numerical analysis that underline the benefits of integrated milkrun processes. According to the findings, integrating these sub-processes can increase logistics efficiency by up to 45%. This improvement is not just limited to time savings; it also extends to a reduction in the number of resources required to carry out the milkrun operations.

Keywords: energy consumption, in-plant supply, optimization, process integration

Introduction

Milkrun supply solutions play a critical role in enhancing the efficiency of production, manufacturing, and assembly systems. These systems streamline the transportation of materials and parts between suppliers, warehouses, and production lines, leading to significant reductions in inventory, transportation costs and logistics resources. The milkrun supply system not only influences the efficiency of logistics processes but also affects the overall efficiency of the production process. With an effectively functioning milkrun supply system, the availability, flexibility, efficiency, sustainability, and transparency of both production and logistics processes can be improved. According to a research presented by the Saloodoblog (Wolff, 2024), the benefits of the milkrun supply solutions are the followings: cost-effective operation, strong relationship between the players of the supply chain or value chain, sustainability by low energy consumption, support just-in-time and just-in-sequence supply. However, milkrun solutions are widely used in industry, but the complexity of operational processes requires a sophisticated logistics design.

The milkrun-based in-plant supply solutions are generally based on a conventional concept, where the collection and distribution operations are separated. It means that there are collection milkrun routes and distribution milkrun routes in the production or assembly plants. This separation of collection and distributions processes are generally based on the different characteristics of goods (components, final products, tools and fixtures, packaging materials) to be collected or distributed. Within the frame of this article, the author proposes a new approach, which focuses on the analysis of integrated milkrun supply solution to improve the efficiency of the production, assembly and logistics system.

This chapter is organised, as follows. Section 2 presents a systematic literature review to summarize the available research background and research results published. Section 3 presents the model framework and mathematical model of milkrun-based in-plant supply to support the comparison of conventional and integrated supply strategies. Section 4 presents the results of the numerical analysis of the model. Conclusions and future research directions are discussed in the last section.

Literature review

Milkrun supply systems have been extensively researched over the past 30 years, with numerous studies exploring various aspects of optimization, technology integration, and cost reduction. The literature includes multiple research fields, including automotive assembly lines, logistics management, and environmental sustainability. This extensive body of work highlights the continued relevance and evolving complexity of milk-run systems in modern supply chain practices and logistics systems. A research focuses on optimizing the milkrun material distribution system in automotive mixed-model assembly lines (MMALs) by addressing the challenges of timely part supply (Zhou & Wen, 2024, p. 24). A bi-objective optimization model is proposed to minimize line-side inventory and energy consumption, while optimizing Kanban numbers and material bin capacities to improve scheduling. To solve this, the study introduces a multi-objective artificial electric field algorithm with a SARSA mechanism (MOAEFASA), which enhances material distribution scheduling and demonstrates superiority through numerical experiments. It is possible to explore the integration of the milkrun system with the Internet of Things (IoT) to enhance material distribution in manufacturing lines. By developing an analytical model for dynamic routing of tugger trains, a research study ensures that materials are delivered to workstations based on time slot requirements, while minimizing total route distance (Facchini et al., 2024, p. 20). The model, validated through a real-world automotive case study, improves inventory stock management, optimizes tugger train utilization, and reduces daily travel distances compared to traditional in-plant logistics strategies. An optimization-based research work focuses on optimizing milk-run vehicle scheduling in supply hubs to achieve just-in-time production, minimizing energy consumption and time penalties for early or late deliveries. To solve the problem, an adaptive artificial bee colony algorithm enhanced by a deep Q-learning network (AABC-DQN) is proposed, demonstrating good performance in solution quality and convergence compared to benchmark algorithms (Zhou & Zhao, 2023, p. 16).

An international research team explores the transformation of conventional milk-run supply systems into cyber-physical systems using Industry 4.0 technologies, enabling real-time decision-making for scheduling, routing, and resource planning in in-plant logistics. A mathematical model is developed to analyse the impact of these technologies, showing significant improvements in performance, energy efficiency, and sustainability in milk-run supply logistics (Akkad & Bányai, 2023, p. 33). A practical case study explores the application of clustering and reverse milkrun to optimize logistics resources for a freight forwarding company. By analysing transport routes, truckload utilization, and unused capacities, the study demonstrates how reverse milkrun logistics can reduce costs and improve efficiency, supporting the company overcome profitability challenges as its client base expanded (Sarkar et al., 2023, p. 10). It is possible to evaluate and optimize the milkrun logistics system by analysing current delivery routes and transportation volume capacity (Mohd Salleh et al., 2023, p. 24). Using the saving matrix method with tabu search and ant colony optimization, the research demonstrates a reduction in unutilized capacity from 49% to 3%, significantly improving logistics efficiency, reducing transportation costs, and minimizing inventory with the Just-In-Time concept. The dynamic optimization of milkrun systems is also a potential research direction. By employing an ant colony optimization algorithm for routing and a genetic algorithm for delivery schedule, the study significantly reduces lead time by 39%, material handling time by 48%, and work in process by 22%, while improving workstation and machine efficiency (Marialuisa et al., 2023, p. 29).

A research addresses the challenges of material-feeding in mixed-model assembly lines by proposing a milkrun scheduling problem for the two-level logistics network between a central warehouse and line-integrated supermarkets (Zhou & Zhao, 2022, p. 18). A mathematical model is developed to minimize the number of electric vehicles used and their maximum travel distance. The study introduces a multi-objective decomposition evolutionary algorithm (MOEA/D-DFMB) that leverages double-faced mirror boundary theory to improve solution distribution and speed. Comparative experiments demonstrate that the proposed algorithm outperforms several others in both solution quality and convergence rate for optimizing milkrun logistics. The potentials of eKanban are discussed in a research exploring the implementation of a digitized milkrun system integrated with eKanban to enhance the efficiency of supplying consumables in production processes. By developing a simulation model, the study highlights the impact of this digital approach on key performance indicators, aiming to reduce waste and optimize material flow (Vojdani & Drechsler, 2022, p. 8).

The transportation cost is in the focus in a study addressing the rising transportation operating costs faced by the vehicle manufacturing and sales industries in Indonesia, which have exceeded targets and led to potential losses (Setiawan et al., 2022, p. 12). By employing the Dynamo++ methodology, the research identifies causes and implements improvements in the Milk Run system, significantly reducing transportation costs. The results reveal a substantial cost reduction of $77,861, representing a 79.3% decrease, benefiting both vehicle manufacturers and sales operations. A research evaluates the effectiveness of ant colony optimization (ACO) compared to mixed integer programming (MIP) for optimizing milkrun systems, which are used for cyclic and need-based deliveries in lean manufacturing (Uygun & Rustemaj, 2022, p. 14). The study demonstrates that ACO outperforms MIP in all benchmark scenarios for the capacitated vehicle routing problem (CVRP), showing more optimal routes without compromising vehicle utilization. While MIP is traditionally dominant in vehicle routing, ACO offers superior route optimization and equal vehicle utilization. A real-life data-based research develops and evaluates multiple linear programming models, multi-objective, ordinary fuzzy, and intuitionistic fuzzy, for optimizing milkrun delivery methods, focusing on minimizing transportation costs and addressing uncertainties in arrival and loading times (Çakir et al., 2022, p. 15). Applied to real-life data from Borusan Logistics, a major logistics firm in Turkey, the study demonstrates the effectiveness of these models in handling time window constraints and improving operational efficiency.

A research enhances the traditional milk-run model by incorporating energy consumption and carbon emission costs, addressing the need for low-carbon economic development (Quan et al., 2021, p. 8). Using an improved ant colony algorithm to solve the revised model, the study demonstrates reduced total journey distance, lower overall costs, and decreased carbon emissions, thereby aligning with environmental goals and improving logistics efficiency. An integrated inbound logistics (IIL) mode is proposed in a research combining milkrun collection with drop and pull delivery, while utilizing LNG vehicles to address high transportation costs associated with conventional milkrun methods. Applying a mixed integer mathematical model and genetic algorithm, the study shows significant reductions in driving mileage, wait times, and gas emissions, highlighting the IIL mode as a promising and efficient alternative for inbound logistics (Chen et al., 2021, p. 9). A research addresses the milkrun vehicle routing and scheduling problem under fuzzy constraints by applying an analytical approach with ordered fuzzy numbers, enhancing the interpretability and efficiency of solutions. By comparing this method to traditional computer simulations, the study demonstrates that the proposed approach offers a competitive and effective solution for designing scalable and robust logistics systems (Boczewicz et al., 2021, p. 18).

A research introduces the Dynamic Milk-Run Vehicle Routing (DMRVR) solution, which employs dynamic routing algorithms and fog-based vehicular networks to manage goods collection and adhere to time windows despite unexpected delays (Adriano et al., 2020, p. 24). Using simulations with OMNeT++ and SUMO, the study shows that DMRVR effectively reduces average route time and improves message delivery success rates in dense network scenarios, while highlighting the need for enhanced network coverage in sparse areas. The progress-lane (P-LANE) is integrated into the milkrun vehicle routing problem to enhance part collection efficiency in the automotive industry in a research work (Mao et al., 2020, p. 28). The proposed mixed integer programming model significantly reduces total costs and improves transportation efficiency compared to the zero-inventory approach, with cost reductions of 10% for small instances and 30% for large instances. A milk-run delivery model is presented for scheduling and loading tow trains in mixed-model assembly lines, aiming to minimize line-side inventory by optimizing delivery times and quantities. The NSICSA algorithm, combining immune clonal selection with neighbourhood search and simulated annealing, effectively addresses these scheduling challenges and maintains control over inventory peaks, providing robust solutions for various scale instances (Zhou & Zhu, 2020, p. 20). A cost-related research proposes a mixed-integer linear programming (MILP) model to optimize the distribution network for the automotive industry, incorporating conditions like 3D-packing, order compatibility, and return logistics. The study demonstrates that the milk-run strategy significantly reduces transportation costs compared to direct shipping, particularly when applied to real-world auto-parts shipment data from a major Iranian automobile company (Ranjbaran et al., 2020, p. 16). An optimization-related study explores the use of the milk-run approach to optimize transportation and inventory costs in a just-in-time production environment, demonstrating its effectiveness in reducing these costs for the studied company (Minh et al., 2020, p. 22). The findings confirm that milkrun is a viable strategy for companies aiming to maintain competitive advantages and operational efficiency in the context of globalization and industrial advancements.

Based on the above-discussed sources, research on milkrun supply systems reveals significant advancements and directions as follows:

- Optimization Models: Zhou & Wen (2024, p. 24) propose a bi-objective model to reduce inventory and energy use in automotive assembly lines, using MOAEFASA for improved scheduling. Zhou & Zhao (2023, p. 16) use an AABC-DQN algorithm to optimize vehicle scheduling, achieving better performance in just-in-time production.
- Technological Integration: Facchini et al. (2024, p. 20) and Akkad & Bányai (2023, p. 33) explore integrating IoT and Industry 4.0 technologies, respectively, to enhance material distribution, improve stock management, and increase energy efficiency.
- Cost Reduction: Setiawan et al. (2022, pp. 12) show that using Dynamo++ methodology can drastically cut transportation costs by 79.3%. Chen et al. (2021, p. 9) propose an integrated logistics mode using LNG vehicles to lower costs and emissions.
- Dynamic and Fuzzy Constraints: Marialuisa et al. (2023, p. 29) employ dynamic optimization techniques to reduce lead and handling times, while Boczewicz et al. (2021, p. 18) use fuzzy numbers to enhance solution efficiency under uncertainty.
- Algorithmic Advances: Uygun & Rustemaj (2022, p. 14) demonstrate that ant colony optimization outperforms traditional mixed integer programming in route optimization, and Vojdani & Drechsler (2022, p. 8) integrate eKanban to optimize material flow.
- Practical Applications: Sarkar et al. (2023, p. 10) apply reverse milkrun strategies to improve freight forwarding efficiency, and Mohd Salleh et al. (2023, p. 24) use advanced methods to reduce unutilized capacity and costs.
- Environmental Impact: Quan et al. (2021, p. 8) enhance milkrun models to include carbon emission costs, achieving lower emissions and improved logistics efficiency.

– Dynamic Routing: Adriano et al. (2020, p. 24) develop the DMRVR solution to manage routing and time windows effectively, improving route times and success rates in various network scenarios.

Based on the above literature review, the integration of milkrun processes, combining collection and distribution functions, represents a novel research direction in logistics. Traditionally, solutions have focused on separate aspects of these processes, addressing either collection or distribution independently. This segmented approach often overlooks the potential efficiencies gained from a unified system. Integrating these functions can streamline operations, reduce redundancy, and optimize resource utilization. Emerging research highlights the benefits of such integration, including cost savings and improved operational performance. Exploring this integrated approach offers new opportunities for enhancing supply chain efficiency and effectiveness.

The main contribution of this article includes: (1) a methodology to describe the conventional and integrated milkrun supply solutions in a U-shaped production or assembly cells based production system; (2) comparative analysis of conventional and integrated milkrun-based in-plant supply and (4) computational results of the scenario analysis.

Research methodology

Within the frame of this chapter, a mathematical model is described, which makes it possible to model the milkrun-based in-plant supply in production systems based on U-shaped production or assembly cells. The model is suitable to compare the conventional and integrated milkrun supply solutions. In the case of conventional milkrun supply, the collection and distribution operations are organized separately, it means, that the collection and distribution routes need different milkrun trolleys to perform the in-plant supply operations.

The objective function of the optimization model is the minimization of the total length of the transportation routes, which includes the distances from the warehouse to the first location of the millrun route, the distances from the last location of the millrun route back to the warehouse, and the distances among the U-shaped production or assembly cells:

$$L = \sum_{i=1}^{\alpha_{max}} \left(l\left(p_0, p_{x_{i,1}}\right) + l\left(p_{x_{i,j}}, p_{x_{i,\beta_{max}(i)}}\right) + \sum_{j=1}^{\beta_{max}(i)-1} l\left(p_{x_{i,j}}, p_{x_{i,j+1}}\right)\right), \quad (8.1)$$

The decision variable of the optimization problem is the assignment matrix $X = x_{i,j}$, which defines, that component demand $x_{i,j}$ is assigned to milkrun route i, as station j.

In the case of conventional milkrun supply, the following constraints has to be taken into consideration:

$$\forall i: \forall j: \vartheta_{x_{i,j}} = 0 \lor \vartheta_{x_{i,j}} = 1. \quad (8.2)$$

In the case of integrated milkrun supply, where within the same milkrun route both collection and distribution operations can be performed, constraint 2 need not to be taken into account. It means, that the value of $\vartheta_{x_{i,j}}$ is not constrained.

The optimization can be influenced by three different constraints. The first constraint defines the upper limit of the milkrun trolleys and it is not allowed to exceed this upper limit:

$$\forall i:\ \max_{j} q_{i,j} \leq C. \tag{8.3}$$

The second constraint defines the lower and upper limit of in-plant supply demands, and it is not allowed to exceed this time limit:

$$\forall i: \tau_{x_{i,j}}^{min} \leq t_{i,j} \leq \tau_{x_{i,j}}^{max}. \tag{8.4}$$

The third constraint defines the upper limit of available milkrun trolleys, and it is not allowed to exceed this upper limit, which means, that the number of simultaneous scheduled milkrun trolleys is constrained:

$$\alpha_{max} \leq MT. \tag{8.5}$$

Based on the above-described model, it is possible to analyse and compare the conventional and integrated milkrun supply and compute the following parameters: total length of milkrun routes, transportation time, materials handling time, utilization of milkrun trolleys, materials handling performance.

The used notations are summarized in Table 8.1.

Table 8.1. Explanation of notations and symbols

Notations and symbols	Explanation of notations and symbols
L	The total length of the transportation distance of milkrun trolleys in [m].
$x_{i,j}$	The decision variable of the optimization problem: the assignment matrix, which defines, that demand $x_{i,j}$ is assigned to the station j of milkrun route i.
$p_{x_{i,j}}$	Position of the assembly cell of the demand $x_{i,j}$.
α_{max}	The maximum number of milkrun routes.
$\beta_{max}(i)$	The maximum number of stations (delivery operations) assigned to milkrun route *i*.
p_0	Position of the warehouse.
$\vartheta_{x_{i,j}}$	The type of the delivery task $x_{i,j}$. $x_{i,j} = 0$ is for collection operations, and $x_{i,j} = 1$ for distribution operations.
$q_{i,j}$	The load of the milkrun trolley at station *j* of milkrun route *i*.
C	Capacity of milkrun trolleys.
$t_{i,j}$	The departure time of the milkrun to the station *j* of milkrun route *i*.
$\tau_{x_{i,j}}^{min}$	Lower timelimit of in-plant supply demand assigned as station *j* to milkrun route *i*.
$\tau_{x_{i,j}}^{max}$	Upper timelimit of in-plant supply demand assigned as station *j* to milkrun route *i*.
MT	Upper limit of avaliable milrun trolleys.
d_k	Component demand k. d_k^C is for collection demand and d_k^D is for distribution demand.

Source: Own study based on research.

Research results and discussion

Within the frame of this chapter, the numerical analysis and the comparison of conventional milkrun supply and integrated milkrun supply are discussed. For the optimization of the conventional and integrated milkrun supply solutions, the OpenSolver Version 2.9.3 was used. The input parameters of the scenario are the followings:

- Layout of the production system including the position of input and output storages of U-shaped production and assembly cells.
- Collection and distribution demands of U-shaped production and assembly cells:

$$d^C = (0,8,0,0,14,0,9,0,12,14,0,20,8,0,0,8,17,0). \quad (8.6)$$

$$d^D = (14,2,12,7,0,22,0,10,0,0,4,0,0,15,22,0,0,11). \quad (8.7)$$

- Capacity of milkrun trolleys: $C = 50$ pcs.
- Number of available milkrun trolleys: $MT = 8$ pcs.

In the case of the conventional milkrun supply, based on the above-mentioned mathematical model, it is possible to solve the routing of milkrun supply for both the collection and the distribution operations. In the case of the collection operations, three milkrun routes are defines. The length of the transportation route for the first collection milkrun (see Figure 8.1a) is 178 m, the transportation time is 71.2 sec, the materials handling time is 192 sec, the materials handling intensity is 6698 pcsm, and the maximum utilization of the milkrun trolley is 100%. The length of the transportation route for the second collection milkrun (see Figure 8.1b) is 72 m, the transportation time is 28.8 sec, the materials handling time is 64 sec, the materials handling intensity is 1592 pcsm, and the maximum utilization of the milkrun trolley is 64%. The length of the transportation route for the third collection milkrun (see Figure 8.1c) is 136 m, the transportation time is 54.4 sec, the materials handling time is 64 sec, the materials handling intensity is 1328 pcsm, and the maximum utilization of the milkrun trolley is 74%.

In the case of the distribution operations, the optimization resulted also three milkrun routes. The length of the transportation route for the first distribution milkrun (see Figure 8.1d) is 164 m, the transportation time is 65.6 sec, the materials handling time is 96 sec, the materials handling intensity is 3132 pcsm, and the maximum utilization of the milkrun trolley is 92%. The length of the transportation route for the second distribution milkrun (see Figure 8.1e) is 106 m, the transportation time is 42.4 sec, the materials handling time is 96 sec, the materials handling intensity is 1638 pcsm, and the maximum utilization of the milkrun trolley is 68%. The length of the transportation route for the third distribution milkrun (see Figure 8.1f) is 94 m, the transportation time is 37.6 sec, the materials handling time is 96 sec, the materials handling intensity is 1856 pcsm, and the maximum utilization of the milkrun trolley is 60%.

The optimization led to a reduced number of milkrun routes. Figure 8.2 shows the results of route optimization of the integrated milkrun solutions, showing the route, the loading and unloading points and the warehouse entry and exit points. The length of the transportation route for the first integrated milkrun (see Figure 8.2a) is 174 m, the transportation time is 69.6 sec, the materials handling time is 256 sec, the materials handling intensity is 6966 pcsm, and the maximum utilization of the milkrun trolley is 100%. The length of the transportation route for the second integrated milkrun (see Figure 8.2b) is 100 m, the transportation time is 40 sec, the materials handling time is 160 sec, the materials handling intensity is 3568 pcsm, and the maximum utilization of the milkrun trolley is 96%. The length of the transportation route for the third integrated milkrun (see Figure 8.2c) is 100 m, the transportation time is 57.6 sec, the materials handling time is 160 sec, the materials handling intensity is 4002 pcsm, and the maximum utilization of the milkrun trolley is 94%. The total length of the transportation routes in the case of integrated milkrun-based supply is 418 m, the transportation time is 167.2 sec, the materials handling time is 576 sec, the materials handling intensity is 14536 pcsm.

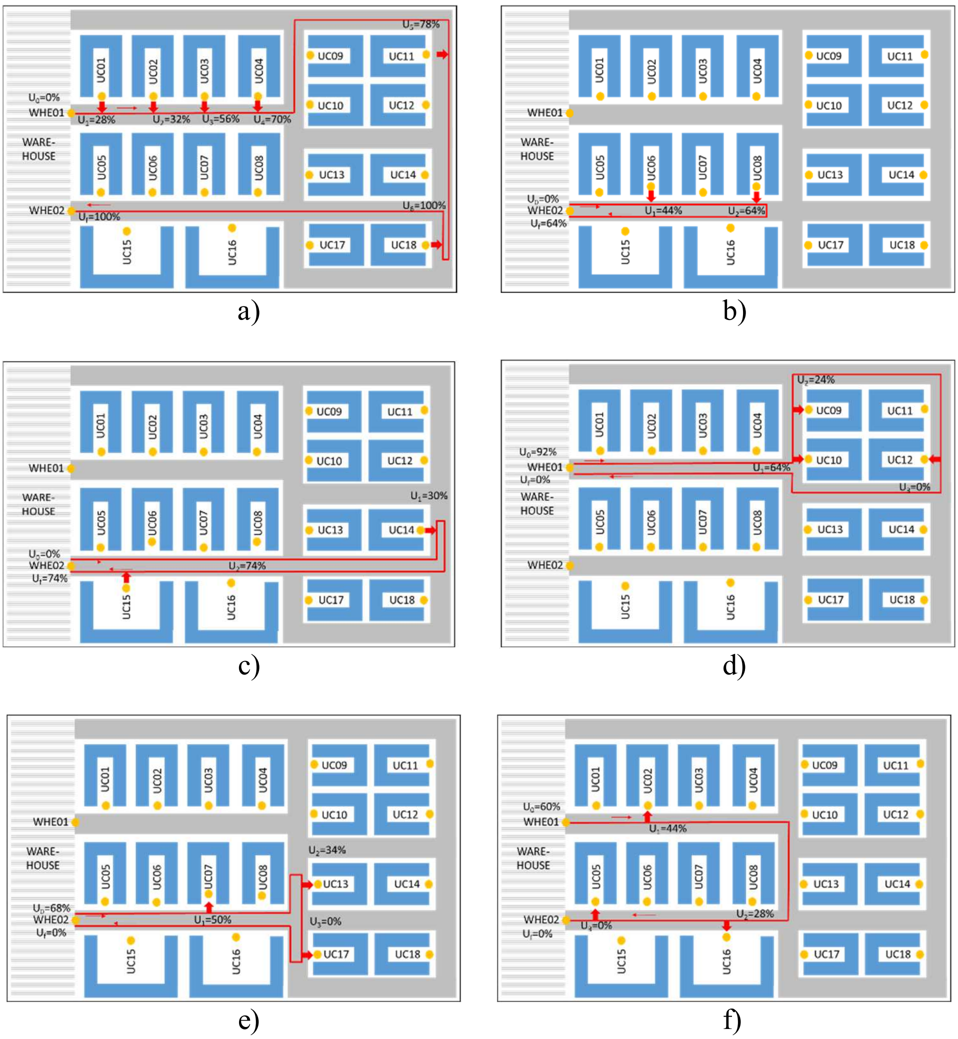


Figure 8.1. The collection and distribution routes in the case of conventional milkrun supply: a) the first collection route, b) the second collection route, c) the third collection route, d) the first distribution route, e) the second distribution route, f) the third distribution route

Source: Own study based on research.

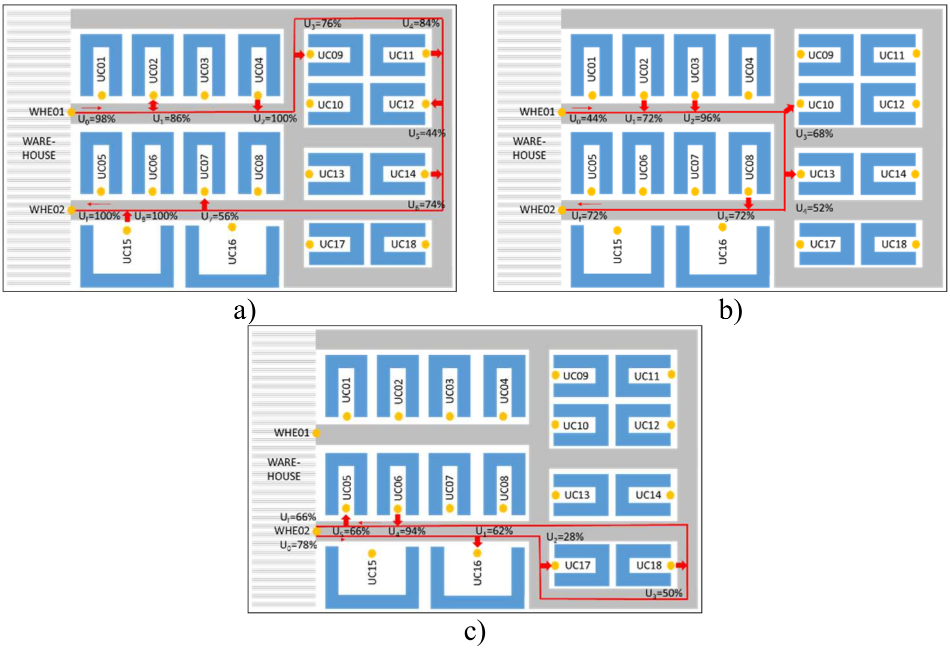


Figure 8.2. The routes in the case of the integrated milkrun supply: a) the first integrated milkrun route, b) the second integrated milkrun route, c) the third integrated milkrun route

Source: Own study based on research.

Table 8.2 summarizes the comparison of conventional and integrated milkrun supply solutions, based on the scenario analysis.

As Table 8.2 shows, the integrated solution resulted:

- 45% total transportation distance reduction,
- 45% transportation time reduction,
- 6% materials handling time reduction,
- 19% total in-plant supply time reduction,
- 11% reduction in materials handling performance.

The optimization results of the milkrun supply optimization demonstrate significant improvements in various performance metrics. The integrated solution achieved a 45% reduction in total transportation distance, highlighting more efficient routing. Similarly, the transportation time was also cut by 45%, indicating quicker deliveries. While the solution made substantial progress, materials handling time only saw a modest 6% reduction, suggesting some room for improvement in this area. There was a 19% reduction in total in-plant supply time including transportation and materials handling time, showing better synchronization between supply points and demand. The 11% reduction in materials handling performance reflects a slight improvement in efficiency. Overall, the integrated solution successfully reduced both transportation-related metrics, in-plant supply time and the number of required logistics resources (milkrun trolleys), contributing to a leaner supply chain. The results demonstrate that the milk run optimization led to impressive logistics improvements.

Table 8.2. Comparison of parameters of conventional and integrated milkrun supply solutions based on the scenario analysis

Routes	Route length [m]	Time [sec]			Performance [pcsm]
		Transportation	Materials handling	Total	
Conventional solution					
Collection 1	178	71.2	192	263.2	6698
Collection 2	72	28.8	64	92.8	1592
Collection 3	136	54.4	64	118.4	1328
Distribution 1	164	65.6	96	161.6	3132
Distribution 2	106	42.4	96	138.4	1638
Distribution 3	94	37.6	96	133.6	1856
Total	750	300	608	908.0	16244
Integrated solution					
Route 1	174	69.6	256	325.6	6966
Route 2	100	40.0	160	200.2	3568
Route 3	144	57.6	160	217.6	4002
Total	418	167.2	576	743.2	14536

Source: Own study based on research.

Conclusion

Within the frame of this research work, the author developed a novel model to analyse the impact of the integration of collection and distribution processes of milkrun-based in-plant supply in a U-shaped production cells-based production system. The proposed model makes it possible to describe the collection and distribution processes of milkrun trolleys among U-shaped production cells focusing of the number of required milkrun trolleys, transportation time, materials handling time, materials handling performance. More generally, this paper focuses on the mathematical description of in-plant milkrun supply in a special production environment including U-shaped production cells.

The added value of the paper is in the description of the integration of collection and distribution processes of milkrun trolleys on the number of required logistics resources, materials handling and transportation time and material handling performance. The scientific contribution of this paper for researchers in this field is the mathematical modelling of relationship between milkrun-based supply and efficiency parameters. The results can be generalised because the model can be applied for different production systems.

Managerial decisions can be influenced by the results of this research, because the described method makes it possible to analyse available solutions of in-plant production supply and strategic decisions can be supported by the results of the analysed scenario especially resource and efficiency parameters point of view.

However, there are also limitations of the study and the described model, which provides direction for further research. Within the frame of this model, the energy efficiency of the solution was not taken into consideration. In further studies, the model can be extended to a more complex model including energy efficiency; the virtual emission of the proposed model can be calculated taking the energy generation sources of logistics resources into consideration.

References

Adriano, D.D., Montez, C., Novaes, A.G.N., & Wangham, M. (2020). DMRVR: Dynamic milkrun vehicle routing solution using fog-based vehicular ad hoc networks. *Electronics* (Switzerland), 9(12), 2010. DOI: 10.3390/electronics9122010.

Akkad, M.Z., & Bányai, T. (2023). Energy consumption optimization of milk-run-based in-plant supply solutions: An Industry 4.0 approach. *Processes*, 11(3), 799. DOI: 10.3390/pr11030799.

Bocewicz, G., Banaszak, Z., Rudnik, K., Smutnicki, C., Witczak, M., & Wójcik, R. (2021). An ordered-fuzzy-numbers-driven approach to the milk-run routing and scheduling problem. *Journal of Computational Science*, 49, 101288. DOI: 10.1016/j.jocs.2020.101288.

Çakir, E., Ulukan, Z., Kahraman, C., Sağlam, C.Ö., Kuleli Pak, B., & Pekcan, B. (2022). Intuitionistic fuzzy multi-objective milk-run modelling under time window constraints. *Journal of Intelligent and Fuzzy Systems*, 42(1), 47-62. DOI: 10.3233/JIFS-219174.

Chen, J., Wang, K., & Huang, Y. (2021). An integrated inbound logistics mode with intelligent scheduling of milk-run collection, drop and pull delivery and LNG vehicles. *Journal of Intelligent Manufacturing*, 32(8), 2257-2265. DOI: 10.1007/s10845-020-01637-3.

Dat Minh, N., Trung Kien, D., & Khac Hau, P. (2020). Applying milk-run method to optimize cost of transport: An empirical evidence. *International Journal of Supply and Operations Management*, 7(2), 178-188. DOI: 10.22034/IJSOM.2020.2.6.

Facchini, F., Mossa, G., Sassanelli, C., & Digiesi, S. (2024). IoT-based milk-run routing for manufacturing system: an application case in an automotive company. *International Journal of Production Research*, 62(1-2), 536-555. DOI: 10.1080/00207543.2023.2254408.

Mao, Z., Huang, D., Fang, K., Wang, C., & Lu, D. (2020). Milk-run routing problem with progress-lane in the collection of automobile parts. *Annals of Operations Research*, 291(1-2), 657-684. DOI: 10.1007/s10479-019-03218-x.

Marialuisa, M., Matteo M.S., & Muhammad, S. (2023). Optimizing milk-run system and IT-based Kanban with artificial intelligence: an empirical study on multi-lines assembly shop floor. *Production and Manufacturing Research*, 11(1), 2179123. DOI: 10.1080/21693277.2023.2179123.

Mohd Salleh, N.A., Ahmad, S.F., Shaharudin, M.R., & Rahim, S.A. (2023). Evaluation of transportation distance optimization route for milk run logistics system. *International Journal of Supply and Operations Management*, 10(3), 295-318. DOI: 10.22034/ijsom.2022.109361.2347.

Quan, C., He, Q., Ye, X., & Cheng, X. (2021). Optimization of the Milk-run route for inbound logistics of auto parts under low-carbon economy. *Journal of Algorithms and Computational Technology*, 15, 1. DOI: 10.1177/17483026211065387.

Ranjbaran, F., Husseinzadeh Kashan, A., & Kazemi, A. (2020). Mathematical formulation and heuristic algorithms for optimisation of auto-part milk-run logistics network considering forward and reverse flow of pallets. *International Journal of Production Research*, 58(6), 1741-1775. DOI: 10.1080/00207543.2019.1617449

Sarkar, B.D., Joshi, P.V., & Shah, N. (2023). Reverse milk run – the logistics retrenchment strategy. *Emerald Emerging Markets Case Studies*, 13(4), 1-23. DOI: 10.1108/EEMCS-11-2022-0437.

Setiawan, I., Kurnia, H., Setiawan, S., Purba, H.H., & Hernadewita, H. (2022). Reduce transportation costs using the milk-run system and dynamo stages in the vehicle manufacturing industry. *Operational Research in Engineering Sciences: Theory and Applications*, 5(2), 17-27. DOI: 10.31181/oresta240622030s.

Uygun, Y., & Rustemaj, A. (2022). Ant colony optimisation for milk-runs in manufacturing systems. *International Journal of Advanced Operations Management*, 14(2), 167-181. DOI: 10.1504/IJAOM.2022.123267.

Vojdani, N., & Drechsler, P. (2022). Simulationsbasierte Analyse eines innerbetrieblichen digitalisierten Milk Run Systems. *Logistics Journal*, (11), 2. DOI: 10.2195/lj_proc_vojdani_de_202211_02.

Wolff, J. (2024). *Optimizing Supply Chains with Milk Run Logistics: Benefits, Challenges, and Implementation*. https://www.saloodo.com/blog/milk-run-logistics/.

Zhou, B., & Wen, M. (2024). A multi-objective artificial electric field algorithm with reinforcement learning for milk-run assembly line feeding and scheduling problem. *Computers and Industrial Engineering*, 190, 110080. DOI: 10.1016/j.cie.2024.110080.

Zhou, B., & Zhao, L. (2022). A multi-objective decomposition evolutionary algorithm based on the double-faced mirror boundary for a milk-run material feeding scheduling optimization problem. *Computers and Industrial Engineering*, 171, 108385. DOI: 10.1016/j.cie.2022.108385.

Zhou, B., & Zhao, Z. (2023). An adaptive artificial bee colony algorithm enhanced by Deep Q-Learning for milk-run vehicle scheduling problem based on supply hub. *Knowledge-Based Systems*, 264, 110367. DOI: 10.1016/j.knosys.2023.110367.

Zhou, B., & Zhu, Z. (2020). Optimally scheduling and loading tow trains of in-plant milkrun delivery for mixed-model assembly lines. *Assembly Automation*, 40(3), 511-530. DOI: 10.1108/AA-01-2019-0013.

Chapter 9

Evaluation of Reverse Logistics in the Supply Chain of Bottling Companies: A Case Study of Junac and La Sien Water Bottling Company, Port Harcourt, Nigeria

Anna Budzik[1], Gift Oriaku Eke Agwu[2]

[1] Czestochowa University of Technology, Faculty of Management, Poland
anna.budzik@pcz.pl ORCID 0000-0001-5870-2847
[2] Czestochowa University of Technology, Poland

Abstract: The chapter investigates the implementation and understanding of reverse logistics in the supply chain of water bottling companies in Port Harcourt, Nigeria, focusing on Junac and La Sien companies. It reviews theoretical concepts related to reverse logistics, examines the methods used for data collection and analysis, and presents the study's findings. Key results indicate a high level of awareness (73.2%) of reverse logistics among the companies, with practices mainly involving the proper disposal and reuse of plastic bottles. The primary motivations for adopting reverse logistics include enhancing customer satisfaction, generating profit, and reducing raw material costs. However, significant challenges such as high costs and financial constraints, along with a lack of expertise, hinder effective implementation. The study concludes that while there is a strong understanding and commitment to reverse logistics in these companies, further collaboration with suppliers and customers is essential to overcoming these challenges and addressing environmental issues.

Keywords: supply chain, reverse logistics, customer satisfaction, waste management

Introduction

In today's competitive landscape, every industry, including manufacturing, constantly seeks opportunities for improvement. Logistics play a crucial role in maximizing the efficient use of labor, equipment, and supplies within manufacturing companies. Competition has evolved from firm-level rivalry to supply chain competitiveness. Management now understands that any supply chain error can impact profitability. Despite the importance of recycling, businesses have historically overlooked the reverse supply chain, also known as reverse logistics.

Reverse Logistics can be defined as the process of efficiently moving products and materials from the point of consumption back to the point of origin for proper disposal or reuse. This process can help businesses recover value from returned goods, improve customer satisfaction, and provide insights for product improvements. Companies employing reverse logistics can achieve cost savings and enhance their competitive Edge (Pinna & Paolo, 2012, pp. 91-114).

Countries like the United States, China, and the United Kingdom have well-established reverse logistics systems. These countries have integrated reverse logistics into their supply chains, leading to significant cost savings, improved customer satisfaction, and enhanced environmental sustainability. For instance, companies in these countries have developed sophisticated systems for handling returns, recycling, and reusing materials, which have become integral parts of their operations (Salas-Navarro et al., 2024).

In Nigeria, bottling companies use plastics extensively for packaging. While plastics can be reused, the concept of reverse logistics has not been widely recognized or implemented in Nigeria, leading to limited studies on the subject. This research aims to fill that gap by assessing the reverse logistics practices in the supply chains of Nigerian bottling companies, focusing on Junac and La Sien in Port Harcourt.

The primary objective is to evaluate the challenges and potential solutions for efficient reverse logistics in water bottling companies to protect the environment and meet economic needs. Specific research objectives include assessing the understanding and practice of reverse logistics, identifying driving forces and challenges, and examining supply chain practices in these companies.

The study will focus on water bottling companies in Port Harcourt, involving supervisors, senior staff, and managers in logistics, production, operation, marketing, and general management. The findings are expected to benefit bottling companies by enhancing their understanding and implementation of reverse logistics, informing strategic planning, and promoting environmental sustainability. Additionally, the study aims to contribute to the body of knowledge and serve as a reference for further research in the field.

Literature review

Reverse logistics encompasses a variety of practices and definitions, addressing the movement and management of goods after their initial sale. This review covers the primary issues related to reverse logistics, focusing on its definitions and practices (Rubio et al., 2008, pp. 1099-1120).

Among the several definitions, this section will focus on and provide insight into the fundamental definitions of reverse logistics. Rogers & Tibben-Lembke defined Reverse Logistics, including the goal and the processes (the logistics) involved as: "The process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal" (Rogers & Tibben-Lembke, 2001, pp. 129-148). Another description of reverse logistics, defines it as "the process of planning, implementing, and controlling flows of raw materials, in-process inventory, and finished goods from a manufacturing, distribution, or use point to a point of recovery or proper disposal". (RevLog, 1998; Szymonik & Stanisławski, 2023).

The Reverse Logistics Magazine, published in 2006, defines reverse logistics as "all activity related to a product or service after the point of sale, with the ultimate goal of optimising or making aftermarket activity more efficient in order to save money and natural resources" (Reverse Logistics Association, 2006, p. 26).

Reverse logistics practices involve a range of activities that a corporation undertakes to handle returned products and materials. These activities include collecting discarded, damaged, unwanted, or outdated products, as well as packaging and shipping materials from customers or resellers. Once products are returned to the manufacturer, the company can choose from various disposal options. Key practices in reverse logistics include gatekeeping, sorting and storing, transportation, asset recovery, reuse, recycling, refurbishing, remanufacturing, and cannibalization (Bulger, 2024; Rogers & Tibben-Lembke, 2001, pp. 129-148; Thierry et al., 1995, pp. 114-135).

Gatekeeping refers to the initial screening of defective and undesirable returned items at the entry point into the reverse logistics process. This step helps businesses control and reduce the number of returns while maintaining excellent customer service. By filtering out unwanted returns, companies can avoid excessive costs and manage materials more efficiently. Sorting and storing involve categorizing returned products to decide their fate, whether to process, sell, or dispose of them. This step is crucial as it determines what happens to the returned products and how they are handled (hollingsworthllc.com).

Transportation in reverse logistics involves the actual movement of items within the reverse logistics network. This activity is typically the most significant expense, accounting for a substantial portion of overall reverse logistics costs. Asset recovery is the classification and disposition of returned goods as surplus, obsolete, scrap, trash, and excess materials to optimize returns and minimize costs and liabilities. The goal of asset recovery is to recover as much economic and ecological value as possible, thereby reducing the total amount of waste (Alok & Choudhary, 2014).

Reuse is an effective way to clean the environment and promote zero waste and zero emissions. By reusing products and materials, companies can reduce production costs and extend the lifecycle of goods. Recycling involves reprocessing end-of-life products to save production costs and reduce environmental impact. This practice has gained significant attention in recent years, with various sectors exploring ways to improve recycling processes. Recycling can save up to 50% on production costs and reduce greenhouse gas emissions when implemented effectively (Alok & Choudhary, 2014; Mishra et al., 2012, pp. 2396-2406; Williams et al., 2008, pp. 6446-6454; Yao & Askin, 2019, pp. 2226-2246).

Remanufacturing has become increasingly important in reverse logistics and supply chain management (Nasr et al., 2006). This process involves disassembling, cleaning, inspecting, repairing, replacing, and reassembling used products to restore them to like-new conditio (Matsumoto, 2009, pp. 1547-1555). Remanufacturing supports a resource-efficient manufacturing industry and circular economy by restoring the function of discarded items and creating new value. This practice is common in industries such as automotive parts, electronics, and office equipment (Yu & Solvang, 2016, pp. 2693-2711).

Refurbishing involves repairing and reselling returned products to customers, often at a lower price or with a warranty. This practice can include internal repair, where the company repairs the product itself, or external repair, where an external vendor is contracted to perform the repair. Refurbished products are usually sold at a lower price, offering customers a more affordable option while reducing waste (Narayanan, 2010)

Cannibalization is a strict process that involves breaking down discarded products to salvage usable components. These components must meet specific quality standards and can be reused in other recovery operations such as repairs, refurbishing, or remanufacturing. Cannibalization helps reduce environmental impact, lower costs, and improve brand reputation by promoting sustainable production practices (interlakemecalux.com; Heda et al., 2017).

The four main drivers of reverse logistics are economic factors, legislation, corporate citizenship, and environmental issues. These drivers' significance to a business and its goals is crucial. To be successful in reverse logistics, companies must implement six main business concepts, focusing on customer satisfaction, innovation in technology, eco-compatibility, strategic alliances, knowledge management, and value recovery.

Customer satisfaction is central to reverse logistics management. Efficient product disposal and reverse logistics can significantly enhance customer loyalty and profitability (Guldem & Fevzi, 2011, pp. 161-171). New technology implementations improve business performance by aiding compliance reporting, tracking returns, and managing returns data, while being adaptable to future expansions and exceptions (Mishra et al., 2012, pp. 2396-2406, 26). Eco-compatibility emphasizes reducing hazardous materials and energy usage due to regulations and consumer knowledge. Companies are increasingly focusing on sustainability (Kosacka-Olejnik & Werner-Lewandowska, 2020, pp. 9-14). Strategic alliances streamline operations and enhance competitive positions by allowing companies to leverage strengths and seek complementary partners. Knowledge management involves creating and implementing processes to improve knowledge application, which is essential for continuous innovation in reverse logistics (Power & Sohal, 2001, pp. 247-265).

Value recovery aims to maximize resale value and efficiency in handling returns, thereby saving costs.

Reverse logistics is becoming critical in supply chain management, with businesses investing in it to cut costs, increase revenue, and improve customer service (Guldem & Fevzi, 2011, pp. 161-171). This includes reusing items, recycling, and managing returns due to marketing returns, damages, quality issues, overstocks, refurbishments, or remanufacturing. Effective reverse logistics can enhance market effectiveness and internal cost efficiency, boosting revenues through market growth and customer satisfaction (Kokkinaki et al., 2001).

Challenges in reverse logistics include technical, economic, political, and social aspects. Technical challenges involve forecasting returns, estimating the quality and quantity of returned goods, and managing diverse materials and compositions in returned items. Economic challenges arise from the financial burdens of implementing reverse logistics systems, stakeholder reluctance due to uncertainties, and the need for eco-oriented partnerships. Political challenges include the lack of updated regulations, varying national laws, and insufficient political and governmental support for reverse logistics. Social challenges are linked to stakeholder reluctance, lack of environmental commitment, and consumer perceptions of remanufactured goods (Gifford, 1997, pp. 11).

The supply chain is a network of businesses involved in producing and delivering a product or service, extending from raw material suppliers to the final customer (Ganeshan & Harrison, 1995). Effective supply chain management involves coordinating various functions such as marketing, distribution, manufacturing, and procurement. It requires practices like managing supplier and customer relationships, data sharing, internal operations, information technology, and training.

Supplier and customer relationships are crucial for promoting consumer loyalty and aligning supply chain activities. Internal operations must be efficient and adaptable to changes in the market. Data sharing is essential for cross-functional and inter-organizational integration, reducing stock levels and production costs. Information technology enhances communication and coordination within the supply chain, offering cost reductions and improved customer service. Training is necessary to ensure that employees understand supply chain management and can effectively use data and technology for better performance (Ilgin & Gupta, 2010, pp. 563-591).

Research methodology

This study used a descriptive research design. This design is a collection of methods and procedures for describing variables. It entails collecting data describing events, then organizing, tabulating, illustrating, and describing the data. Descriptive research describes the variables by addressing the who, what, and how questions (Babbie, 2020).

Data was collected from two water bottling companies in Port Harcourt, Nigeria using a questionnaire that served as a major instrument for data collection in this study. The instrument was self-administered and structured using a four-point Likert scale with the following scores: Strongly Agree (SA) = 4 points; Agree (A) = 3 points, Disagree (D) = 2 points, and Strongly Disagree (SD) = 1 point.

The instrument comprised sections A and B. Section A contains demographic and socio-economic information about the target population. Section B contained questions relating to the perceptions of supervisors, senior staff members, middle and top level managers who are directly or indirectly involved in reverse logistics, logistics and supply chain, production, operation, marketing, and general management in the selected companies under study.

Due to cost, time, geographical limits, and data availability, it will be difficult to analyse all of the personnel in these companies. Consequently, the population of interest for this study will be limited to supervisors, senior staff members, and middle and top level managers who are directly or indirectly involved in reverse logistics, logistics and supply chain, production, operation, marketing, and general management in the selected companies. Consequently, based on the human resource management businesses' active list report as of January 31, 2021. These companies have a total of 125 permanent supervisors, senior staff members, and middle and upper-level managers.

A stratified sample is a sampling strategy in which the researcher divides the population into several groups called strata, from which a probability sample (simple random sample) is selected. Consequently, 125 supervisors, senior employees, and middle and upper-level managers are targeted among these two organizations (JUNAC and La Sien). The suitable sample size was determined by employing Yamane's 1967 (Yamane, 1967) statistical formula for sample size, and 95 employees were obtained were sampled. (Table 9.1).

Table 9.1. Population distribution

Water bottling company	Population	Sample Size ($n_h = \frac{N_h}{N} \times n$)
JUNAC	53	40
LA SIEN	72	55
Total	**125**	**95**

Source: Businesses' active list report as of January 31, 2021.

The researcher obtained the organization's permission for the study. Employees who completed the questionnaire would be told about the goal of data collection, analysis, and the agreement to keep their responses private.

Research results

This section revealed the results obtained from the field survey based on the responses of respondents as regards the administered questionnaire.

Table 9.2. Responses on the level of understanding of reverse logistics concept in two water bottling companies in Port Harcourt, Nigeria

	Reverse logistics practices	SA (4)	A (3)	D (2)	SD (1)	Mean	Rank	Remark
1	Our organization's management and employees understand the concept of reverse logistic practices and its importance.	38	33	15	9	3.05	1st	Agreed
2	Our organization gives attention and put effort towards the implementation of reverse logistics practice.	38	27	18	12	2.96	2nd	Agreed
3	Our organization allocates enough resources to the practice of reverse logistics.	34	30	19	12	2.91	3rd	Agreed
4	Our organization's environmental policies and actions are aligned with minimizing the impact of after-use plastic bottle wastes on the environment.	35	29	12	19	2.84	5th	Agreed
5	Our organization allocates enough resources to the practice of reverse logistics.	29	41	11	14	2.89	4th	Agreed
	Grand Mean					2.93 (73.2%)		

Mean criterion: Disagree if mean value is lower than 2.5 otherwise, Agree

Source: Researcher's Field Work, 2022.

Table 9.2 showed that the statement "our organization's management and employees understand the concept of reverse logistic practices and its importance ranks 1st as 38 respondents strongly agree, 33 agree, 15 disagree and 9 strongly disagree resulting to a mean score of 3.05.

Ranking 2nd is the statement "our organization gives attention and put effort towards the implementation of reverse logistics practice" as 38 respondents strongly agree, 27 agree, 18 disagree and 12 strongly disagree which gives a mean score of 2.96.

In the 3rd position is that statement that says "our organization allocates enough resources to the practice of reverse logistics as 34 respondents strongly agree, 30 agree, 19 disagree and 12 strongly disagree resulting to a mean score of 2.91.

29 respondents strongly agree, 41 agree, 11 disagree and 14 strongly disagree to the statement "our organization allocate enough resources to the practice of reverse logistics" which yields to a mean score of 2.89 and ranking 4th.

The statement "our organization's environmental policies and actions are aligned with minimizing the impact of after use plastic bottle wastes to the environment" with a mean score of 2.84 ranks 5th.

Table 9.3. Responses on the current trend of reverse logistics practice in water bottling companies in Port Harcourt, Nigeria

	Current trend of reverse logistics practice	SA (4)	A (3)	D (2)	SD (1)	Mean	Rank	Remark
1	Our organization contributes to a proper disposal and collection of used plastic bottles in order to protect the environment and to make plastic bottles as a source of income.	32	40	13	10	2.99	1st	Agreed
2	Our organization has its own design and standard on its materials for the purpose of reuse.	34	29	15	17	2.84	4th	Agreed
3	Our organization has the technology and the resource to engage in the process of recycling plastic bottle products.	36	32	12	15	2.94	3rd	Agreed
4	Our organization has the capacity and the resources to reuse back and to generate profit from the renewable materials.	36	34	11	14	2.97	2nd	Agreed
5	Our organization creates awareness to the society about proper disposal and management of after consumption plastic bottles.	28	34	20	13	2.81	5th	Agreed
	Grand Mean					2.93 (73.2%)		

Mean criterion: Disagree if mean value is lower than 2.5 otherwise, Agree

Source: Researcher's Field Work, 2022.

Ranking 1st in Table 9.3 is the statement "our organization contributes to a proper disposal and collection of used plastic bottles in order to protect the environment and to make plastic bottles as a source of income" with a mean score of 2.99 as 32 respondents strongly agree, 40 agree, 13 disagree and 10 strongly disagree.

With a mean score of 2.97, the statement "our organization has the capacity and the resources to reuse back and to generate profit from the renewable materials" ranks 2nd. 36 respondents strongly agree, 34 agree, 11 disagree and 14 strongly disagree.

On the 3rd positon is the statement "our organization has the technology and the resource to engage in the process of recycling plastic bottle products" as 36 respondents strongly agree, 32 agree, 12 disagree and 15 strongly disagree yielding to a mean score of 2.94.

34 respondents strongly agree, 29 agree, 15 disagree and 17 strongly disagree that "our organization has its own design and standard on its materials for the purpose of reuse" yielding to a mean score of 2.84 and ranking 4th.

The statement "our organization creates awareness to the society about proper disposal and management of after-consumption plastic bottles ranks 5th. 28 respondents strongly agree, 34 agree, 20 disagree and 13 strongly disagree resulting to a mean score of 2.81.

Table 9.4 reveals responses on driving forces behind the implementation of reverse logistics. "To increase customer satisfaction" with a mean score of 3.42 ranks 1st as 58 respondents strongly agree, 26 agree, 4 disagree and 7 strongly disagree.

Table 9.4. Responses on driving forces behind the implementation of reverse logistics in water bottling companies in Port Harcourt, Nigeria

	Driving forces behind the implementation of reverse logistics	**SA (4)**	**A (3)**	**D (2)**	**SD (1)**	**Mean**	**Rank**	**Remark**
1	To generate profit and to decrease raw materials cost.	38	32	12	13	3.00	2nd	Agreed
2	To remain competitive in the industry.	28	39	17	11	2.88	3rd	Agreed
3	Governments and company's rule and regulations.	33	26	20	16	2.80	4th	Agreed
4	To increase customer satisfaction.	58	26	4	7	3.42	1st	Agreed
5	Social and environmental responsibility.	26	33	20	16	2.73	5th	Agreed
	Grand Mean					2.93 (73.2%)		

2022Mean criterion: Disagree if mean value is lower than 2.5 otherwise, Agree

Source: Researcher's Field Work.

38 respondents strongly agree to "to generate profit and to decrease raw materials cost", while 32 agree, 12 disagree and 13 strongly disagree yielding to a mean score of 3.00 and ranking 2nd.

Ranking 3rd is "to remain competitive in the industry" as 28 respondents strongly agree, 39 agree, 17 disagree and 11 strongly disagree resulting to a mean score of 2.88.

On the 4th positon is "governments and company's rule and regulations" as 33 respondents strongly agree, 36 agree, 20 disagree and 16 strongly disagree yielding to a mean score of 2.80.

"Social and environmental responsibility" ranks 5th as 26 respondents strongly agree, 33 agree, 20 disagree and 16 strongly disagree, which results to a mean score of 2.73.

Table 9.5. Responses on the challenges for the successful implementation of reverse logistics in water bottling companies in Port Harcourt, Nigeria

	Challenges in reverse logistics	SA (4)	A (3)	D (2)	SD (1)	Mean	Rank	Remark
1	Lack of awareness, commitment, and attention of top management to the practice of reverse logistics.	33	31	19	12	2.89	3rd	Agreed
2	Poor cooperation and integration of different organizations in reverse logistics	30	34	18	13	2.85	4th	Agreed
3	High cost related to reverse logistics and organization's financial barrier.	39	34	11	11	3.06	1st	Agreed
4	Unavailability of clear policy and regulation on reverse logistics practice and lack of support from the government.	27	30	19	19	2.68	5th	Agreed
5	Lack of available expertise in reverse logistics process.	39	30	17	9	3.04	2nd	Agreed
	Grand Mean					2.93 (73.2%)		

Mean criterion: Disagree if mean value is lower than 2.5 otherwise, Agree

Source: Researcher's Field Work, 2022.

The statement "high cost related to reverse logistics and organization's financial barrier" rans 1st with a mean score of 3.06 as 39 respondents strongly agree, 34 agree, 11 disagree and 11 strongly disagree.

Ranking 2nd is the statement "lack of available expertise in reverse logistics process" with a mean score of 3.04 as 39 respondents strongly agree, 30 agree, 17 disagree and 9 strongly disagree.

33 respondents strongly agree, 31 agree, 19 disagree and 12 strongly disagree to the statement "lack of awareness, commitment, and attention of top management to the practice of reverse logistics" which yields to a mean score of 2.89 and ranks 3rd.

The statement "poor cooperation and integration of different organizations in reverse logistics" ranks 4th with a mean score of 2.85 as 30 respondents strongly agree, 34 agree, 18 disagree and 13 strongly disagree.

With a mean score of 2.68, the statement "unavailability of clear policy and regulation on reverse logistics practice and lack of support from government" ranks 5th as 27 respondents strongly agree, 30 agree, 19 disagree and 19 strongly disagree.

Table 9.6 showed that Ranking 1st is the statement "integration is an important supply chain practice in our organization" as 42 respondents strongly agree, 31 agree, 13 disagree and 9 strongly disagree resulting to a mean score of 3.12.

Table 9.6. Responses on supply chain practices in water bottling companies in Port Harcourt, Nigeria

	Supply chain practices	SA (4)	A (3)	D (2)	SD (1)	Mean	Rank	Remark
1	Integration is an important supply chain practice in our organisation	42	31	13	9	3.12	1st	Agreed
2	Information sharing is an important supply chain practice in our organisation	33	29	20	13	2.86	5th	Agreed
3	Customers and delivery management is an important point of use in our organisation	42	31	11	11	3.09	2nd	Agreed
4	Our company deals with a third-party who specializes in business logistics and supply	34	34	17	10	2.97	3rd	Agreed
5	Speed of responsiveness is a important supply chain practice in our organisation	38	26	19	12	2.95	4th	Agreed

Mean criterion: Disagree if mean value is lower than 2.5 otherwise, Agree

Source: Researcher's Field Work, 2022.

The statement "customers and delivery management is an important point of use in our organization" ranks 2nd with a mean score of 3.09 as 42 respondents strongly agree, 31 respondents agree, 11 respondents disagree and 11 respondents strongly disagree.

On the 3rd positon is the statement "our company deals with a third-party who specializes in business logistics and supply" as 34 respondents strongly agree, 34 agree, 17 disagree and 10 strongly disagree, yielding to a mean score of 2.97.

38 respondents strongly agree, 26 agree, 19 disagree and 12 strongly disagree that speed of responsiveness is an important supply chain practice in our organization which results to a mean score of 2.95 and ranking 4th.

With a mean score of 2.86, the statement "information sharing is an important supply chain practice in our organization" ranks 5th as 33 respondents strongly agree, 29 agree, 20 disagree and 13 strongly disagree.

Conclusion

This study has been concerned with the assessment of reverse logistics in the supply chain of bottling companies in Nigeria. a case study of Junac and La sien water bottling company, Port Harcourt, Nigeria. Theoretical concepts such as Reverse Logistics, Reverse Logistics Practices/Activities, Reverse Logistics Strategies, Reverse Logistics

Importance, Challenges in Reverse Logistics, Supply Chain and Its practices were all reviewed. Chapter two earmarked the methods and procedures for data collection and analysis. The following chapter presents the results and discussion. Descriptive and inferential statistical techniques were employed for the study. A total of 95 copies of the questionnaire were administered to supervisors, senior employees, and middle and upper-level managers of these two organizations.

Based on the results obtained from the study the following findings were made and summarised as follows:

1. The level of understanding of reverse logistics concept in water bottling companies in Port Harcourt, Nigeria is high with a percentage of 73.2% which has an equivalent mean score of 2.93 on a likert scale rating of 1-4.
2. The current trend practiced in water bottling companies in Port Harcourt, Nigeria is proper disposal and reusage of plastic bottles in order to protect the environment and to make plastic bottles as a source of income.
3. The major driving forces behind the implementation of reverse logistics in water bottling companies in Port Harcourt, Nigeria are to increase customer satisfaction, to generate profit and to decrease raw materials cost.
4. The major challenges for the successful implementation of reverse logistics in water bottling companies in Port Harcourt, Nigeria are high cost related to reverse logistics and organization's financial barrier and lack of available expertise in the reverse logistics proces.
5. The major supply chain practices in water bottling companies in Port Harcourt, Nigeria are integration and customers and delivery management.

This study concludes that water bottling companies in Port Harcourt, Nigeria with emphasis on JUNAC and La Sien understand the concept of reverse logistics, they are goal driven to protect the environment as well as generate profit from renewable materials. Though the practice of reverse logistics seem to be high in this organisations, the major challenges they face is the issue of high cost related to reverse logistics and the organization's financial barrier. However, there is a still need for collaboration in Reverse Logistics the by direct commitment of these organisations with its suppliers and customers so as to help in solving environmental problems.

To enhance reverse logistics in water bottling companies in Port Harcourt, a collaborative approach with suppliers and customers is essential to establish a closed-loop supply chain. Implementing cost-effective recycling methods, leveraging government incentives, and integrating technology for tracking and optimization can help reduce financial barriers. Training programs should be introduced to build employee expertise in reverse logistics, while customer incentives like discounts for returning used bottles can boost participation. Pilot testing these strategies in smaller regions can refine the process before scaling up, ensuring both environmental and economic benefits.

References

Alok, A., & Choudhary, V., (2014). Reverse logistics: Performance measures and their effect in product lifecycle. *An International Journal of Core Engineering and Management* (IJCEM) 1(2) May, 2014.

Babbie, E. (2020). *The Practice of Social Research.* Belmont, CA: Thomson/Wadsworth.

Bulger R (2024), *Going Circular the Evolution of Reverse Logistics into a Competitive Weapon*. Brown Books Publishing Group.

Ganeshan, R, & Harrison, T.P. (1995). *An Introduction to Supply Chain Management*. Department of Management Sciences and Information Systems.

Gifford, Dun, Jr. (1997). The value of going green. *Harvard Business Review*, 75, 11.

Guldem, E., & Fevzi, E., (2011). The importance of Reverse Logistics. *International Journal of Business Management Studies*, 3(1), 161-171.

Heda, S., Mewborn, S., & Caine, S. (2017). How customers perceive a price is as important as the price itself. *Harvard Business Review*, 3, 5. [Internet: https://hbr.org/2017/01/how-customers-perceive-a-price-is-as-important-as-the-price-itself; downloaded on 2023-02-05.]

Ilgin, M.A., & S.M. Gupta (2010). Environmentally conscious manufacturing and product recovery (ECMPRO). A review of the state of the art. *Journal of Environmental Management* 91(3), 563-591.

Kokkinaki, A., Dekker, R., Lee, R., & Pappis, C. (2001). Integrating a web-based system with business processes in closed loop supply chains. No. EI 2001-31.

Kosacka-Olejnik, M., & Werner-Lewandowska, K. (2020). Reverse logistics as a trend of XXI century – state of art. *Management Systems in Production Engineering*, 28(1), 9-14.

Matsumoto, M. (2009). Business frameworks for sustainable society: a case study on reuse industries in Japan. *Journal of Cleaner Production*, 17(17), 1547-1555.

Mishra, N., Kumar V., & Chan, F.T.S. (2012). A multi-agent architecture for reverse logistics in a green supply chain. *International Journal of Production Research* 50(9), 2396-2406.

Narayanan, S. (2010). *Optimizing reverse logistics with SAP ERP*. Bonn, Galileo Press.

Nasr, N., & Thurston, M. (2006). Remanufacturing: A key enabler to sustainable product systems. *Rochester Institute of Technology*, 23, 14-17.

Pinna, R., & Paolo, P. (2012). Reverse logistics and the role of fourth party logistics provider. *Pathways to Supply Chain Excellence*, 91-114.

Power, D.J., & Sohal, A. (2001). Critical success factors in agile supply chain management: An empirical study. *International Journal of Physical Distribution and Logistic*, 31(4), 247- 265.

Reverse Logistics Association (2006). Spring/Summer. Reverse Logistics Magazine 2006, 22.

RevLog, The European Working Group on Reverse Logistics (1998).

Rogers, D.S, & Tibben-Lembke, R.S. (2001). An examination of reverse logistics practices. *Journal of Business Logistics*, 22, 129-148.

Rubio, S., Chamorro, A., & Miranda, F.J. (2008). Characteristics of the research on reverse logistics (1995-2005). *International Journal of Production Research*, 46(4), 1099-1120

Salas-Navarro, K., Castro-García, L., Assan-Barrios, K., Vergara-Bujato, K., & Zamora-Musa, R. (2024). Reverse logistics and sustainability: A bibliometric analysis. *Sustainability*, 16(113), 5278.

Szymonik, A., & Stanisławski, R. (2023), *Supply Chains in Reverse Logistics the Process Approach for Sustainability and Environmental Protection*, Productivity Press.

Thierry, M., Salomon, M., van Nunen, J., & van Wassenhove, L.N. (1995). Strategic issues in product recovery management. *California Management Review*, 37(2), 114-135.

Williams, E., Kahhat, R., Allenby, B., Kavazanjian, E., Kim, J., & Xu, M. (2008). Environmental, social, and economic implications of global reuse and recycling of personal computers. *Environmental Science & Technology*, 42(17), 6446-6454.

www.hollingsworthllc.com/guide-reverse-logistics

www.interlakemecalux.com/blog/cannibalization-reverse-logistics

Yamane, Y. (1967). Mathematical formulae for sample size determination. *J. Mathemetics*, 1, 1-29.

Yao, X., & Askin, R. (2019). Review of supply chain configuration and design decision-making for new product. *International Journal of Production Research*, 57(7), 2226-2246.

Yu, H., & Solvang, W.D. (2016). A general reverse logistics network design model for product reuse and recycling with environmental considerations. *The International Journal of Advanced Manufacturing Technology*, 87(9-12), 2693-2711.

PART III

Transport and Logistics Economics

Chapter 10

URBAN ROAD TRANSPORT IN A LARGE CITY: IDENTIFICATION OF KEY CHALLENGES

Marta Daroń

Czestochowa University of Technology, Faculty of Management, Poland
marta.daron@ pcz.pl ORCID 0000-0002-5000-0573

Abstract: Currently, large cities face a number of challenges related to managing urban road transport. The increase in the number of vehicles, the need for effective parking space management, and the organization of traffic are key aspects affecting the daily functioning of residents. The aim of this article is to identify the most important challenges related to urban road transport in Częstochowa. The study was conducted using the CAWI (Computer-Assisted Web Interviewing) method on a sample of 400 residents of Częstochowa. The survey included questions about the way information is provided about planned and current traffic disruptions, the adaptation of paid parking zones in the city center to current conditions and needs, the costs of paid parking in the city, the organization of traffic in the center of Częstochowa, and the organization of transport related to the reconstruction of the road network. The survey results provided valuable insights into residents' perceptions and key areas requiring improvements.

Keywords: urban transport, road transport, urban transportation system management

Introduction

Road transport in cities, especially in those with high population density, represents one of the most critical issues in contemporary urban space management. The increase in the number of vehicles on the roads and the growing transport needs of residents and visitors present numerous challenges for local authorities related to ensuring traffic flow (Hou et al., 2021; Zheng et al., 2022), optimizing parking space, and minimizing environmental impacts (Georgakopoulos et al., 2023). Particularly in large urban agglomerations, the intense use of road infrastructure leads to system overloads, which directly affects residents' quality of life and the overall efficiency of the agglomeration's functioning (Głębocki, 2024).

The growing interest in the urban transport system topic stems from the increasing importance of this system for the daily functioning of urban communities. In large urban areas, the complexity of challenges related to traffic management, parking space organization, and informing residents about ongoing changes in road infrastructure requires systematic study and monitoring. It is also important to note the rising maintenance costs and the necessity to adapt road transport to modern environmental and economic realities.

The aim of this chapter is to identify the key challenges faced by urban road transport in Częstochowa. Based on conducted survey research residents' perceptions regarding the effectiveness of current solutions in traffic management, parking policy, and transport information management are analyzed. It also examines which of these factors influence the choice of transport mode (private/public) by the city's residents. The following research hypotheses were established:

- Hypothesis 1: The residents of the surveyed city recognize and accept modern solutions in urban transport.
- Hypothesis 2: Higher parking fees contribute to an increase in the number of people using public transport.
- Hypothesis 3: Changes in urban transport organization, including on road sections under renovation, impact the choice of public transport.

The survey, conducted using the CAWI method on a sample of 400 residents of Częstochowa, provided valuable data on the local community's perception of urban road transport. The analysis of the survey results helps identify key areas requiring improvement and points to directions for actions that could enhance road transport organization in the city.

Problems of urban transport – review

The review is based on an analysis of scientific articles available in the ScienceDirect database, with particular attention given to works published in the last few years, i.e., since 2019. During this period, a noticeable increase in publications on intelligent urban transport management systems was observed. Literature related to urban road transport highlights several challenges faced by large cities. Studies on public transport present various approaches to improving its functioning in cities, focusing on aspects such as pricing strategies, operational efficiency, passenger satisfaction, system integration, and the use of intelligent solutions. For example, challenges related to improving the efficiency of urban transport systems are presented by Laatabi et al. (2024). Using agent-based modeling, these authors identified the issue of buses skipping stops and pointed to the need for introducing free transfers. Similarly, Yap et al. (2024), analyzing the perception of transfers in London, emphasize differences in the reception of various types of transfers – cross-platform transfers are rated more positively than those requiring level changes or bus-to-bus transfers. In the context of pricing strategies for urban public transport, Wallimann et al. (2023) showed that a 29% reduction in annual ticket prices resulted in a 10.6% increase in passenger numbers. These studies underscore the importance of structural changes and pricing policies in promoting more sustainable and accessible urban transport.

In the context of increasing congestion on the main arteries of large cities, interesting research was presented by Neradilová et al. (2023), who suggested introducing priority for public vehicles. According to these authors, this could contribute to improved traffic flow and increased system efficiency. Many studies also focus on public transport passenger satisfaction. Authors studying this issue identify key factors such as cleanliness, frequency of services, vehicle availability, safety, and even drivers' driving styles or the service quality-to-price ratio (Khademi-Vidra et al., 2024; Ong et al., 2023; Soza-Parra et al., 2019).

A lot of attention is also given to integrated transport systems that combine traditional and flexible forms of transport. These are becoming increasingly popular in response to changing urban mobility patterns and may represent the future of transport in large agglomerations. Examples of such works include Melis et al. (2024), who propose a model integrating on-demand buses with the existing metro network, and Ballantyne et al. (2024), who developed accessibility indicators for bus, rail, and bicycle infrastructure, considering demand for these modes of transport. Additionally, Kubera & Ślusarczyk (2003, 2024) analyzed the context of shared mobility.

From the perspective of urban transport users, modern solutions such as electronic ticketing systems and real-time traffic information systems are also essential, as they increase the convenience of using public transport (Pomianowski, 2023). A separate and equally important topic in urban transport is related to the design of parking spaces and parking fee systems. Studies such as those by Campisi et al. (2022), Kushchenko et al. (2022), and Chomiak-Orsa et al. (2022) provide examples of various simulation methods used in this type of analysis.

Despite differences in approach, all studies share a common goal – improving public transport functionality, increasing its attractiveness and supporting sustainable urban development.

Research methodology

The survey, on the basis of which the analysis was conducted, was carried out using the CAWI (Computer-Assisted Web Interviewing) method on a sample of over 400 residents of the city of Częstochowa. The survey was targeted at individuals with varying demographic statuses, including diverse age groups, gender, place of residence, and employment status. The questionnaire consisted of more than 20 questions, with the number varying depending on the respondent's employment status group – see Figure 10.1.

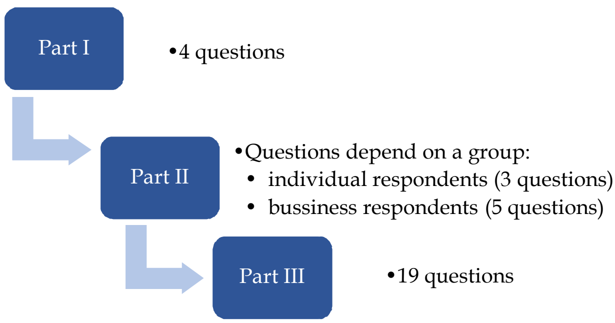


Figure 10.1. Structure of the questionnaire

Source: Own study based on research.

The analysis of respondents' characteristics allows for several conclusions (Table 10.1). First, the majority of responses come from individuals in the 36-50 age group. This may suggest that this age group most frequently uses the city's transport system. Second, residents from districts other than the city center make up the largest group (56%) in terms of place of residence. Third, women accounted for 68% of respondents, which is somewhat understandable as the survey was distributed via social media, and women are generally more inclined to participate in online surveys. Fourth, a specific trend among the city's residents is revealed – the majority of respondents (79%) use their own means of transport when moving around the city.

Table 10.1. Respondents' characteristics

Age	Density	%
10-19	21	5
20-25	33	7
26-35	60	14
36-50	273	62
51-65	39	9
66 and more	15	3
Total	441	100
Gender	**Density**	**%**
man	143	32
woman	298	68
Total	441	100
Place_of_living	**Density**	**%**
city center	42	9
city	246	56
other	153	35
Total	441	100
Activity	**Density**	**%**
student	47	11
employee	225	51
employer	139	31
other	30	7
Total	441	100
Transport_mode	**Density**	**%**
On foot/bike/scooter/other	9	2
Public transport	85	19
Own transport	347	79
Total	441	100

Source: Own study based on research.

The survey included questions regarding the preferred mode of transport, perceptions of traffic issues, and sources of information about local traffic disruptions. The main topics covered in the study involved the most frequently used modes of transport (walking, cycling, scooter, public transport, private transport), the use of various information channels (announcements, posters, applications) to monitor current traffic disruptions, and opinions on traffic management and paid parking zones in Częstochowa.

The data was collected in a way that allowed for further statistical analysis, enabling conclusions to be drawn about residents' perceptions and identifying areas in need of improvement in terms of road transport. Specifically, the collected data was analyzed to identify general trends in the perception of the transport system and existing solutions in Częstochowa. A correlation analysis was then conducted to examine the relationships between residents' ratings in the surveyed areas and their choice of transportation mode.

Research results and discussion

In the main part of the survey, respondents were asked, among other things, for their opinions on the usefulness of various urban transport system solutions existing in the studied city (Table 10.2). Based on the analysis of the results regarding the evaluation of various elements of transport infrastructure in Częstochowa, it is noticeable that the time displays at bus stops are among the highest-rated solutions. As many as 61.9% of respondents consider them very useful, with an additional 31.5% finding them useful. This means that almost all survey participants (93.4%) view these displays as a helpful tool in their daily use of public transport. This result may stem from the widespread use of public transport and the residents' need to be informed about the current waiting times for vehicles. Similarly, cashless parking meters were positively evaluated, with 52.2% of respondents considering them very useful and 40.1% finding them useful. A total of 92.3% positive opinions indicate that residents appreciate the convenience of cashless payments, which may reflect their broad acceptance within the city's infrastructure. The growing popularity of cashless technologies and their common availability in other aspects of daily life, such as shopping or services, could be the main factor behind such positive evaluations.

Table 10.2. Assessment of selected urban transport system solutions in the opinion of respondents

Urban transport system solutions		do not know	useless	useful	very useful
time diplays	N	27	2	139	273
	%	6.1	0.5	31.5	61.9
cashless_parking_meters	N	31	3	177	230
	%	7.0	0.7	40.1	52.2
bus_stop_displays	N	19	9	159	254
	%	4.3	2.0	36.1	57.6
speed_control_displays	N	33	48	210	150
	%	7.5	10.9	47.6	34.0
city_bikes_system	N	82	9	181	169
	%	18.6	2.0	41.0	38.3
carsharing	N	140	54	150	97
	%	31.7	12.2	34.0	22.0

Source: Own study based on research.

Bus stop displays also received recognition from respondents, with 57.6% considering them very useful and 36.1% finding them useful, leading to a total of 93.7% positive opinions. These displays, like those providing information about arrival times, play an important role in improving the convenience of public transport use, enabling residents to better plan their journeys. Speed control displays, on the other hand, received mixed reviews. While 47.6% of people found them useful and 34.0% very useful, totaling 81.6% positive opinions, a noticeable percentage of respondents (10.9%) considered these displays useless. This may be due to the fact that not all drivers perceive speed displays as an effective tool for increasing safety, or their placement does not always address the real needs of road traffic.

The city bike system was positively evaluated by 79.3% of respondents, with 38.3% considering it very useful and 41.0% finding it useful. At the same time, 18.6% had no opinion on the matter, which may suggest that the system is not yet widely used by residents. Possible explanations could include limited availability of city bikes or a lack of cycling infrastructure in certain parts of the city. In the case of car-sharing, the results indicate a relatively low level of awareness or popularity of this service among residents. As many as 31.7% of respondents had no opinion on car-sharing, which could be due to a lack of knowledge about its availability in the city. Only 22.0% rated car-sharing as very useful, and 34.0% as useful. The lower ratings compared to other modes of transport may be related to the limited car-sharing network in the city or insufficient promotion of this service.

Next, the respondents were asked to evaluate selected system solutions related to transport in the studied city. The frequency of responses is presented in Table 10.3.

Table 10.3. Evaluation of selected areas of the transport system in the studied city

Scale		**do not know**	**very bad**	**bad**	**midly**	**good**	**very good**
x_1 – electronic ticketing system	N	208	3	9	51	109	61
	%	47.2	0.7	2.0	11.6	24.7	13.8
x_2 – information about traffic disruptions	N	79	35	57	181	57	32
	%	17.9	7.9	12.9	41.0	12.9	7.3
Scale		**do not know**	**very few**	**few**	**midly**	**many**	**very many**
x_3 – number of available parking spaces in the paid parking zone	N	60	28	82	169	78	24
	%	13.6	6.3	18.6	38.3	17.7	5.4
Scale		**do not know**	**very high**	**high**	**midly**	**low**	**very low**
x_4 – cost of paid parking in the city center	N	57	51	100	145	78	10
	%	12.9	11.6	22.7	32.9	17.7	2.3
Scale		**do not know**	**very bad**	**bad**	**midly**	**good**	**very good**
x_5 – traffic management in the city center	N	30	46	127	130	98	10
	%	6.8	10.4	28.8	29.5	22.2	2.3
x_6 – changes in transport organization on road sections under renovation	N	54	88	107	99	75	18
	%	12.2	20.0	24.3	22.4	17.0	4.1

Source: Own study based on research.

The analysis of the results concerning the evaluation of various aspects of urban road transport in Częstochowa allows for the identification of several key challenges. The assessment of the electronic ticketing system indicates that a significant portion of respondents (47.2%) have no opinion on the matter, which suggests that many residents may not use this solution or are unfamiliar with its operation. However, among those who do use the system, positive opinions prevail – 24.7% rate it as good, and 13.8% as very good. This may indicate that the system operates efficiently, but its usage is still limited, potentially due to a lack of promotion or insufficient accessibility.

The information about traffic disruptions is rated as "average" by 40.6% of respondents, indicating moderate satisfaction with the quality of the information provided. At the same time, 20.9% of respondents find the information inadequate, suggesting that this system needs improvement. The problem may lie in the lack of easy access to up-to-date data on disruptions or in the insufficient adaptation of communication methods to residents' needs.

Another significant aspect is the number of parking spaces in the paid parking zone in the city center, which is considered insufficient by 24.9% of residents, while 38.3% rate it as "average". Although parking issues are evident, they are not perceived as critical by the majority of respondents. It is possible that this situation results from a limited number of parking spaces in the city center, forcing residents to seek alternatives, such as parking on the outskirts of the city.

The evaluation of paid parking costs also suggests some dissatisfaction – 34.3% of respondents consider these costs high, and 32.9% as "average". High fees may pose a barrier to using parking facilities in the city center, which could discourage residents from driving in this part of Częstochowa. It would be worth considering adjusting the pricing policy to encourage parking in the city center while maintaining traffic flow.

The organization of traffic in the city center elicits mixed reactions. Nearly 40% of respondents express dissatisfaction, indicating difficulties related to traffic flow or the availability of road infrastructure. Only 22.2% rate the organization as good, and just 2.3% as very good, suggesting that significant improvements are needed, especially in traffic management in key areas of the city. Possible explanations include the complicated street structure in the center and traffic congestion, particularly during peak hours.

Even greater challenges concern changes in transport organization on road sections under renovation, which are negatively evaluated by 44.3% of respondents. Residents express dissatisfaction with temporary solutions, which may be due to a lack of adequate communication about detours and changes in traffic organization. This situation points to the need for better planning and informing residents about changes, especially in the context of long-term road renovations that affect the city's daily functioning.

In the next step, it was decided to examine the relationship between variables x_1-x_6, which are independent variables, and the mode of transport chosen by residents (x0), which is the dependent variable. In the first phase, the variables were coded as follows:

– each of the variables x_1-x_6 refers to the assessment of aspects of the functioning of transport infrastructure and urban services on a three-point scale: negative assessment (1), neutral (2), and positive (3).

– for variable x_0, code 0 was assigned for “own transport”, while code 1 was assigned for "public transport" and "on foot/bike/scooter/other," as these modes of transport are most desirable in urban areas.

Next, data related to variables x_1-x_6, excluding responses containing “I don't know”, were filtered, and a chi-square test was conducted to examine the relationship between these variables and the dependent variable x_0. Given that the analyzed variables are categorical/ordinal, Spearman's rank correlation coefficient was also used (Table 10.4).

Table 10.4. Relationship between variables – results

Variable	Chi-square	df	p-value	Number of valid observa-tions	Contingency coefficient	Spearman correlation
x_1	0.094	2	0.954	233	0.020	0.005
x_2	30.471	2	< 0.001	362	0.279	0.216
x_3	28.09	2	< 0.001	381	0.262	0.247
x_4	9.51	2	0.009	384	0.155	0.09
x_5	1.45	2	0.378	411	0.069	0.01
x_6	18.252	2	< 0.001	387	0.212	–0.056

Source: Own study based on research.

On the basis of results presented in Table 10.4 there can be indicated whether there is a relationship between the assessments of various aspects of the functioning of transport and urban infrastructure and the choice of transport mode. For the electronic ticketing system (x_1), the chi-square test result ($p = 0.954$) indicates that the evaluations of this system's functionality do not significantly influence the choice of transport. This suggests that to increase the use of public transport, the ticketing system alone may not be sufficient – other amenities or campaigns promoting the benefits of the system may be necessary.

In the case of the evaluation of traffic disruption information (x_2), a significant chi-square test result ($p < 0.001$) indicates that a better assessment of this aspect may encourage the use of public transport. The contingency coefficient (0.279) and Spearman's correlation (0.216) suggest that residents using public transport rate the quality of traffic disruption information higher than those using private transport. This means that improving access to traffic disruption information could be a key factor influencing the choice of public transport.

Adjusting the number of parking spaces in the paid parking zone (x_3) also significantly impacts the choice of transport ($p < 0.001$). For this variable, the following scale was applied: 1 – “few”, 2 – “adequate”, 3 – “many” parking spaces. Public transport users rate the availability of parking spaces higher than those using private transport, which suggests that an insufficient number of parking spaces may lead people to opt for public transport over private transport. The contingency coefficient (0.262) and Spearman's correlation (0.247) emphasize the importance of this aspect.

For the evaluation of the cost of paid parking (x_4), with the applied scale: 1 – “high”, 2 – “appropriate”, 3 – “low”, the chi-square test ($p = 0.009$) indicates that there is a statistically significant relationship between the assessment of parking costs and the choice of transport. The contingency coefficient (0.155) and Spearman's correlation (0.09) show that individuals who rate parking costs as high are more likely to choose public transport. This suggests that increasing parking costs in the city center could encourage residents to forgo private transport in favor of public transport.

The organization of traffic in the city center (x_5) does not show a significant relationship with the choice of transport ($p = 0.378$). This means that the organization of traffic in the city center is not a sufficient factor to influence transportation preferences.

However, with regard to variable x_6 - changes in transport organization on road sections under renovation – there can be said that it is a significant factor influencing the choice of transport ($p < 0.001$). The contingency coefficient (0.212) indicates a significant relationship, while the negative Spearman correlation (–0.056) suggests that negative evaluations of changes in transport organization may discourage the use of public transport. Improving the organization of transport on road sections under renovation could, therefore, increase the share of public transport users. It is possible that residents, not knowing exactly which transit lines to use under the new conditions, opt for private transport.

In summary, improving elements such as providing information on traffic disruptions, the availability of parking spaces, and the organization of transport on road sections under renovation could increase the number of residents using public transport, which is a key goal in the development of sustainable urban transport.

Conclusion

In light of the conducted analyses, the research hypotheses were largely confirmed, allowing for a better understanding of the key challenges related to urban road transport in Częstochowa and identifying factors that may encourage residents to use public transport. Hypothesis 1, which assumed that the city's residents recognize and accept modern solutions in urban transport, was confirmed. The analysis of collected opinions shows that time displays at bus stops and cashless parking meters are highly rated by Częstochowa residents, with positive feedback at 93.4% and 92.3%, respectively. At the same time, it was noted that car-sharing services are less popular in the studied city, with 31.7% of respondents having no opinion on the matter. This may result from limited availability or promotion of this form of transport.

Hypothesis 2, which stated that higher costs associated with private transport, such as parking fees, encourage the use of public transport, was also confirmed. High costs of paid parking in the city center are one of the factors that force some residents to switch from private to public transport. Therefore, increasing parking fees could be an effective mechanism for promoting public transportation, especially in central areas where parking space is limited. Moreover, the analysis results indicate that the assessment of aspects such as traffic disruption information and the availability of parking spaces also significantly influences the choice of transport mode. Residents who rated these aspects better were more likely to use public transport, suggesting that investments in improving infrastructure and better urban information management could influence transportation preferences.

Hypothesis 3, which proposed that changes in urban transport organization, especially on road sections under renovation, impact the choice of public transport, was also confirmed. Negative evaluations of these changes were associated with a reduced inclination to use public transport, meaning that better traffic organization during roadworks could improve the perception of public transport and increase its attractiveness to residents. Poorly organized and inefficient communication during renovations leads to user frustration, which may discourage the use of public transport.

Regarding other research results, it is worth noting that the assessment of the electronic ticketing system and traffic management in the city center had no significant impact on the choice of transport, indicating that other factors, such as costs and the availability of information, are more critical.

Based on the research, it can also be concluded that Częstochowa residents most value those infrastructure elements that directly improve traffic management and make daily use of public transport easier, such as time displays and cashless parking meters. Less known or less commonly used services, such as car-sharing or the city bike system, still have great potential for development, which requires further promotional efforts and infrastructure investments.

Despite its advantages, the paper also has some limitations. Due to limitations related to the online data collection method, the sample may not be fully representative of the entire city population. Respondents were selected based on their availability and willingness to participate in the study, which means that random selection was not used. Future research should consider more diverse sampling methods to obtain better representativeness of the data.

In summary, the research results provide a better understanding of the factors influencing transport choices in Częstochowa and indicate that the research goal – identifying the most important challenges related to urban road transport – was achieved. Key challenges such as improving the quality of traffic disruption information, the availability of parking spaces, and optimizing transport organization during roadworks could form the basis for further actions aimed at promoting public transport in the city. Improving these elements of infrastructure and transport policy could help increase the number of people using public transport, which is a crucial step towards the sustainable development of urban transport.

References

Ballantyne, P., Filomena, G., Rowe, F., & Singleton, A. (2024). Developing two-dimensional indicators of transport demand and supply to promote sustainable transportation equity. *Computers, Environment and Urban Systems*, 113, 102179. DOI: 10.1016/j.compenvurbsys.2024.102179.

Campisi, T., Caselli, B., Rossetti, S., & Torrisi, V. (2022). The evolution of sustainable mobility and urban space planning: Exploring the factors contributing to the regeneration of car parking in living spaces. *Transportation Research Procedia*, 60, 76-83. DOI: 10.1016/j.trpro.2021.12.011.

Georgakopoulos, D., Nikolaou, D., Roussou, J., & Yannis, G. (2023). The impact of mobility characteristics on public transport and road safety performance in selected European cities. *Transportation Research Procedia*, 72, 1547-1551. DOI: 10.1016/j.trpro.2023.11.622.

Głębocki, K. (2024). Smart city strategic planning: are there social grounds in medium-sized polish cities? *Polish Journal of Management Studies*, 29(1), 132-143. DOI: 10.17512/pjms.2024.29.1.08.

Hou, Y., Chen, J., & Wen, S. (2021). The effect of the dataset on evaluating urban traffic prediction. *Alexandria Engineering Journal*, 60(1), 597-613. DOI: 10.1016/j.aej.2020.09.038.

Khademi-Vidra, A., Nemecz, G., & Bakos, I.M. (2024). Satisfaction measurement in the sustainable public transport of Budapest. *Transportation Research Interdisciplinary Perspectives*, 23, 100989. DOI: 10.1016/j.trip.2023.100989.

Kubera, M., & Ślusarczyk, B. (2023). Carsharing as an element of mobility management. Polish *Journal of Management Studies*, 27(2), 188-205. DOI: 10.17512/pjms.2023.27.2.12.

Kubera, M., & Ślusarczyk, B. (2024). *Rethinking Sustainable Transportation: The Role of Shared Mobility in Urban Environments*. In Kot, S., & Khalid, B., & ul Haque, A. (eds.), *Corporate Practices: Policies, Methodologies, and Insights in Organizational Management*, (939-950). Springer Proceedings in Business and Economics. DOI: 10.1007/978-981-97-0996-0_55.

Kushchenko, L., Kushchenko, S., Novikov, I., & Novikov, A. (2022). The paid parking space organization as one of the ways to increase the capacity of the road in Belgorod urban agglomeration. *Transportation Research Procedia*, 63, 868-877. DOI: 10.1016/j.trpro.2022.06.084.

Laatabi, A., Benchra, A., Marilleau, N., & Nguyen-Huu, T. (2024). Assessing public transport strategies in marrakesh using ABMS. *Procedia Computer Scienc*e, 238, 566-571. DOI: 10.1016/j.procs.2024.06.061.

Melis, L., Queiroz, M., & Sörensen, K. (2024). The integrated on-demand bus routing problem: Combining on-demand buses with a high-frequency fixed line public transport network, *Computers & Operations Research*, 164, 106554, DOI: 10.1016/j.cor.2024.106554.

Neradilová, H., Fedorko, G., Molnár, V., Fabianová, J., Michalik, P., & Lacková, L. (2023). Increasing public transport system operation efficiency in the city of Košice – the case study, *Transportation Research Procedia*, 74, 275-283. DOI: 10.1016/j.trpro.2023.11.145.

Ong, A.K.S., Agcaoili, T.I.F., Juan, D.E.R., Motilla, P.M.R., Salas, K.A.A., & German, J.D. (2023). Utilizing a machine learning ensemble to evaluate the service quality and passenger satisfaction among public transportations. *Journal of Public Transportation*, 25, 100076. DOI: 10.1016/j.jpubtr.2023.100076.

Pomianowski, A. (2023). The use of smartphone applications when buying public transport and paid parking zone tickets on the example of Szczecin. *Procedia Computer Science*, 225, 2449-2456. DOI: 10.1016/j.procs.2023.10.236.

Soza-Parra, J., Raveau, S., Muñoz, J.C., & Cats, O. (2019). The underlying effect of public transport reliability on users' satisfaction. *Transportation Research Part A: Policy and Practice*, 126, 83-93, DOI: 10.1016/j.tra.2019.06.004.

Wallimann, H., Blättler, K., & von Arx, W. (2023). Do price reductions attract customers in urban public transport? A synthetic control approach, *Transportation Research Part A: Policy and Practice*, 173, 103700. DOI: 10.1016/j.tra.2023.103700.

Yap, M., Wong, H., & Cats, O., (2024). Passenger valuation of interchanges in urban public transport. *Journal of Public Transportation*, 26, 100089. DOI: 10.1016/j.jpubtr.2024.100089.

Zheng, Y., Wang, S., Dong, C., Li, W., Zheng, W., & Yu, J. (2022). Urban road traffic flow prediction: A graph convolutional network embedded with wavelet decomposition and attention mechanism. *Physica A: Statistical Mechanics and its Applications,* 608, 128274. DOI: 10.1016/j.physa.2022.128274.

Chapter 11

Factors shaping freight rates in road transport

Katarzyna Grondys*, Aleksandra Placek

Czestochowa University of Technology, Faculty Management, Poland
*katarzyna.grondys@pcz.pl ORCID 0000-0001-6461-5475

Abstract: The transport sector is systematically experiencing an increase in operating costs. Changes in fuel prices, tolls, and labour costs, in turn, have a direct impact on the development of freight rates in road transport, forcing hauliers to adjust prices on an ongoing basis in order to maintain profitability. Fuel expenditure is a key cost element that oscillates between 27% and 37% of all operating costs. Proper cost management allows transport companies to identify potential savings and set competitive prices for their services, which is crucial in the fast-growing TFL sector. Therefore, the objective of the article is to analyze cost management in a transport company, taking into account the specificity of the Polish TSL market and the changes that occur in it. The analysis was based on a database analysis and a case study using the TCO (Total Cost of Ownership) approach. The results obtained made it possible to observe the mechanism of cost formation in a transport company. The recommendations developed on this basis identified practical directions for optimising operations that can bring significant economic benefits to transport companies.

Keywords: road transport, transport costs, freight rate

Introduction

The domestic TSL sector is one of the fastest growing sectors of the national economy (Road freight transport..., 2023). Road transport is the most common mode of transport worldwide, with more than 86% of freight transported by this mode (Transport - Performance Results, 2023, p. 15). Road transport stands out from other modes in terms of increasing efficiency (Ciszewska et.al., 2023, pp. 31-52). This translateş into opportunities for door-to-door delivery processes, which are characterised by the direct flow of goods between sending and receiving points (Grondys & Sałek, 2017, p. 1592). On the other hand, macroeconomic risks of an economic nature, which include rising wages, inflation, rising energy prices, high interest rates, and economic fluctuations, stand in the way of the industry's continued growth. Driver shortages, the decarbonisation process, or unfair competition resulting from the opening of international markets are also a problem. The latter factor has had a particularly strong impact on the competitiveness of domestic transport in recent times and is forcing companies to change the way they calculate costs for the services they provide (Poliak et al., 2021, pp. 86-88). The competitive environment increases the demand for more accurate costing. These factors expose road transport to constant changes and, above all, increasing operating costs. These relate in particular to the operating costs of the vehicle fleet, road infrastructure costs or employee wage costs. Road regulations also play an important role in their level, affecting fines and penalties (Statkienė, 2022, pp. 25-26).

It can also be costly to comply with emission regulations, which requires investment in new and modern trucks (Paradowska & Kociszewski, 2018, p. 85).

Therefore, the process of effective cost management in a transport company is particularly important and should include:
- cost analysis and monitoring,
- financial auditing and advice,
- budget planning taking into account future price change forecasts.

Effective cost management requires a holistic and innovative approach (Jarocka, 2016, p. 57). The combination of these activities allows for an effective response to market changes, minimising losses, and maintaining the ability to invest and grow. All this influences the determination of the level of the freight rate, which depends on a number of factors and is subject to change as much as its individual components. As a result, the company can achieve sustainable profitability and a better competitive position in the market (Hermundsdottir & Aspelund, 2021, p. 3).

The role of the production characteristics of transport services in shaping operating costs

The basic transport cost model takes into account the sum of the marginal costs incurred by transport companies and the profit margin for a specific transport order. These costs include (Fan et al., 2023, pp. 2-4):
- direct costs i.e.: freight and insurance charges,
- indirect costs that relate to goods in transit, their storage, loading activities in multimodal transport, etc. Container loading and other concepts.

A key element in the process of shaping the above-mentioned costs is the compatibility of the production and consumption of transport services. The lack of warehousing of services necessitates the determination of an assessment of the level of capacity of transport means and the choice of matching supply with average, maximum, or minimum demand (Baller, 2019, p. 1015). Reaching maximum capacity means that the system is operating at the limit of its operational capacity. Minimum capacity, on the other hand, means the operational floor below which the transport system cannot operate without inefficiency or financial loss (Liu et al., 2015, p. 315-316). Both the level of maximum capacity and the decision to choose a service provision strategy determine the subsequent production costs of transport services, especially under conditions of high demand fluctuation in this market (Tunç & Büyükkeklik, 2017, pp. 39-42). The availability of services in response to market demand, in turn, determines the level of competition in the domestic market and, in the case of an individual company, forces a reduction in operating costs (Cioc & Dumitru, 2013, p. 89; Wheat et al., 2019, p. 2).

In freight transport, handling facilities at shipping and receiving points are important. The need to use these facilities leads to a significant burden on transport costs. The same applies to combined transport, which uses different modes of transport and carriers. This is further related to the costs of the simultaneous use of transport means and transport infrastructure (Krajewska & Łukasik, 2017, p. 204). The type and level of costs differ in different modes of transport. In freight transport, an important aspect can be seasonal fluctuations due to seasons, times of day, and holiday breaks, which limit the possibility of loading and unloading goods at any time (Bronk, 2014, p. 22). The features of transport service production are directly reflected in the costs incurred by transport companies, influencing the demand and supply of the transport services market in various transport industries (Krajewska & Łukasik, 2017, p. 205).

Factors driving freight rates

One of the key factors influencing road transport costs is the determination of the so-called freight rate, between the customer and the haulier. Freight rates in road transport are shaped by a number of cost factors. A detailed discernment has been carried out in their research by Chow and Gill (2011, pp. 5-10) or Yoko et al. (2012, pp. 6-7). To determine this rate, it is first necessary to establish what costs will be imposed on the service to help determine the price at which the carrier will contract the service. Factors affecting the freight rate depend on (Russell et al., 2014; Saeedi et al., 2020, pp. 511-512):

- the distance of transport calculated from the place of loading to the place of unloading – calculated in kilometres both ways,
- the place of loading and unloading of the goods to be transported – this may be a place that requires special authorisations, additional charges, compliance with special regulations,
- order execution time – in addition to the standard transport time, delays in delivery are important and may incur financial penalties; moreover, delays in delivery may also result in additional costs related to the necessity to store the cargo,
- the size and type of load – the weight of the load influences the fuel consumption, while the type of load determines the choice of vehicle, which the more specialised the more expensive it is,
- the timing of the transport and the time constraints of the service provided.

These factors determine fuel costs, staff costs, toll costs, permit costs, insurance costs and vehicle operating costs. The cost structure in transport operations can also be analysed in terms of (Bronk, 2014, p. 28):

- costs related to depreciation of transport vehicles,
- operating costs, including fuel, oil and lubricant consumption,
- personnel costs,
- In freight transport, handling facilities at shipping and receiving points are also important. The need to use these facilities leads to a significant burden on transport costs (Karam et al., 2023, pp. 2-3). The same applies to combined transport, which uses a variety of transport modes and carriers.

Statistical treatment of transport costs

Analyses of the operating costs of Polish transport companies are carried out by the Motor Transport Institute. The results of these studies make it possible to determine the cost structure in the road transport sector in Poland, as illustrated in Figure 11.1. The analyses carried out by the ITS show that the largest share in the costs of carrying out transport tasks, which directly affects the competitiveness of enterprises, is represented by fuel, which accounts for 40.6% of the cost of 1 km of travel. The costs of driver salaries and business trips come second with 17.30%, and tolls come third with around 10.8%.

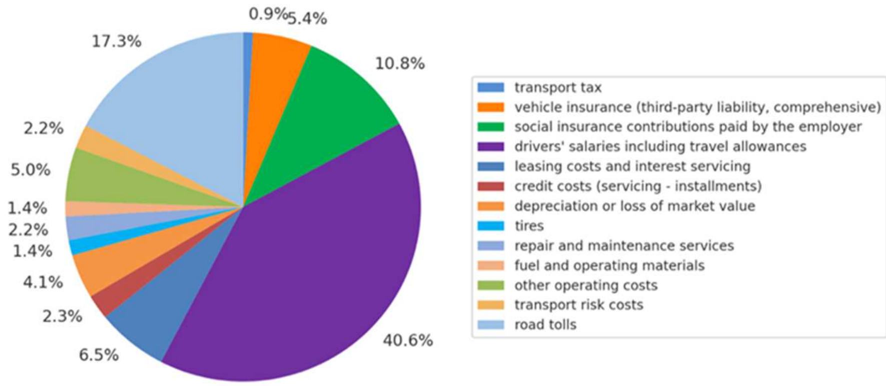


Figure 11.1. Cost structure per km in road transport in Poland (quoted after Osińska & Zalewski, 2012, p. 907)

In Poland, fuel costs, personnel costs and vehicle maintenance are the three main components of transport companies' expenses. In contrast, in Germany, the Netherlands, Belgium and France, the biggest burden is the cost of drivers (Fig. 11.2).

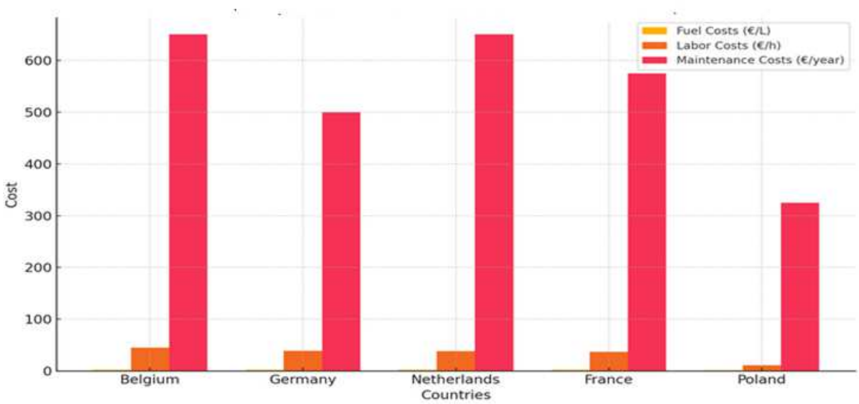


Figure 11.2. Comparison of vehicle costs in Europe (https://www.globalpetrolprices.com)

The effects of inflation, the increase in diesel prices caused by, among other things, the conflict in Ukraine, as well as new regulations with higher wage and business costs, have noticeably impacted the transport industry, which has reflected on freight rates (Xing et al., 2023, pp. 3-4). In the first quarter of this year, the European road freight rate index reached a record high of 110.9 points, an increase of 7.5 points compared to the first quarter of 2021.

According to a report by the EC, fuel expenses account for between 27 and 37% of all transport business costs (Aji & Surjandari, 2020, p. 2). One significant change is the increase in drivers' salaries, which is the result of the adaptation of Polish legislation to the European mobility package. The effect of this is to increase the cost of employing an international driver in a Polish transport company by up to 22%. The analyses by the Motor Transport Institute show that fuel accounts for the largest share of the costs of transport companies (40.6% of the cost per km), while drivers' salaries and business trips (17.3%) and road taxes (10.8%) are also significant. Road and bridge tolls are another considerable cost element, particularly in Europe, where many countries use various forms of road tolls. These costs are directly passed on to the principals, affecting final freight rates (Losik, 2024). The level of freight rates in Poland compared to Europe is presented in Table 11.1.

Table 11.1. Freight rates – most popular destinations in Europe [prices in euro] (The European Road Freight Rate Benchmark…, 2024)

Contract market			
Direction		**Q1 2024**	**Q2 2024**
Poland	Germany	1,508	1,542
Poland	Italy	2,114	2,118
Germany	Poland	1,209	1,192
Italy	Poland	1,729	1,746
Average price on the European market		1,459	1,336
Spot market			
Direction		**Q1 2024**	**Q2 2024**
Poland	Germany	1,657	1,716
Poland	Italy	2,294	2,218
Germany	Poland	1,414	1,511
Italy	Poland	2,018	2,125
Average price on the European market		1,563	1,504

Freight prices at the European level indicate an average rate of €1.46/km in Q1 2024 and €1.37/km in Q2 2024 in the contract market. On the spot market, the average rate was €1.56/km in Q1 2024 and €1.50/km in Q2 2024. The rate on the spot market is slightly higher than on the contract market. At the same time, the cost of transport in both markets has fallen slightly in the quarters under review. Analysing, in turn, the most popular directions of international transport in Poland to Germany and Italy, it is observed that transport rates on the contract market are slightly higher than in the previous quarter, while the direction of transport to Poland is cheaper. The situation is similar in the spot market. At the same time, freight rates are forecast to increase as a result of (The European Road Freight Rate Benchmark..., 2024):

- problems filling driver positions for almost half of European companies,
- the requirement to implement the eurovignette directive,
- an increase in fuel prices due to global political instability,

– continued low levels of industrial production linked to the contract market,
– Reduced demand in the spot market.

In all Baltic, Eastern, and Southern Member States, transport price levels are often below the European average. The highest price levels are observed in Denmark and Sweden, and the lowest in Poland, Bulgaria, Romania, or Hungary (key figures on European transport, 2024). A transport price level index based on the cost of maintenance and operation of the fleet and the cost of ancillary services places Poland in the penultimate place among the thirty European countries (index EU = 100; PL = 75) (Eurostat, 2023).

Research results – case study

In order to present and analyse the cost and freight rate formation in transport activities, a selected example of a company that occupies a significant position in the national transport market was used. For this purpose, a TCO analysis was applied, which includes an analysis of all vehicle owner costs generated in relation to the owned fleet in the case study (Wadud, 2017, p. 164). This means that external factors, such as potential infrastructure costs that have not been internalised through taxes or other charges, are not considered here (Szumska et al., 2012, p. 9). The company under study offers comprehensive temperature-controlled freight services within the country. Within the company's operations, refrigerated contract logistics plays an important role, which is a key element in ensuring efficiency and effectiveness in the area of domestic transport as well as the entire cold supply chain. The company also works 'spot' by performing one-off transports with customers who are not covered by permanent contractual agreements. This means that external factors, such as potential infrastructure costs that have not been internalised through taxes or other charges, are not taken into account.

The freight rate in the company under study is conditioned by several of its components. Details are included in Table 11.2.

Table 11.2. Cost structure in a transport company

Category	Type of cost	Description	Cost share in freight rate
Operating costs	Vehicle maintenance costs	Regular maintenance, repairs, replacement of consumables	35-40%
	Road tolls	Road tolls (e-Toll)	
	Parking charges	Costs for the use of parking spaces	
	Fuel expenditure	Fuel costs for the vehicle fleet	
	Salaries of drivers	Net salaries, social security contributions, other benefits	
	Purchase of parts	Costs of purchasing vehicle parts	

cont. Table 11.2

Administrative costs	Office costs	Office rental, office supplies, utility bills	10-15%
	Fleet management costs	Information systems, GPS monitoring	
	Expenditure on accounting and legal and financial advice	External services of accountants and legal advisors	
	Salaries for administration and management	Salaries for administrative and management staff	
Depreciation costs	Depreciation of vehicles	Depreciation of the value of vehicles	5-10%
	Depreciation of office equipment and supplies	Depreciation of computers, office furniture and other equipment	
Insurance costs	Carrier liability insurance	A policy that indemnifies a transport company against liability for damage to goods entrusted to it that has arisen from fortuitous and unforeseen causes	5-10%
	Vehicle insurance	Insurance policies for company vehicles	
	Employee health and life insurance	Group health and life insurance policies for employees	
Tax costs	Income tax	Corporate income tax	5-10%
	VAT	Tax on goods and services	
	Property taxes	Taxes on owned business property	
Financial costs	Leasing costs	Costs of leasing vehicles and machinery	5-19%
	Interest on loans and borrowings	Interest paid on loans and borrowings taken out	
Marketing costs	Cost of participation in trade fairs and industry conferences	Expenses for participation in industry events	1-5%
	Maintenance of the website and social media activities	Costs related to website maintenance and social media presence	
	Expenditure on advertising and promotions	Costs related to advertising and promotion of the company	
Other costs	Costs of technical inspections of vehicles	Costs of technical inspections	1-3%
	Staff training and development costs	Costs of training, language courses, and other forms of staff development	
	Fees for certifications and industry standards	Costs of obtaining and maintaining industry licenses, certificates, and standards	

Calculation of the freight rate

The company has a fleet of ten truck combinations in the > 12-tonne vehicle category, consisting of a road tractor and a refrigerated semi-trailer. The freight rate calculation process is shown in Figure 11.3.

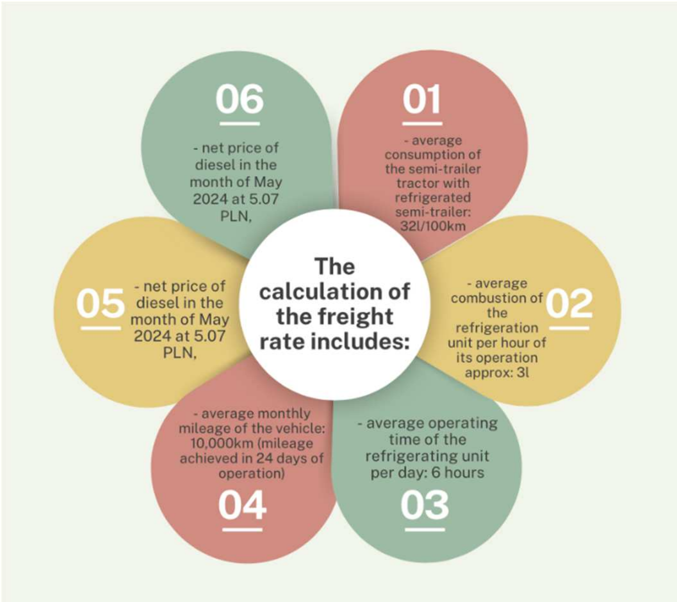


Figure 11.3. The freight rate calculation process in Company X

The freight rate calculation process includes fuel costs, wage costs, road user charges, e-toll system.

Table 11.3. Fuel costs per month

Category	Consumed fuel [L]	Net fuel costs [PLN]	Total net costs	Total gross costs
Heavy goods vehicle	3,200	16,224	18,414	22,649
Refrigeration unit	432	2,190		
Total costs for the entire vehicle fleet			**184,142**	**226,495**

The costs estimated in Table 11.3 show that the average monthly fuel cost per vehicle including a refrigerated trailer is 18,414 PLN. With a fleet of 10 trucks, the total monthly cost is PLN 184,142, this underlines the scale of expenses a transport company has to face and points to potential areas for optimization. Better route planning, responsible fleet management, and investment in driver training can all contribute to a significant reduction in fuel consumption. Meanwhile, long-term forecasts for 2026-2030 assume that oil costs will rise to $115 per barrel (today it is $71 per barrel), which could increase fuel costs for transportation companies by as much as 60% over the next few years (Kane, 2024).

Driver costs account for approximately 40 percent of truck operating costs in developed countries, making a significant proportion of road transport costs come from personnel resources (Engholm et al., 2020, pp. 518-519). In the company under study, each truck has a service, while at the same time, the personnel costs also include administrative and workshop staff. Therefore, the calculation process (Table 11.4) takes into account:

- All employees are employed based on an employment contract,
- The rate for the driver is PLN 350 net/working day,
- The driver works an average of 24 days per month,
- The salary for administrative and workshop employees is fixed at PLN 5,000 net,
- Employees are at least 26 years of age.

Table 11.4. Salary costs for drivers and staff every month

Category	Number of staff	Number of days	Net wage costs [PLN] per employee	Gross wage costs [PLN] per employee	Total gross costs [PLN] for all employees	Total net costs [PLN] for all employees
Drivers	10	24	8,400	11,838	118,384	84,000
Other employees	6	21	5,000	6,850	41,100	30,000
Total costs for all staff					**159,484**	**11,4000**
Total					**273,484.3**	

Drivers work 24 days per month, resulting in salaries of PLN 8,400 net for one driver. The gross amount is PLN 118,384. Administrative and workshop employees work an average of 21 days per month, and receive salaries of 5,000 PLN net which gives a gross amount of 6,850 PLN, the total cost to the employer is 8,253 PLN. The monthly cost to be covered by the employer, who employs 16 workers including 10 drivers and 6 office administration workers together with mechanics, is PLN 192,147 gross. However, in an environment of technological and environmental change, as a result of the rollout of autonomous vehicles, the cost of driver wages may decrease in exchange for higher costs associated with maintaining a modern vehicle. According to Mohan and Vaishnav (2022), up to 94% of drivers will be affected in some way by automation in road transportation (Mohan & Vaishnav, 2022).

Another component is the fee for the use of council roads (Table 11.5). The company provides services to the domestic market, the total amount of kilometers driven per month is 100 000 km. Vehicles meet the latest EURO 6 emission standards.

Half of the mileage is covered by roads of class A or S, the other half by roads of class GP or G. The rate for driving on roads of class A or S is 2.35/km. The rate for driving on roads of the GP or G class is 1.8/km. As a result, this gives a monthly cost of 3,350 PLN for driving 10,000 km with an EURO 6 car. In the case of 10 cars, this amount is 41,500 PLN gross per month.

Table 11.5. Cost of road user charges – e-toll system every month

Category of road	Number of kilometres	Gross charge per km [PLN]	Total gross costs
A	25,000	0.47	11,750
S	25,000	0.47	11,750
GP	25,000	0.36	9,000
G	25,000	0.36	9,000
Total costs for the entire vehicle fleet			**41,500**

The costs of vehicle maintenance and upkeep (Table 11.6) include the costs of technical inspection once a year, maintenance costs i.e. oils and greases, tire costs, costs of vehicle washing service, and costs of required repairs. The cost of maintaining an electric truck will become more cost-competitive over time due to lower maintenance costs, lower energy consumption and favorable depreciation rates. In the case of diesel trucks, the depreciation rate is unstable, while electric vehicle depreciation assumes a fixed depreciation rate of 7.5 percent per year, resulting in a depreciation of 37.5 percent after five years (Electric truck costs..., 2024).

Table 11.6. Fleet maintenance and upkeep costs per month

<table>
<tr><th>Category</th><th>Cost of technical inspection</th><th>Maintenance costs</th><th>Tyre purchase cost per set</th><th>Cost of cleaning (per single service)</th><th>Cost of repairs</th><th>Total gross costs</th></tr>
<tr><td>Tractor unit</td><td>177</td><td rowspan="2">123</td><td rowspan="2">1,845</td><td rowspan="2">150</td><td>2,460</td><td>4,755</td></tr>
<tr><td>Semi-trailer/trailer</td><td>176</td><td>1,230</td><td>3,524</td></tr>
<tr><td colspan="6">Total costs for the entire vehicle fleet</td><td>8,279</td></tr>
</table>

The total monthly costs for vehicle maintenance and servicing amount to around PLN 8,279 gross per vehicle. With 10 vehicles, this gives a total of PLN 82,790.

Table 11.7. Insurance costs per month

Category	OC insurance costs [PLN]	AC insurance costs [PLN]	OCP insurance costs [PLN]	Total gross costs
Tractor unit	316	100	-	416
Semi-trailer/trailer	19	20	-	39
Road hauler	-	-	541	541
Total				**996**

The insurance for one truck (Table 11.7) per month is PLN 455. On a scale of 10 vehicles, this equates to 4,550 PLN. The total monthly insurance outlay per vehicle plus the included road hauler's oc premium is 996 PLN.

The total monthly office cost for a transport company is PLN 10,700. Office rental accounts for the largest share of costs at 46.73%, followed by communication costs at 18.69% and utilities 13.55%.

Table 11.8. Total costs per month incurred by the company

Category	Cost [PLN]	Cost share [%]
Fuel cost	184,142	40.67%
Cost of employing drivers	142,629	31.50%
Cost of employing other staff	49,518	10.93%
Road tolls	33,500	7.40%
Maintenance and repair of vehicles	33,030	7.30%
Office costs	10,700	2.36%
Fleet management costs	3,615	0.80%
Insurance costs	5,091	1.12 %
Other costs	1,120	0.25%
Total	**463,346**	**100%**
Unit cost for 40,000 km per month	**12,00**	**-**

Table 11.8 shows the cost structure of a transport company, with fuel costs accounting for the largest share (40.67%), followed by driver employment costs (31.50%), and insurance and other costs accounting for the smallest share (1.37% in total). This distribution of costs is typical for transport companies, where fuel and salaries are the main expenses. When comparing this structure with industry data, it can be seen that a similar distribution is found in most transport companies, suggesting that the company operates according to industry cost standards. According to DAT Freight & Analysis (2024), refrigerated shipping can be up to 15% more expensive than standard shipping. Current reefer shipping rates range from about $2.80 to nearly $3.75 per kilometer.

Comparing the results obtained with those of the entire sector, it is observed that the formation of the rate has a macroeconomic dimension. At the same time, it largely depends on the demand for transportation services. Meanwhile, it is projected that in the long term until 2050, the global transportation industry will grow rapidly. It is expected that the volume of cargo in global road freight transport could increase by up to five times (DHL Report, 2023). The increase in freight demand is one of the key factors affecting freight rates as well as other costs associated with road transport, and can result in changes in fuel costs, driver salaries, fleet and management expenditures, as well as technological investments. Rising demand but also environmental regulations will increase freight costs, especially in the road transportation sector, where the number of available vehicles is time-limited. The results of the analysis can help in making decisions related to transport services or the purchase of new means of transport, as well as being an important criterion in assessing the economic efficiency of the transport system. The company should analyze fuel and labor costs on a regular basis, looking for opportunities for optimization, such as negotiating fuel prices or implementing performance management systems.

Conclusions

The specific features of transport service production significantly impact the scale and structure of the costs associated with transport management, which in turn affects how these costs are accounted for. On the one hand, the use of accurate cost accounting is crucial in the management of transport activities, while on the other hand, this means that the technical and organizational aspects of the transport service production process need to be taken into account in the accounting, with a particular focus on market conditions.

Macroeconomic risks such as rising wages, inflation, energy prices, interest rates, and economic fluctuations have come to the fore in the transport sector. Structural problems such as driver shortages, decarbonization and unfair competition are currently less important, but their impact is expected to increase soon.

Effective management of these costs is essential to maintain the profitability and operational efficiency of the business. A deep understanding of the payroll cost structure allows for more accurate financial planning, budgeting, and hiring and investment decisions.

References

Aji A., & Surjandari I. (2020). Hybrid vector autoregression-recurrent neural networks to forecast multivariate time series jet fuel transaction price. IOP Conference Series: Materials Science and Engineering. 909, 1-11, DOI: 10.1088/1757-899X/909/1/012079.

Baller, A.C., Dabia, S., Dullaert, W.E.H., & Vigo, D. (2019). The dynamic-demand joint replenishment problem with approximated transportation costs. *European Journal of Operational Research*, 276 (3), 1013-1033. DOI: 10.1016/j.ejor.2019.01.070.

Bronk H., (2014). Transport costs and prices. *Scientific Papers of the University of Szczecin, Problems of transport and logistics*, No. 25, University of Szczecin, Szczecin, 21-40.

Chow, G., & Gill, V. (2011). Transportation and Logistics International Competitiveness: How does Canada fare? *Canada: Canadian Transportation Research*, 5-23.

Cioc M., & Dumitru F. (2013). Transportation Cost Reduction and Competitive Advantage Through Defensive Driving Programmes. Conference: International Management Conference, Faculty of Management, Bucharest, Romania: Academy of Economic Studies Art, 7(1), 88-94.

Ciszewska, M., Ślusarczyk, B., & Streimikiene, D. (2023). Changes in Cargo Transport in the European Union in the Face of the COVID-19 Pandemic. In Forum Scientiae Oeconomia (11, 3, pp. 31-52), DOI: 10.23762/FSO_VOL11_NO3_2.

DAT Freight & Analysis, (2024), *National Reefer Rates*, https://www.dat.com/trendlines/reefer/national-rates, (access: 07.11.2024).

DHL Report, *Global Freight Transport Statistics*, (2023). International, Europe, and Germany, https://dhl-freight-connections.com/en/trends/global-freight-transport-statistics-international-europe-and-germany/.

Electric truck costs: TCO of EV and ICE, (2024), https://web.uta.com/en/electric-truck/electric-truck-costs (access: 09.11.2024)

Engholm, A., Pernestål, A., & Kristoffersson, I. (2020). Cost analysis of driverless truck operations. *Transportation Research Record*, 2674(9), 511-524. DOI: 10.1177/03611981209 30228.

Eurostat (online data code: prc_ppp_ind), Price level index for transport, 2023.

Eurostat: Labor costs in Poland in 2023 increased by 12.4 percent, https://www.obserwatorfinansowy.pl/forma/dispatches/eurostat-koszty-pracy-w-polsce-w-23-wzrosly-o-124-proc-rdr/

Fan, H., Ha, V., Thi, T., Zhang, W., Li, S. (2023). The influence of trade facilitation on agricultural product exports of China: empirical evidence from ASEAN countries. *Economic Research-Ekonomska Istraživanja*, 36, 2, 1-23, DOI:10.1080/1331677X.2022.2143845.

Gang, L., Yongshu, L., Jiawei, G., Zheng, L. (2015). Maximum transport capacity of a network, *Physica A: Statistical Mechanics and its Applications*, 432, 315-320, DOI: 10.1016/ j.physa.2015.03.039

Grondys, K., & Sałek, R. (2017). Conditions for the use of modern ICT technologies supporting transport activities in road transport. *Autobusy*, 18, 12, 1592-1596.

Hermundsdottir, F., & Aspelund, A. (2021). Sustainability innovations and firm competitiveness: A review. *Journal of Cleaner Production*, 280, 1, DOI: 10.1016/j.jclepro.2020.124715.

Jarocka, M. (2016). Innovative pricing policy for transport services. *Studia Ekonomiczne Zeszyty Naukowe Uniwersytetu Ekonomicznego w Katowicach*, 306, 56-69.

Kane, J., (2024). *Oil Price Forecast 2024-2030: WTI and Brent Overview*, https://www.liteforex.pl/ blog/analysts-opinions/prognoza-cen-ropy-naftowej/ (access: 07.11.2024).

Karam, A., Jensen, A.J.K., & Hussein, M. (2023). Analysis of the barriers to multimodal freight transport and their mitigation strategies. *Euro. Transp. Res.* Rev. 15, 43, 1-16, DOI: 10.1186/s12544-023-00614-0.

Key figures on European transport – 2023 edition, Eurostat 2023, Luxembourg: Publications Office of the European Union, 2024.

Krajewska, R., & Łukasik, Z. (2017). *Efficient use of transport infrastructure in cities: examples of good practice*, Radom: Instytut Naukowo-Wydawniczy "SPATIUM".

Losik, J., Road Tolls Will Go Up. *Many Carriers Won't Survive*, https://www.money.pl/gospodarka/oplaty-za-drogi-pojda-w-gore-to-dotknie-nas-wszystkich-6844460638722624a.html (access: 03.06.2024)

Mohan, A., & Vaishnav, P. (2022). Impact of automation on long haul trucking operator-hours in the United States. *Humanit. Soc. Sci. Commun.* 9, 82. DOI: 10.1057/s41599-022-01103-w.

Osińska, M., & Zalewski, W. (2012). Ekonometryczna analiza przychodów i kosztów w przedsiębiorstwie transportowym na tle koniunktury w branży, *Logistyka*, No. 6, 1-15.

Paradowska, M., & Kociszewski, K. (2018). *Ekonomika transportu. Teoria dla praktyki*, Wrocław: Wyższa Szkoła Bankowa we Wrocławiu.

Poliak, M., Poliakova, A., Svabova, L., Zhuravleva, A.N., & Nica, E. (2021). Competitiveness of Price in International Road Freight Transport. *Journal of Competitiveness*, 13(2), 83-98. DOI:10.7441/ joc.2021.02.05.

Road freight transport by type of operation and type of transport (t, tkm, vehicle-km) – annual data, *Eurostat* 2023, https://ec.europa.eu/eurostat/databrowser/view/road_go_ta_tott/default/ table (access: 18.07.2024).

Russell, D., Coyle, J.J., Ruamsook, K., & Thomchick, E.A. (2014). The real impact of high transportation costs. *Supply Chain Quarterly*, 1. http://www.supplychainquarterly.com/ archives/2014/01.

Saeedi, H., Wiegmans, B., Behdani, B., & Zuidwijk, R. (2017). European intermodal freight transport network: Market structure analysis. *Journal of Transport Geography*, 60, 141-154. DOI: 10.1016/j.jtrangeo.2017.03.002.

Statkienė, E. (2022). Penalties for the road traffic offences – the goal is to punish or to educate? *Contemporary Research on Organisation Management and Administration*, 10 (1), 24-47. DOI:10.33605/croma-012022-003.

Szumska, E.M., Pawełczyk, M., & Jurecki, R. (2012). Total cost of ownership analysis and energy efficiency of electric, hybrid and conventional urban buses. *Eksploatacja i Niezawodność*, 24, 1, 7-14, DOI: 10.17531/ein.2022.1.2.

The European Road Freight Rate Benchmark – Q4 2023 (2024). Ti & Upply & IRU.

Transport – business results in 2022. (2023). Report, Główny Urząd Statystyczny, Warsaw.

Road transport in Poland 2023, Report, https://tlp.org.pl/wp-content/uploads/2023/07/raport-transport-drogowy-w-polsce-2023.pdf (access: 11.08.2024).

Tunç, T., & Büyükkeklik, A. (2017). Reducing the negative effects of seasonal demand fluctuations: A proposal based on cost-benefit analysis. *Journal of Engineering Research and Application*, 7, 3, (Part-3), 38-46.

Wadud, Z. (2017). Fully Automated Vehicles: A cost of ownership analysis to inform early adoption. *Transportation Research Part A: Policy and Practice*, 101, 163-176.
Wheat, P., Stead, A.D., Huang, Y., & Smith, A. (2019). Lowering transport costs and prices by competition: Regulatory and institutional reforms in low-income countries. *Sustainability* 2019, 11, 5940, 1-19, DOI: 10.3390/su11215940.
Xing, X., Cong, Y., Wang, Y., & Wang, X. (2023). The Impact of COVID-19 and the war in Ukraine on the energy prices of oil and natural gas. *Sustainability* 15, 14208, 1-16, DOI: 10.3390/su151914208.
Yoko, K., Mun, S., Yoshihiko, N., & Sung, J. (2012). *Determinants of transport costs for interregional trade* (Discussion Paper No. 12-E-016). Tokyo: ROETI, The Research Institute of Economy, Trade, and Industry, 1-36.
https://www.globalpetrolprices.com/ (access: 17.05.2024)

Chapter 12

INVESTIGATING THE STATE OF AUTONOMOUS VEHICLES ON SUPPLY CHAIN: A LITERATURE REVIEW

Negar Sohaee[1*], Sara Sohaee Urbina[2] , Navidreza Ahadi[3], Farnaz Azadjoutabari[4]

[1]Yorkville University, Canada
nsohaee@yorkvilleu.ca ORCID 0009-0005-1948-5225
[2]Portland State University, United States of America
ssu2@pdx.edu ORCID 0000-0003-0084-8936
[3]University of Derby, United Kingdom
n.ahadi@derby.ac.uk ORCID 0000-0002-5866-0218
[4]Utrecht University, The Netherlands
farnazazadjoo@gmail.com ORCID 0009-0009-4165-272X

Abstract: This study focuses on the analysis of the economic impact of autonomous vehicles (AVs) on beverages and food supply chain costs in Europe. AVs are going to have huge potential impacts both on supply chains and transport. Thus, this research studies how AVs can help resolve existing logistical challenges by boosting efficiency, minimizing operational costs, enhancing supply chain resilience, and reducing delivery time. Through secondary data analysis and the economic model's assessment, the benefits and cost savings that AVs can provide to businesses are measured. The findings of this research are intended to inform industry leaders, lawmakers, and academics about the transformative potential of AVs implementation and their future impact on supply chain management in Europe.

Keywords: autonomous vehicle, supply chain resilience, cost efficiency, time efficiency, fuel efficiency, European food and beverage sectors

Introduction

Autonomous vehicles (AVs) have become part of the supply chain networks and have the possibility to revolutionize how distribution and logistics performance is done. These technological advancements in transportation and logistics are mostly important to the European market, where logistics and transportation play a key role in economic growth and stability. According to Transparency Market Research, the European perishable goods transportation market is estimated to grow at a compound annual growth rate (CAGR) of 3.3% from 2023 to 2031. Due to the sensitive nature of perishable and semi-perishable products, AV technology could help solve several long-standing challenges, such as reducing labor and operation costs (Hopkins, 2021), improving delivery time and fuel efficiency, optimizing routes, and improving supply chain resilience (Johnson & Brown, 2021; Smith, 2022; Zhao & Lee, 2023).

EU food and beverage industries largely impact regional economic growth; therefore, efficient logistic and supply change management is in high demand (Olencevičiūtė et al., 2016). Adopting AVs in the supply chain and logistics might overcome some challenges such as labor shortages, rising transportation costs, minimizing human error, optimizing fuel consumption, and improving the reliability of drivers and delivery efficiency (Khalafi et al., 2024; Marcucci et al., 2024).

This study examines AVs' economic impact on European food and beverage supply chains. With a focus on these sectors, the study explores how AVs can enhance supply chain resilience, reduce operational costs, and improve efficiency. We reviewed the main literature using SCOPUS to analyze economic models to quantify the benefits and cost savings AVs can deliver (Davis, 2023). It provides a comprehensive review of the transformative potential of AVs in these industries and fills existing research gaps.

To attain its aims, this initiative will study many research issues. How do AVs affect European food and beverage supply chain resilience and efficiency? What is the impact of cutting costs with AVs on the economy? Finally, how does AV deployment help European businesses overcome labor shortages and fragmented regulations? These factors are significant as Europe automates transportation. Companies must compete in fast-changing marketplaces (Guo et al., 2024; Wilson, 2023; Thomas, 2022).

This study matters for several reasons. First, it examines the economic implications of AVs on European food and beverages, filling a large research gap. Second, industrial leaders considering AV technology to boost productivity and save costs are informed (Hernandez, 2023). Furthermore, this research informs policymakers about the pros and cons of AV integration. Policy and infrastructure complementary to each other will be developed. As a result of this study, academics can conduct AV and supply chain management research, which will be beneficial to them (Martin & Lopez, 2022).

Literature review

The fact that AVs are increasingly integrated into supply chains means that their potential for solving some of the most critical logistical challenges is catching the attention of significant researchers and industry leaders. To understand the complete landscape of impacts that the AVs have on the supply chains, it will be relevant to explore the extant literature in respect of how AVs improve efficiency and reduce costs of the supply chains and build resilience within them. The following literature summarizes what could be considered the range of findings from various studies on logistics AV deployments, keeping in mind how these technologies stand to reshape operational strategies toward key persistent issues such as labor shortages and rising transportation costs.

Overview of AVs in supply chains

AVs have become one of the logistics industry's revolutionary innovations, particularly in terms of cutting operating costs and increasing supply chain efficiency. In fact, according to some recent studies, deployments of AVs into the supply chain help tackle key challenges such as labor shortages and volatility in transport costs. Khalafi et al. (2024) highlight this advantage, noting that integrating AV technology into logistics can foster strategic collaboration among stakeholders, leading to long-term improvements in financial sustainability. This includes benefits such as enhanced reliability and reduced operational costs. Additionally, Nagurney et al. (2021) demonstrated through game-theory modeling that the adoption of AVs has been successful in maintaining supply chain performance even in the presence of labor constraints. This adds support to the idea that AVs can further stabilize costs and produce more resilient logistics operations in the event of disruption (Nagurney, 2021; Nagurney et al., 2023).

In fact, AVs can be a potential solution to the issue common in logistics for quite some time and recently further propelled by growing demand and aging workforces in most regions. This will add to the possibility of deploying autonomous trucks in long-haul routes without compromising operational efficiency with minimum dependency on human drivers (Marcucci et al., 2020). For example, UPS and DHL have started testing AVs for last-mile deliveries, a segment where efficiency is paramount because of labor constraints and customer demands for speedier deliveries. Multiple studies have proved various advantages of AVs in their operational cost savings, whereby autonomous trucks can operate without rest breaks or driver shift limits, thus enhancing fleet utilization. Besides that, AV will go a step further to enhance route planning and save fuel with the intention of reducing frills associated with transport. These benefits are much sought after, during peak seasons when holidays fall because it is during these times that labor shortages most often worsen and the demands for logistics increase by a big margin (Cohen & Cavoli, 2019; Howard & Dai, 2014).

Global application of AV technology to supply chains

Globally, the applications of AV technology to the supply chains have been developing very fast, with key players across regions pressing ahead with the adoption of these systems. Guo et al. (2024) study the scheduling problems of green vehicles, including AVs, and report that multi-objective optimization models will play a vital role in improving both environmental and economic performance for fleets of AVs. This work stresses placing AVs within a broad sustainability framework, an imperative in line with global trends towards greener, more efficient transportation systems.

In the US, companies like Tesla, Waymo, and Uber Freight are setting the standard for AVs in logistics by utilizing completely autonomous trucks to complete long-distance journeys. In Europe, impetus has also gathered for testing AV technology in logistics, driven by private sector investment together with government support. Despite such developments, there are still lots of challenges, mainly regarding updated legal frameworks and public infrastructure, which should all be adapted to AVs. For instance, huge obstacles to the wide adoption of AVs are the regulatory fragmentations in Europe. In different countries, there are different rules concerning the spread of AVs. In Europe, companies such as DHL and DB Schenker have been pioneers in testing AV technologies in logistics, particularly for long-distance routes and last-mile delivery services. Furthermore, countries like Germany and Sweden, private sector investments in AVs are matched by government initiatives, making these countries leaders in the European AV market (Marcucci et al., 2024). However, fragmented regulations across different countries present a major barrier to widespread AV adoption, as each nation has its own legal framework for the operation of autonomous trucks, creating complexities for cross-border logistics (Automotive Logistics, 2024).

Key trends and players driving AV adoption in logistics

Various key trends are driving the adoption of AVs within logistics. Of many, one of the more prominent is indeed the push toward transportation solutions that are more sustainable and cost-effective. AVs are meanwhile seen to reduce fuel consumption and improve route optimization, particularly in industries where timely deliveries have become critical, such as the food and beverage sector (Marcucci et al., 2024). Additionally, many research studies highlight how AVs can contribute to decreasing the carbon footprint of supply chains thanks to route optimization and a general reduction of unnecessary vehicles in operations (DHL, 2024; Marcucci et al., 2024).

The increasing speed of AVs' implementation, above all for last-mile logistics, is enhancing time efficiency in e-commerce and is increasing service reliability. Nowadays, more companies rely on AVs for handling high-demand delivery schedules, especially in congested city centers where traffic congestion and labor shortages may bring everything to a stop (Supply Chain World, 2024). The report also highlights the potential use of AVs in enhancing supply chain resilience by reducing dependence on human labor, mainly during crises such as the COVID-19 pandemic. Large logistics players like Amazon and DHL have been among the early adopters that tested AV technology with serious investments in autonomous systems to gain efficiency and reduce costs. These companies have focused on the integration of AVs with other advanced technologies, such as Artificial Intelligence (AI) and the Internet of Things (IoT), for enhancing the intelligence of supply chain networks based on big data. Indeed, these will further inspire developments in AV technology, hence very important in logistics operations in the future (DHL, 2024).

Methodology

This comprehensive literature review examines the economic impacts that AVs may have on food and beverage supply chains in Europe. We synthesize findings, look for trends, and identify gaps in the extant literature as to how AVs improve supply chain efficiency, cost, and resilience.

The literature review includes peer-reviewed studies, industry reports, and pertinent research collected, analyzed, and synthesized. In this analysis, we examine how AV technology solves logistical problems in European food and beverage supply chains and the economic impacts they have.

The literature study relies on academic databases and industry reports. These resources were used:

- The SCOPUS Database was searched for peer-reviewed journals, conference papers, and reviews. Keywords were “Autonomous Vehicles”, “Supply Chain Resilience”, “European Food and Beverage Supply Chains”, “Logistics Efficiency”, and “Economic Impact”.

– Research and industry reports were analyzed to understand the deployment of AV technology in European transportation and logistics.

By utilizing Boolean operators and wildcards, we extended our search to capture as many relevant publications as possible. The data extraction in this review covered the years from 2015 to 2024. The following search formula, which utilized keywords, yielded 1,879 papers:

TITLE-ABS-KEY ("self-driving trucks" OR "autonomous vehicles" OR "automated freight transport" OR "logistics") AND TITLE-ABS-KEY ("supply chain efficiency" OR "fuel consumption" OR "economic impact") AND PUBYYEAR > 2015 AND PUBYYEAR < 2024.

Discussion

Our study focuses on the research landscape related to AVs in the food and beverage supply chain in Europe. The results are based on an analysis of 1,879 documents. Several factors are considered, including the number of publications, citations, and the strength of the links between countries, to understand the extent of research productivity, influence, and collaboration. Study results indicate the importance of countries like the United Kingdom, Germany, and Italy in advancing AV research. The analysis of these metrics also reveals how some nations have become hubs for cross-border innovation and research through the strength of their inter-country collaborations. This discussion interprets these data points, pointing to their implications for the adoption of AVs in supply chains. It also highlights emerging trends and potential areas for future research. Its purpose is to provide a detailed examination of the research contributions across Europe, illustrating the role of AVs in improving food and beverage logistics and efficiency.

Table 12.1. Research collaboration and impact on autonomous vehicles in European food and beverage supply chains

Country	Documents	Citations	Total link strength
United Kingdom	117	2784	147
Germany	79	1004	71
France	63	1253	61
Spain	72	1156	59
Sweden	46	945	58
Italy	83	1485	57
Netherland	39	1075	44
Norway	27	421	40
Turkey	50	692	35
Belgium	19	189	28

Source: Authors' elaboration.

Table 12.1 shows the several contributions and collaborations that different European countries have made to the research output in AVs and their impact on the supply chain of food and beverages. The table represents 117 documents, 2784 citations, and 147 total links, which shows the leading position of the UK in terms of research output and international collaboration. Similarly, in Germany and Italy, both the number of publications and link strengths were conspicuous, with substantial citation counts supporting them. In countries like France and Spain, although the number of publications are relatively low, citation counts are high with regards to the number of documents, thereby indicating the impact of research from those countries. Despite the number of publications in Belgium and Norway are lower, they still indicate recent growth of interest in research relating to the AVs in development of supply chains networks. The total link strength metric represents the collaboration between countries. It therefore means that the UK, Germany, and Italy, which have higher values, are producing more research and, thus, collaborating with other countries on active levels to develop a wider AV and supply chain ecosystem in Europe.

Figure 12.1 illustrates international collaborations, in particular, European countries. The two countries are acting like central hubs with a high number of linkages to countries like France, Spain, and the UK. For the last few years, Italy and Germany have been contributing a great deal to collaborative research. Along with the USA, UK, France, and Spain, these countries also have strong research collaborations. By contrast, the thin, lighter-colored line extending from Ukraine suggests more isolation with fewer connections. Even when Ukraine did participate in international research collaborations, it did so less frequently than central European countries. Generally, Figure 12.1 suggests well-developed and solid collaboration networks in Europe, dominated by Italy and Germany and their immediate neighbors.

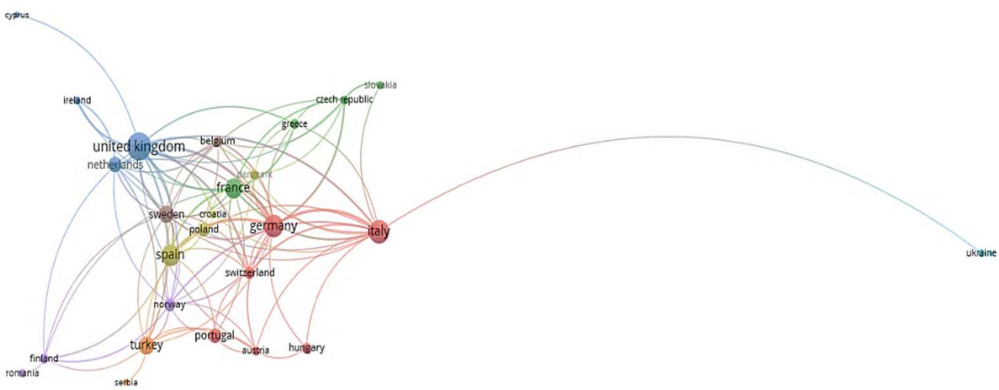


Figure 12.1. Network visualization of collaborative research on autonomous vehicles in European food and beverage supply chains

Source: Authors' elaboration by VOSviewer.

This network diagram provides insight into the shifting pattern of collaboration in European research on AV in supply chains. Thicker and darker lines can indicate older collaborations, dating back to around 2016, that were crucial in building leading countries such as the United Kingdom, Germany, and France into strong and well-connected networks. The newer members in the network, like Poland, the Czech Republic, and Ukraine, have lighter lines from right to left, showing the emerging collaborations between 2020 and 2024. The continued presence of Italy and Germany as linchpins allows for further collaboration between established and emerging research teams. Newcomers, such as Slovakia and Ukraine, have joined more established countries like the USA and Italy in contributing to the rising participation of researchers in this field. The timeline for this growing collaboration is shown by the gradient color spectrum, indicating an increase because every day AV technology becomes more significant.

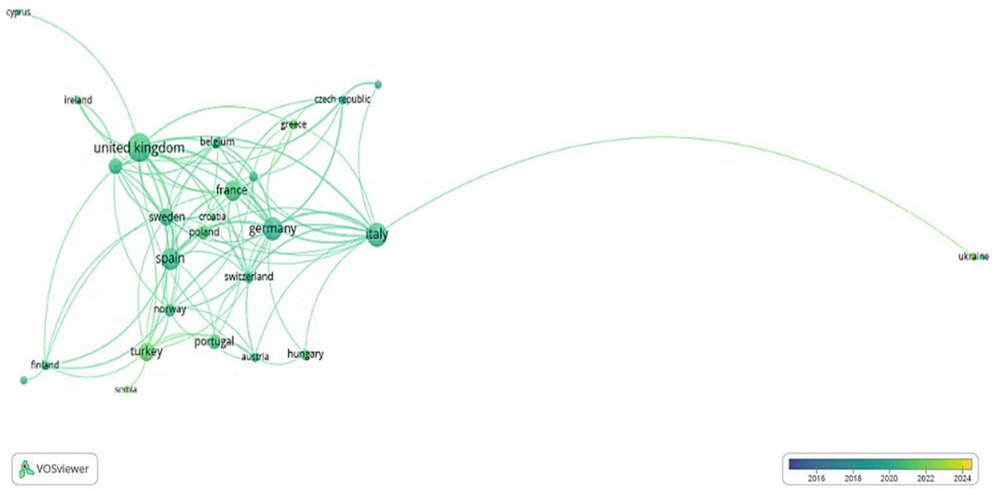


Figure 12.2. European research temporal collaboration dynamics on autonomous vehicles in food and beverage supply chains

Source: Authors' elaboration by VOSviewer.

Density map (Fig. 12.2) showing intensity of research collaboration between various countries in Europe concerning AV and their impact on food and beverages supply chains. The gradient of color through green and into yellow describes the level of research activity and collaboration, with brighter areas going to yellow being higher in research concentration and darker areas going to blue/green representing low levels of involvement. Of all the brightest yellow hotspots on this map, Italy is very much a player in this research area, high in its output contribution and collaboration with other countries. Italy's prominence is a result of high involvement in both the academic and practical aspects of AVs in supply chains, particularly to optimize logistics and efficiency. The UK also comes out as an important research hub, showing a dense yellow area. This would therefore imply that the UK is one of the biggest contributors and collaborators in research on AVs, probably impelled by technological capabilities, strong academic institutions, and economic interest in the betterment of supply chains through automation.

27 items (8 clusters):

Cluster 1 (6 items)
austria
germany
hungary
italy
portugal
switzerland

Cluster 2 (4 items)
czech republic
france
greece
slovakia

Cluster 3 (4 items)
cyprus
ireland
netherlands
united kingdom

Cluster 4 (4 items)
croatia
denmark
poland
spain

Cluster 5 (3 items)
finland
norway
romania

Cluster 6 (2 items)
latvia
ukraine

Cluster 7 (2 items)
serbia
turkey

Cluster 8 (2 items)
belgium
sweden

Figure 12.3. Geographic heatmap of global research collaboration on autonomous vehicles in supply chains

Source: Authors' elaboration by VOSviewer.

The countries are being mapped to represent their networks of cooperation and volume of research regarding the case of AVs or supply chains. A cluster may be thought of as countries that have stronger intra-cluster collaborations compared to another (but not the strongest inter-cluster) collaboration (Figs. 12.3 and 12.4).

– **Cluster 1** (Germany, Italy, Austria, Switzerland, and others) well-anchored partnerships largely over Western and Central Europe. These countries are key players for AV tech development and supply chain logistics.
– **Cluster 2** with France, Greece, Slovakia, and other countries, indicating large amount of cooperation in southern and eastern Europe, with AV studies being increasingly popular in these regions.
– **Cluster 3** includes the UK, Netherlands, Ireland, and Cyprus and emphasizes the strong research in Western Europe that is prevalent, with the UK leading many of the collaborative initiatives.

- **Cluster 4** includes countries like Denmark, Spain, and Croatia. These countries are on a medium level in the research network, collaborating often both with Eastern and Western Europe. Their involvement is significant, though not as marked since it links different regions.
- **Cluster 5** consists of Nordic countries such as Finland, Norway, and Romania; the latter, however, is not generally considered Nordic but shows trends like Nordic countries. These countries have shown growing interest in AV and supply chain research over recent years. Again, this trend should be welcomed because it shows that countries are increasingly committed to such important issues.
- **Cluster 6** consists of Ukraine and Latvia and incorporates the emergent players in the field. These will provide an insight into areas of possible growth for collaborative research-in-effect, which countries should be involved in extended initiatives. Though still at a developmental stage, these countries are a promising choice.
- **Cluster 7** also comprises several countries, such as Turkey and Serbia, which are showing regional cooperation within this area of AV research. Their participation is not so deep compared to the other clusters, but they are relevant for stability and development in the region.
- **Cluster 8** consists of Belgium and Sweden and reflects strong collaboration across northern Europe, which also reflects their advanced engagement of these countries in AV technologies. The contributions are geographically concentrated, but the effects spread out due to the advanced technological capability.

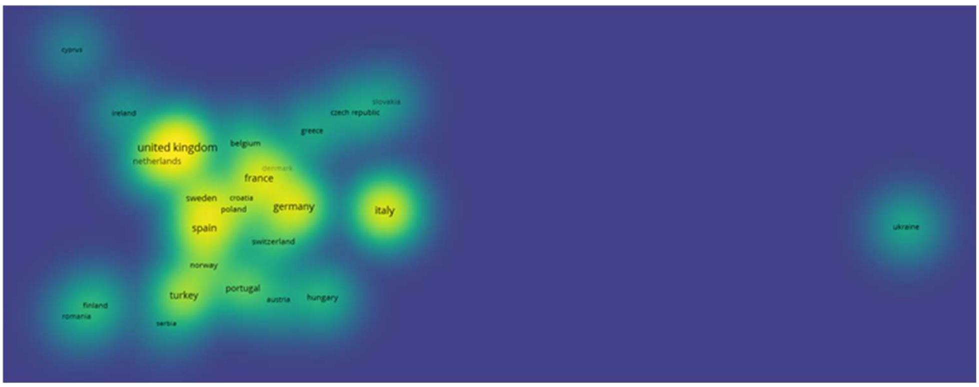


Figure 12.4. Collaboration Networks Among Countries

Source: Authors' elaboration.

The importance of AVS in supply chain

Although full implementation or widespread adoption of AV technologies has not occurred, their potential impacts have been speculated by various researchers. The theoretical studies predict that the integration of AVs, particularly in logistics, can significantly enhance economic outcomes at all levels by reducing labor costs, improving fuel economy, and reducing accident-related costs to construct overall resilience (Kim et al., 2022).

Most of the food and beverage industries have a major problem while transporting perishable products. With AVs, there is real-time monitoring of the systems to ensure that goods are moved under optimum conditions, hence reducing cases of spoilage and generally improving efficiency and reliability in supply chains (DHL, 2024). Moreover, in urban cities, where there are often congestions and labor shortages, AVs help smooth the last-mile deliveries. Companies like DB Schenker and DHL already adapt to such technologies that solve such logistics bottlenecks, enhancing operational efficiency and resulting in more sustainable practices with less emission (Automotive Logistics, 2024; Marcucci et al., 2024). The application of AVs has become more critical in the food and beverage supply chain across Europe due to the continuous increase in demand for efficiently managed logistics. Major sectors in food and beverage are time-sensitive concerning delivery timings of especially perishable goods; therefore, this sector will greatly benefit from AV technology (Marcucci et al., 2024). The following assessment is organized into two parts that are organized to include: the first one, looking at the economic impacts of automated cars on supply chains; and the second one, which looks at the case of the impact of automation on the food and beverage supply chain.

Part 1: Economic impact of AVs on supply chains

- Labor costs: The drivers are eliminated due to the introduction of the AV technology, thus reducing labor costs significantly. Various studies, such as Makahleh et al. (2024), investigate how investment in AVs reduces labor costs, especially in long-haul transportation. These can support continuous operation without mandatory rest breaks, result in reducing human labor input and increasing efficiency. The reduction in labor expenses by eliminating the need for drivers on long-haul routes, is particularly helpful in countries facing worker shortages. Since AVs don’t require rest breaks, they allow for higher vehicle utilization, further lowering operational costs. According to Heutger and Kuechelhaus (2019), autonomous technology, allows for continuous operation, reducing downtime and maximizing the efficiency of logistics operations. On a related note, Nagurney (2021) also determined that automating the delivery process reduces the costs related to operations since one would not need to consider using human drivers on very long routes, thereby increasing efficiency in delivery. Since the AVs will work without breaks, this entails an increase in maximum vehicle utilization and reduction of delays due to labor shortages (Khalafi et al., 2024). In this aspect, Chen et al. (2024) cite that the application of AVs in the trucking industry could reduce costs through cooperative systems by minimizing labor and operational costs. A detailed study by Engholm et al. (2020) highlights the significant cost efficiencies that autonomous trucks can bring to freight transport. The authors claims autonomous trucks are projected to reduce total costs by up to 45%. The study by Kang et al. (2019) illustrates that although the upfront costs are higher, with greater market shares, connected autonomous trucks have the potential for billion dollars in savings; their case study of a busy

Illinois corridor yielded impressive net savings, especially when 50 percent or more market shares were realized.

- Impact on fuel and operations costs: Multiple studies show that AV technology enables more accurate route planning and utilizes efficient technologies such as platooning to further optimize operational costs by minimizing downtime and fuel consumption (Engholm et al., 2020; Makahleh et al., 2024; Marcucci et al., 2024). Davis (2023) claims by optimizing route planning, AVs may reduce fuel costs by up to 15-20% in some cases. Moreover, Kang et al. (2019) have conducted an economic and environmental efficiency analysis of truck platooning using connected autonomous vehicle technologies. That results in improved fuel efficiency, a reduction in aerodynamic drag, increase in pavement life, and reduction in truck crashes. Research by Tsugawa et al. (2016) discusses truck platooning, where all trucks are automated driving systems that enable them to travel closely behind each other with very minimal gaps. The automation of this kind reduces fuel consumption through minimal aerodynamic drag and improves efficiency due to cooperative driving. Besides, Le et al. (2024) discussed the application of advanced technologies like artificial intelligence and machine learning in predicting and optimizing fuel consumption. In this respect, the implementation of AI into maritime operations will enhance decision-making, reduce fuel consumption accordingly, and advance sustainability toward more efficient logistics and transportation systems.
- Accident-related costs: Perhaps one of the most important economic benefits attributed to AVs is being able to reduce the costs associated with traffic-related accidents. Wang et al. (2020) discuss that the human element accounts for 94 percent of crashes, and their research study shows this technology. Collision warning systems and lane departure warning systems are just some of the technologies that could reduce casualties and fatalities by as much as 33%. As more AVs hit the roads, significant enhancements in road safety will result in marked reductions in accident costs. On the other hand, Ye et al. (2021) have provided a more conservative estimation. According to the analysis of 133 crash reports involving AVs, their findings indicate that while there have been advances, it also means that the AVs haven't shown a clear reduction in traffic injuries as compared to traditional vehicles. This would, therefore, mean that though AV technology shows promise, up until today, they have not shown any substantial reduction in traffic injuries when compared to conventional vehicles.
- Resilience in supply chain: Multiple valuable studies have been conducted with the aim of conceptualizing the benefits arising from applying AV concepts in supply chains, particularly focusing on improvements in reliability. The enhancement in reliability is due to reduced human errors and AI-powered route optimization, hence keeping delays at a minimum and boosting customer satisfaction. Heutger and Kuechelhaus (2019) emphasize that integrating digital technologies like AI and digital twins greatly improves logistics by allowing for real-time monitoring and optimization, which in turn enhances the performance of autonomous vehicle operations. Simlarly, Perussi et al. (2019) explain how AVs and automated equipment add up to the development of a more resilient supply chain.

It focuses on automated vehicles, autonomous trucks, drones, and industrial conveyors, which are all parts of industry and are major contributors to supply chains. Additionally, AVs have the potential to help in the management of traffic flow, reduce accidents, and further optimization of transport, thereby contributing to general supply chain resilience through minimizing disturbances and ensuring timely deliveries.

Part 2: Impact of automation on transporting the foods and beverages

- Efficiency in transporting perishable goods: The food and beverage industries rely heavily on the timely transportation of perishable products. Automation, especially using autonomous vehicles, enhances the speed, improves predictability and reliability to sustain fewer spoils and associated costs. These are some of the very important aspects in the transportation industry of beverages and food. This is very critical for temperature-sensitive supply chains. Amongst the key benefits of automated delivery systems is that they can work for extended hours without any need to take breaks, which aids in reducing the time of delivery at such a time when the demand is high. In this respect, Marcucci et al. (2024) noted that AVs can cut in 10-15% of the delivery times, which is highly relevant to maintaining the freshness of perishable commodities. Pettigrew et al. (2023) discuss how autonomous food deliveries will impact the Australian context. Indeed, businesses are increasingly using AVs to reduce labor costs, increase service capacity, and expedite deliveries. This would especially imply that for consumables, the delivery would be fresher upon arrival due to enhanced transportation and the reduction of delays caused by human elements such as driver fatigue. Long-distance shipment transportation costs can also be reduced using AV technology. Gružauskas et al. (2018) even claim cost-saving effects for autonomous trucks in supply chains, at a rate of about 5% in saving transport costs. The authors, however, still note that with such huge cost savings, the initial costs to establish technology, coupled with regulatory hurdles, have first to be met before the full benefit of autonomous trucks can be realized.
- Environmental impact: With the automation of trucks within the food and beverage supply chains, carbon emissions might further be reduced, which will be very important for companies aiming to implement sustainability goals. Efficiently, as underlined by Gružauskas et al. (2018), increase supply chains, especially when truck convoys are in operation, or freight is consolidated within logistic clusters. The authors estimate that up to 22% of CO2 can be saved by autonomous trucks with optimized driving and convoy strategies that lower fuel consumption.
- Cost efficiency: By automating transport, AVs mitigate human error and challenges associated with driver shortages that have worsened in recent years. Since these AVs can operate at any time, labor constraints have minimal effects, while route optimizations in the meantime become crucial for cost-efficient and timely delivery (Nagurney, 2021). Figliozzi (2020) gives an overview of the cost-effectiveness of using AVs for food and beverage delivery. The paper focuses on the extent to which AVs, both in the form of drones and ground robots, have the

potential to significantly reduce energy use and carbon emissions compared to the conventional mode of delivery, hence operational cost savings. The findings of the study have been that drones are more economical in rural, small deliveries, whereas AVs for the ground can do well in higher urban delivery densities. There will be no need to bear the cost of human labor; hence, AVs can be considered very efficient in last-mile deliveries. Their efficiency is dependent on the size of the area served and the number of customers availing of the service since different systems give better results with respect to different amounts. On a similar vein, Jennings and Figliozzi (2020) discuss how autonomous delivery robots can increase the level of cost efficiency, especially in urban areas. According to the authors, for timely delivery of perishable commodities such as food and drinks, delivery robots are helpful since they reduce labor costs and increase the speed of delivery.

- Supply chain resilience: Various studies indicate that autonomous trucks enhance supply chain resiliency to a great degree, given their ability to operate without necessarily depending on human labor to create continuity of operations. The effect of such technologies within supply chains often minimizes delays resulting from workforce shortages or disruptions. The use of such trucks would involve advanced technologies such as AI and IoT to route and manage risk in real-time, hence furthering the cause of agility in responding to shocks unpredictably faced by the supply chains. Cost savings through reduced fuel consumption and more efficient driving patterns contribute to long-term resilience. The autonomous trucks would contribute toward sustainability by lowering the carbon emissions, meeting regulatory requirements, and mitigating environmental risks. This, in turn, makes supply chains more flexible, affordable, and resistant to any disruptions. Such factors make supply chains more flexible, cost-effective, and resilient against disruptions (Karanam et al., 2024; Liu et al., 2024; Tuli et al., 2024).

Indeed, AVs are capable of revolutionizing supply chain performance, as the adoption of such vehicles minimizes labor costs by improving fuel efficiency and reducing accident costs, which contributes to resilient and cost-effective logistics networks. Whereas autonomous trucks boast of major operation savings, the literature warns that they may also yield increased urban congestion, possibly limiting their cost benefits. Despite these challenges, strong environmental advantages for automation and increased supply chain resilience exist. Further development of AV technology will be expected to contribute much to higher levels of operation efficiency and sustainability in the food and beverage transportation industry, even though the impact this is to make on urban logistics and congestion will need to be managed with much care.

Implications for policy

General Safety Regulation EU 2019/2144 of the European Union stipulates that cars are equipped with improved safety technologies in order to reduce road accidents and injuries (Galassi, 2022). In recent literature, it has also been pointed out that these regulations will be important in ensuring that AV technology is safe. Joint Research

Centre (JRC) reports on the current testing and certification processes that are being carried out about autonomous vehicles, while indicating that strict standards on safety would be required (Baldini, 2020). The research (EUR-Lex – 32019R2144 – EN – EUR-Lex, 2019) indicates that the regulation makes provision for the amendment of the minimum performance requirements of motor vehicles in the EU through making the fitting of various advanced driver assistance systems (ADAS) compulsory.

Intelligent Speed Assistance (ISA) is a vehicular safety mechanism intended to assist drivers in adhering to speed regulations, hence improving road safety. An ISA may only inform the driver of the prevailing speed limit or may take active control of the vehicle's speed to keep it at or below the limit. The ISA rule of the European Union which calls for ISA installation in new cars, began implementation in July 2022 (McKinsey & Company, 2023). ISA is the system that has been proven beyond reasonable doubt to reduce road accidents and consequently associated deaths. Tests carried out in several European countries revealed that ISA had a potential to reduce hospital admissions by 15% and at the precise death rates of 21% (Juliussen, 2022).

Policymakers can create a clear and enabling regulatory environment that encourages autonomous vehicle use in logistics. This will include proposing standards that ensure safety, setting guidelines on operations, and eventual adherence to the current transportation laws. The U.S. Federal Policy Framework calls for the provision of a federal policy directed toward the deployment and commercialization of technology for AVs (Autonomous Vehicle Industry Association, 2023). It is also most likely that governments provide various financial motivations, such as tax cuts, grants, and subsidies for those businesses ready to invest in autonomous vehicle technology. All this can lower the financial barriers to entry and, therefore, will provide motivation for businesses to take part in the deployment of AVs in their logistical activities. Also, funding for research and development may quicken technological advancements and pave the way to offering AV solutions to the market quickly (Nwankwo & Etukudoh, 2023).

Conclusion

This paper mainly explores visions of AVs in changing the face of European food and beverage supply chains. It also brings significant economic benefits by reducing route inefficiency, minimizing labor costs, and saving fuel consumption. Due to such advantages, not only the perishable goods sector, but also other sectors that have a high reliance on credible, timely delivery systems can highly benefit from these technologies. AVs can further solve labor shortages, eliminate human errors and support the environmental objectives of the European Union.

With more and more AVs on the road, it is certain that jobs in logistics and transportation will change due to the lack of driver employment. On a larger scale, the widespread use of AVs might likely influence the labor markets, infrastructure investments, and regulatory frameworks. But this adoption of automated vehicles does not come without challenges. In the absence of a uniform legal framework in European nations, there are diverse legal frameworks that make full utilization of the benefits of this technology difficult. Most importantly, the regulatory framework needs to shift in a direction that allows cross-border circulation of AVs, particularly in Europe, where the divergent legal frameworks currently pose an obstacle to the intricate implementation of AVs (Cichosz et al., 2020; Automotive Logistics, 2024).

Supply chains will be significantly impacted because of AVs, with this presenting a promising outlook for the future of European industry. Therefore, more research into AVs will be needed to determine their broader social and economic impacts, mainly on the labor markets and legislation. Industry and governments will need to cooperate to meet these challenges and ensure that the application of AV technology is carried out in a smooth way for the economy, society, and prosperity of the countries.

References

Automotive Logistics. (2024). *How autonomous vehicles will impact logistics and supply chains*. Retrieved from https://www.automotivelogistics.media.

Autonomous Vehicle Industry Association. (2023). *Federal Policy Framework for Our AV Future*. https://theavindustry.org/resources/AVIA-Federal-Policy-Framework-for-Our-AV-Future.pdf.

Baldini, G. (2020). Testing and certification of automated vehicles (AV), including cybersecurity and artificial intelligence aspects. *EUR 30472 EN, JRC121631*.

Chen, S., Wang, H., & Meng, Q. (2023). Cost allocation of cooperative autonomous truck platooning: Efficiency and stability analysis. *Transportation Research Part B: Methodological*, 173, 119-141.

Cichosz, M., Wallenburg, C.M., & Knemeyer, A.M. (2020). Digital transformation at logistics service providers: barriers, success factors and leading practices. *The International Journal of Logistics Management*, 31(2), 209-238.

Cohen, T., & Cavoli, C. (2019). Automated vehicles: Exploring possible consequences of government (non) intervention for congestion and accessibility. *Transport Reviews*, 39(1), 129-151.

Davis, M. (2023). Economic impacts of autonomous vehicles on supply chains. *Journal of Transport Economics*, 15(2), 101-115.

DHL (2024). *AI and sustainability continue to shape logistics*. Parcel and Postal Technology International. Retrieved from https://www.parcelandpostaltechnologyinternational.com

Engholm, A., Pernestål, A., & Kristoffersson, I. (2020). Cost analysis of driverless truck operations. *Transportation Research Record*, 2674(9), 511-524.

EUR-Lex – 32019R2144 – EN – EUR-Lex. (2019, November 27). Eur-Lex.europa.eu. https://eur-lex.europa.eu/eli/reg/2019/2144/oj.

Evans, L., & Wright, S. (2022). Autonomous vehicles and supply chain efficiency: A European perspective. *European Journal of Logistics*, 28(3), 200-215.

Figliozzi, M.A. (2020). Carbon emissions reductions in last mile and grocery deliveries utilizing air and ground autonomous vehicles. *Transportation Research Part D: Transport and Environment*, 85, 102443.

Galassi, M. (2022). *Current status of AV Regulation in Europe Symposium on International Rulemaking for Automated/Autonomous Connected Vehicles*. https://www.jasic.org/j/14_innovation-technology/pdf/automated-driving-3/sympo7.pdf

Gružauskas, V., Baskutis, S., & Navickas, V. (2018). Minimizing the trade-off between sustainability and cost effective performance by using autonomous vehicles. *Journal of Cleaner Production*, 184, 709-717.

Guo, H., Wang, J., Sun, J., & Mao, X. (2024). Multi-objective green vehicle scheduling problem considering time window and emission factors in ship block transportation. *Scientific Reports*, 14(1), 10796.

Hernandez, P. (2023). Autonomous vehicles in logistics: Benefits and challenges. *Logistics and Supply Chain Management Journal*, 9(1), 72-89.

Heutger, M., & Kuechelhaus, M. (2019). Digital Twins in Logistics: A DHL Perspective on the Impact of Digital Twins on the Logistics Industry. DHL: San Francisco, CA, USA.

Hopkins, J. L. (2021). An investigation into emerging industry 4.0 technologies as drivers of supply chain innovation in Australia. *Computers in Industry*, 125, 103323.

Howard, D., & Dai, D. (2014, January). *Public perceptions of self-driving cars: The case of Berkeley, California*. In *Transportation research board 93rd annual meeting* (14, 4502, 1-16). Washington, DC, USA: The National Academies of Sciences, Engineering, and Medicine.

https://aircargonext.com/news/best-logistics-hubs-in-europe-named/

Jennings, D., & Figliozzi, M. (2020). Study of road autonomous delivery robots and their potential effects on freight efficiency and travel. *Transportation Research Record*, 2674(9), 1019-1029.

Johnson, D., & Brown, A. (2021). The role of autonomous vehicles in modern supply chains. *International Journal of Logistics Research*, 19(1), 30-48.

Jones, R. (2023). Analyzing the economic impact of AVs on supply chain costs. *Journal of Economic Studies*, 45(3), 250-265.

Juliussen, E. (2022, November 22). *EE Times Europe - Autonomous Vehicles: How Is Europe Doing?* EE Times Europe. https://www.eetimes.eu/autonomous-vehicles-how-is-europe-doing/

Kang, S., Ozer, H., & Al-Qadi, I.L. (2019, July). *Benefit cost analysis (BCA) of autonomous and connected truck (ACT) technology and platooning*. In *International Airfield and Highway Pavements Conference 2019* (pp. 174-182). Reston, VA: American Society of Civil Engineers.

Karanam, R.K., Sachani, D.K., Natakam, V.M., Yarlagadda, V.K., & Kothapalli, K.R.V. (2024). Resilient supply chains: Strategies for managing disruptions in a globalized economy. *American Journal of Trade and Policy*, 11(1), 7-16.

Khalafi, S., Hafezalkotob, A., Mohammaditabar, D., & Taleizadeh, A.A. (2024). A game-theoretic approach for analyzing financial and economic sustainability of dual-channel green supply chain in the presence of corporate social responsibility. *Environment, Development and Sustainability* 26(7), 17131-17157.

Kim, E., Kim, Y., & Park, J. (2022). The necessity of introducing autonomous trucks in logistics 4.0. *Sustainability*, 14(7), 3978.

Le, P.T., Do, T.M.T., Nguyen, T.T.H., Tran, N.B.M., Paramasivam, P., Le, T.T., ..., & Chau, T. H. (2024). An insight into the Application of AI in maritime and Logistics toward Sustainable Transportation. *JOIV: International Journal on Informatics Visualization*, 8(1), 158-174.

Liu, Z., Costa, C., & Wu, Y. (2024). Quantitative Assessment of Sustainable Supply Chain Practices Using Life Cycle and Economic Impact Analysis.

Makahleh, H.Y., Ferranti, E.J.S., & Dissanayake, D. (2024). Assessing the Role of Autonomous Vehicles in Urban Areas: A Systematic Review of Literature. *Future Transportation*, 4(2), 321-348.

Marcucci, E., Gatta, V., de Oliveira Leite Nascimento, A., Teixeira, Â.C., & Ignaccolo, M. (2024). The environmental impact of buying groceries online: A sustainable assessment of the Italian e-grocery market. *Transport Policy*, 149, 222-233.

Martin, K., & Lopez, F. (2022). Autonomous vehicles and the future of supply chain management. *Journal of Business and Technology*, 11(2), 134-150.

McKinsey & Company. (2023, January 6). *Autonomous driving's future: Convenient and connected | McKinsey*. www.mckinsey.com. https://www.mckinsey.com/industries/automotive-and-assembly/our-insights/autonomous-drivings-future-convenient-and-connected.

Nagurney, A. (2021). Supply chain game theory network modeling under labor constraints: Applications to the Covid-19 pandemic. *European Journal of Operational Research*, *293*(3), 880-891.

Nagurney, A. (2023). *Defense-critical supply chain networks and risk management with the inclusion of labor: Dynamics and quantification of performance and the ranking of nodes and links*. In *Handbook for Management of Threats: Security and Defense, Resilience and Optimal Strategies* (pp. 39-57). Cham: Springer International Publishing.

Nwankwo, C.O., & Etukudoh, E.A. (2023). The Future of Autonomous Vehicles in Logistics and Supply Chain Management.

Olencevičiūtė, D., & Gružauskas, V. (2016). *Supply chain optimization in a small market: food industry's case* (Doctoral dissertation, Kauno technologijos universitetas).

Perussi, J. B., Gressler, F., & Seleme, R. (2019). Supply chain 4.0: Autonomous vehicles and equipment to meet demand. *International Journal of Supply Chain Management*, 8(4), 33-41.

Pettigrew, S., Farrar, V., Booth, L., Karl, C., Godic, B., Brown, J., & Thompson, J. (2023). The inexorable rise of automated food deliveries and potential anticipatory policy actions. *Australian and New Zealand Journal of Public Health*, 47(4), 100065.

Smith, J. (2022). Technological advancements in European logistics: The rise of autonomous vehicles. *European Transport and Logistics Journal*, 32(2), 110-125.

Supply Chain World. (2024). *The impact of AI on autonomous logistics*. Retrieved from https://www.scw-mag.com

Thomas, L., Wilson, M., & Rodriguez, E. (2022). Evaluating the impact of autonomous vehicles on European supply chains. *Transportation Research Journal*, 21(4), 89-105.

Transparency Market Research (n.d.). *Europe perishable goods transportation market.* https://www.transparencymarketresearch.com/europe-perishable-goods-transportation-market.html

Tsugawa, S., Jeschke, S., & Shladover, S.E. (2016). A review of truck platooning projects for energy savings. *IEEE Transactions on Intelligent Vehicles*, *1*(1), 68-77.

Tuli, F.A., Mohammed, M.A., & Sachani, D.K. (2024). Supply chain optimization: Machine learning applications in inventory management for e-commerce. *Global Disclosure of Economics and Business*, 13(1), 1-20.

Wang, J., Zhang, L., Huang, Y., & Zhao, J. (2020). Safety of autonomous vehicles. *Journal of Advanced Transportation*, 2020(1), 8867757.

Wilson, M. (2023). Autonomous vehicles and logistics: Case studies from the food and beverage industry. *European Logistics Review*, 15(2), 45-60.

Ye, W., Wang, C., Chen, F., Yan, S., & Li, L. (2021). Approaching autonomous driving with cautious optimism: analysis of road traffic injuries involving autonomous vehicles based on field test data. *Injury Prevention*, 27(1), 42-47.

Zhao, J., & Lee, J. Y. (2023). Effect of connected and autonomous vehicles on supply chain performance. *Transportation Research Record*, 2677(3), 402-424.

Chapter 13

LOGISTICS MARKET FORECASTING: USING INFORMATION STANDARDS TO REDUCE RISK

Katarzyna Sukiennik[1], Tomasz Szczepanik[2]

[1] Czestochowa University of Technology, Faculty of Management, Poland
katarzyna.sukiennik@pcz.pl ORCID 0000-0002-0195-7002
[2] Czestochowa University of Technology, Faculty of Management, Poland
tomasz.szczepanik@pcz.pl ORCID 0000-0003-4932-8229

Abstract: The logistics sector faces significant challenges due to fluctuating demand, supply chain complexities, and global disruptions. Effective forecasting and risk management are crucial for minimizing these challenges. This chapter explores the role of information exchange standards (EDI, GS1, XML) in improving market forecasting accuracy and reducing operational risks in logistics. A qualitative analysis was conducted, reviewing existing literature and case studies that highlight the application of information standards in logistics. The impact of EDI, GS1, and XML on data exchange, forecasting precision, and risk mitigation was analyzed through industry examples and theoretical frameworks.
The research found that the use of standardized information exchange systems, such as EDI, GS1, and XML, enhances the accuracy of market forecasts, reduces communication errors, and strengthens decision-making processes. These standards enable seamless data flow between supply chain partners, improving transparency and enabling proactive risk management. The implementation of EDI, GS1, and XML standards significantly enhances logistics operations by improving the accuracy of data exchange and minimizing errors across the supply chain. These standards enable faster, more efficient communication between partners, resulting in better demand forecasting, inventory management, and quicker responses to disruptions. Ultimately, the adoption of such standards strengthens supply chain resilience, reduces operational risks, and improves overall efficiency, allowing companies to maintain a competitive edge in an increasingly unpredictable market.

Keywords: forecasting, market analysis, logistics, information standards, risk

Introduction

The modern logistics market is facing dynamic changes and growing challenges due to globalization, fluctuating demand, and the increasing complexity of supply chains. In this environment, effective risk management has become a crucial element for the successful operation of logistics companies. Accurate market forecasting and analysis enable businesses to better prepare for future changes, minimize risks, and optimize operational processes.

However, forecasting and analysis alone are not sufficient without proper tools for managing data. In this context, information exchange standards such as EDI (Electronic Data Interchange), GS1, and XML play a vital role in improving data accuracy, streamlining communication between supply chain partners, and enhancing decision-making processes. This article explores how these information standards help reduce risk in logistics operations by enabling more transparent and efficient systems.

The aim of the study is to analyze and evaluate the impact of information exchange standards, such as EDI, GS1, and XML, on improving forecast accuracy and reducing operational risk in logistics. The study seeks to demonstrate how the implementation of these standards can enhance data management efficiency, streamline communication between supply chain partners, and strengthen the ability of logistics companies to respond to dynamic market changes and disruptions. Additionally, the objective is to highlight the importance of data transparency and consistency for better decision-making and minimizing potential losses resulting from unpredictable events in the logistics environment.

Objectives of the article:

1. Analyze the role of information exchange standards (EDI, GS1, XML) in improving logistics market forecasting accuracy – The article aims to examine how these standards contribute to more precise predictions in logistics operations, thereby reducing risks.
2. Evaluate how information standards help streamline data management and communication within supply chains – This objective focuses on assessing how these standards enhance the flow of information between supply chain partners, improving operational efficiency and decision-making processes.
3. Investigate the impact of standardized data on risk reduction in logistics operations – The article seeks to determine how the use of EDI, GS1, and XML standards minimizes operational risks by reducing errors, improving transparency, and enabling faster responses to market changes.
4. Explore the relationship between accurate forecasting, inventory management, and supply chain resilience – The article aims to highlight how better forecasting through standardized information exchange supports inventory management, reduces disruptions, and strengthens supply chain flexibility.
5. Present recommendations for implementing information standards to enhance risk management in logistics – The article concludes with practical insights and suggestions for logistics companies looking to integrate these standards into their operations to improve risk mitigation and operational effectiveness

The novelty of the research presented in this article lies in its comprehensive analysis that connects the topic of information exchange standards with their direct impact on risk reduction in logistics. Unlike existing studies, which often focus on individual aspects of forecasting or the application of specific technologies, this article integrates these areas, demonstrating how the use of EDI, GS1, and XML standards can systematically improve forecast accuracy and risk management. The authors provide a new perspective on the importance of these standards in the context of rapidly changing market conditions, emphasizing their role in enhancing the flexibility and operational resilience of supply chains. The study makes a significant contribution by showing how advanced data management can help organizations prepare for unpredictable disruptions, which is crucial in today's uncertain business environment.

The role of market forecasting and analysis in logistics

Importance of forecasting in logistics

The decision-making process within an enterprise is highly complex and challenging today due to the dynamic changes occurring in the market. The ability to achieve a competitive advantage allows businesses to operate effectively and attain high profits that contribute to their development. Predicting events enables companies to optimize and plan their operations (Maciąg et al., 2013, p. 15). There are numerous logistics phenomena where forecasting can be applied, depending on the nature and type of the business. Forecasting is a fundamental aspect of logistics management, helping organizations predict demand, optimize inventory levels, and mitigate potential disruptions in the supply chain (Duda, 2016, p. 20). In an industry where time and precision are crucial, accurate forecasting allows companies to stay ahead of changing market conditions and customer needs, translating into more efficient and effective operational actions.

One of the primary ways forecasting supports logistics is by providing insight into demand patterns. Accurate predictions of customer demand enable companies to adjust their inventory levels to avoid both stockouts and excess inventory (Chen et al., 2017, pp. 48-50). Stockouts can lead to lost sales and customer dissatisfaction, while excess inventory ties up capital and increases storage costs. With advanced forecasting methods, companies can better align their production and inventory strategies with actual demand, reducing waste and improving cost efficiency. The adaptability of inter-organizational information systems enhances information exchange in supplier-customer relationships and aids in improving shared outcomes (Dong et al., 2017, pp. 63-65).

Accurate forecasting is also critical for inventory management. Well-predicted demand curves allow logistics managers to maintain optimal inventory levels, reducing the need for sudden adjustments or emergency deliveries (Kiba-Janiak & Tronina, 2017, p. 103). This balance is essential for shortening order fulfillment times, as products are ready to ship at the moment of order placement. By maintaining appropriate inventory levels, companies can minimize delays in the supply chain, leading to faster order fulfillment and higher customer satisfaction.

Moreover, forecasting plays a crucial role in preparing for potential disruptions in the supply chain. External factors such as natural disasters, political instability, or global pandemics can significantly disrupt the flow of goods. Effective forecasting models enable logistics teams to anticipate such disruptions and develop contingency plans, for example, by identifying alternative suppliers or adjusting delivery routes. This proactive approach helps minimize delays and ensures business continuity despite unforeseen challenges.

In addition to managing supply and demand, accurate forecasting directly contributes to shortening order fulfillment times. By anticipating future demand with greater precision, companies can streamline production schedules and optimize order fulfillment processes. This leads to faster responses, minimizing the time between order placement and delivery. Shortened lead times are particularly valuable in industries with high customer expectations and tight schedules, such as e-commerce and fast-moving consumer goods (FMCG).

Finally, precise forecasting significantly improves overall operational efficiency. By aligning production schedules, inventory levels, and transportation needs with anticipated demand, companies can reduce inefficiencies across the supply chain. This optimization translates into cost savings, better resource allocation, and a more flexible logistics system capable of quickly responding to market changes. In the long run, companies that employ advanced forecasting techniques can maintain a competitive edge by being more responsive and adaptable. Practically, there is no area of the market where data analysis cannot be applied (Kasza et al., 2018, p. 11).

Forecasting is an indispensable tool in logistics, providing insights that help companies anticipate demand, manage inventory, and reduce the risk of disruptions in the supply chain. Accurate forecasting shortens order fulfillment times and enhances overall efficiency, ensuring that businesses remain competitive in a rapidly changing and unpredictable market.

Challenges in market analysis

Market analysis is an essential element of making effective decisions in logistics, but it encounters several significant challenges. One of the most notable issues is the volatility of market conditions (Jedliński & Marzantowicz, 2017, pp. 171-185). Fluctuations in global trade, the impact of pandemics like COVID-19, and economic changes can drastically alter patterns of demand and supply (Nyszk, 2021, pp. 37-45). The pandemic necessitated changes in the approach to logistics (Herold et al., 2021, pp. 121-132). These unpredictable factors complicate firms' ability to forecast accurately and maintain efficiency within the supply chain, including the supply chain's ability to anticipate, rebuild resilience, and respond to both predictable and unpredictable events (Mahfouz & Marisha, 2017, pp. 16-39). Sometimes, the benefits gained by buyers are realized at the expense of suppliers. Such asymmetric performance improvements can lead to deteriorating relationships between initially cooperating supply chain participants and even result in conflicts among them (Radhakrishnan, 2017, pp. 63-68).

Tensions in international trade and changes in tariffs can disrupt trade routes, leading to delays and increased costs. Similarly, the emergence of global crises, such as pandemics, can cause bottlenecks in supply chains, labor shortages, or transportation delays. These conditions require companies to exhibit greater flexibility and constantly adapt their market analysis tools to respond rapidly to changes.

Another significant challenge in market analysis is the difficulty in predicting demand and supply chain disruptions. Demand forecasting is often complicated by variable consumer behavior, which can change rapidly due to recessions, shifts in preferences, or seasonal factors. Disruptions in the supply chain, such as supplier issues, raw material shortages, or natural disasters, can further exacerbate these uncertainties. The interdependencies in global supply chains mean that even minor disruptions in one area can trigger a domino effect throughout the entire system.

Despite these challenges, forecasting and analysis tools are invaluable in risk management. Data-driven forecasting, utilizing both historical data and predictive algorithms, can assist logistics companies in anticipating demand changes and preparing for disruptions. While it is impossible to predict every change with complete accuracy, advanced analytics enable companies to model various scenarios and adjust strategies for potential shifts. This proactive approach minimizes the impact of volatility, ensuring more stable supply chain performance even in uncertain times.

By integrating comprehensive market analysis with forecasting tools, logistics companies can maintain greater resilience against unpredictable market conditions, manage risk more effectively, and sustain operational fluidity. Utilizing tools that enable data processing for multi-criteria analysis is regarded as a key factor in achieving competitive advantage (Machniewski, 2023, p. 1).

Information standards and risk management

In today's increasingly interconnected logistics sector, the need for seamless and standardized communication among supply chain partners is crucial. Achieving a competitive advantage over competitors can be accomplished by managing the flow of materials and physical distribution effectively, supported by information technology (Colla & Dupuis, 2002, pp. 103-111). However, having access to vast amounts of data limits the ability to fully leverage these resources in a comprehensive decision-making process (Dziurny, 2019, p. 34).

Information standards in logistics

Information standards are the foundation of effective logistics operations, ensuring accurate and timely data exchange among various stakeholders. Three of the most commonly used standards in logistics are EDI, GS1, and XML.

1. **EDI** (Electronic Data Interchange): This system enables companies to exchange business documents, such as invoices, orders, and shipping notifications, electronically and in a standardized format. Automating these transactions through EDI reduces the need for manual data entry, minimizing errors and speeding up communication. This technology is particularly beneficial in logistics, where timely information availability is crucial for ensuring smooth cooperation among different entities in the supply chain. By using EDI, companies can achieve greater efficiency, reduce processing times, and lower operational costs. EDI can significantly enhance customer service by providing a faster, more accurate, and less costly communication method compared to other methods like mail, phone, and in-person deliveries (Andiyappillai & Prakash, 2020, pp. 12-17).
2. **GS1**: This global standard focuses on identifying and tracking products and services using barcodes and RFID (Radio-Frequency Identification) tags. GS1 standards are critical for ensuring complete product traceability at every stage of the supply chain (GS1 Poland, 2022). With barcodes and RFID, companies can quickly and accurately identify and track products, aiding inventory management, reducing errors, and speeding up response times in the event of quality or delivery issues.
3. **XML** (Extensible Markup Language): This versatile markup language is designed for structurally representing data. Developed by the World Wide Web Consortium (W3C) in the late 1990s, XML allows developers to create custom tags that define the structure and meaning of data, making it a powerful tool for information exchange across different systems and platforms. XML has gained widespread popularity across various industries, from logistics to finance, due to its flexibility and capability to integrate with technologies like EDI and ERP sys-

tems. Additionally, XML is key in creating APIs (Application Programming Interfaces), enabling seamless communication between applications and improving system interoperability.

Risk in information flow

Risk can be understood as the possibility of an event occurring that will impact the achievement of organizational goals. Consequently, risk must first be associated with danger and specific conditions to be avoided (Konecka, 2015, pp. 57-58). It can be characterized as a set of factors or actions that cause damage and loss.

In the literature, a three-step strategy for risk management is often proposed: identification, analysis, and reduction (Chaudhary et al., 2022, pp. 42-52). In the dynamic logistics and supply chain management environment, effective information flow is crucial for minimizing risks, reducing errors, and enabling flexible responses to disruptions. By ensuring smooth data flow and adhering to information standards, organizations can mitigate delays, prevent inventory discrepancies, and reduce communication errors (Bartkowiak & Rutkowski, 2018, pp. 121-133).

The flow of information serves as the foundation for decision-making processes and facilitates the execution of core logistics and business processes. Skilled information management allows companies to grow through learning and knowledge management. The value of information can be measured by the benefits it can bring to an organization, which can be expressed through quantitative and qualitative data characterized by the following attributes:

- Clarity
- Precision
- Timeliness
- Completeness
- Reliability
- Uniqueness
- Accuracy
- Processability

In logistics and supply chain management, the application of common standards plays a vital role in risk management by providing a unified framework for data exchange. Technologies improve data accuracy, minimize errors, and support better decision-making, helping to reduce various operational risks. Standardized data exchange through EDI, GS1, and XML allows supply chain partners to utilize consistent formats and terminology, leading to increased data accuracy and reduced error rates. Here's how each of these standards impacts risk management (Francik & Pudło, 2016, pp. 179-189):

1. **Uniformity of Data Formats**: EDI ensures a standardized format for exchanging business documents like orders and invoices. By using these formats, companies reduce the risk of data entry errors and misunderstandings that often arise when different partners use disparate systems. Consistent data structures promote effective communication and efficient transaction processing.

2. **Consistent Product Identification**: GS1 barcodes and Global Trade Item Numbers (GTIN) standardize product identification across the supply chain. This consistency minimizes misunderstandings regarding product specifications, allowing companies to maintain accurate inventory levels and reduce risks related to shortages or surpluses.
3. **Automated Data Entry**: XML enables automated data entry and machine-to-machine communication, reducing reliance on manual information input and limiting error risks. This automation accelerates transactions and increases the reliability of exchanged data.

The use of EDI, GS1, and XML enhances operational transparency, which is a critical factor for effective risk management due to the following features (Vickery, 2021, pp. 212-227):

- **Real-Time Visualization**: Standardized data exchange allows for tracking shipments and inventory levels in real time. This visibility enables organizations to quickly detect potential disruptions, such as delays or inventory shortages, and take corrective actions before these issues escalate.
- **Data-Driven Decisions**: With standardized data formats, organizations can aggregate and analyze information more effectively. Enhanced analysis supports accurate forecasting and demand planning, which is crucial for managing risks associated with market volatility and supply chain disruptions.
- **Strengthened Collaboration**: The transparency provided by standardized data fosters better collaboration among supply chain partners. When stakeholders share a common data foundation, they can work more effectively to mitigate risks, coordinate responses to challenges, and exchange information, enhancing supply chain resilience.

Standards such as EDI, GS1, and XML, through standardized data exchange, contribute to minimizing errors, increasing transparency, and supporting faster decision-making, significantly reducing risks in logistics operations.

The impact of imporved information flow on risk minimization in supply chain

Enhancing information flow through the use of information standards is a key factor in reducing risks in supply chain operations. It enables effective data management, which translates into better coordination, greater accuracy, and faster decision-making. The introduction of uniform standards such as EDI, GS1, and XML contributes to increased transparency and the elimination of uncertainties that are often sources of risk in logistics operations. Table 13.1 presents key risk areas in logistics functions and the impact of improved information flow on their minimization.

Key Benefits of Improved Information Flow:

1. Increased Operational Transparency: This enables quicker identification of issues and disruptions in the supply chain.
2. Shortened Response Time: It facilitates decision-making in response to changing market and operational conditions.

3. Better Collaboration Among Partners: Unified data exchange promotes coordinated actions, enhancing efficiency.
4. Reduction in Operational Costs: Fewer errors and increased efficiency lead to lower costs.
5. Increased Customer Satisfaction: Improved service and product quality lead to higher customer satisfaction.

Table 13.1. Risk areas in logistics functions

Risk Area	Description	Mitigation strategies
Supply Chain Disruptions	Unforeseen events that disrupt the flow of goods and services.	Develop contingency plans and diversify suppliers.
Data Inaccuracies	Errors in data entry leading to incorrect information being used.	Implement robust data validation processes.
Regulatory Compliance	Failure to comply with regulations affecting logistics operations.	Regularly review and update compliance policies.
Inefficient Communication	Delays in communication between supply chain partners.	Enhance communication channels and technologies.
Inventory Management	Challenges in managing inventory levels leading to shortages or overstock.	Utilize advanced inventory management systems.
Transportation Risks	Risks associated with transportation delays and damages.	Monitor transportation performance and establish alternative routes.
Vendor Reliability	Dependence on vendors and their ability to meet supply demands.	Evaluate vendor performance and establish backup suppliers.
Technology Failures	Potential breakdowns or failures in logistics technology.	Invest in reliable technology and maintenance plans.
Customer Demand Variability	Fluctuations in customer demand affecting supply chain stability.	Use demand forecasting tools to better predict changes.
Natural Disasters	Impact of natural disasters on logistics operations.	Create disaster recovery plans and risk assessments.

Source: (Sulewski, 2017, pp. 71-83)

Improving information flow in the supply chain, supported by information standards, not only minimizes risk but also contributes to increased efficiency and competitiveness for organizations in a rapidly changing market environment.

Strengthening resilience during disruptions through information standards

Information standards play a crucial role in promoting resilience by maintaining consistent communication, facilitating real-time data exchange, and enabling collaboration among supply chain partners (Baptiste, 2019, pp. 91-98).

- **Consistency in the Face of Uncertainty**
  - Established Protocols: Information standards provide a communication framework that remains consistent even during crises. When unexpected events occur, such as natural disasters, supply chain disruptions, or pandemics, having

established protocols allows organizations to maintain effective communication with suppliers, customers, and other key stakeholders.
  - Faster Adaptation: Organizations that adhere to information standards can quickly adjust their operations in response to disruptions. For example, if a natural disaster affects a supplier, standardized communication methods allow companies to swiftly identify alternative sources and implement contingency plans, avoiding costly delays.
- **Enhanced Data Exchange for Better Decision-Making**
  - Real-Time Analytics: During disruptions, access to real-time data and analytics becomes crucial for decision-making. Information standards facilitate effective data exchange, enabling supply chain partners to quickly assess the situation and make informed decisions based on reliable information.
  - Scenario Planning: Standardized data formats allow for scenario planning, enabling organizations to simulate various disruption situations and develop strategic responses. This proactive approach strengthens resilience by preparing companies to effectively respond to unforeseen events.
- **Collaboration Across the Supply Chain**
  - Strengthening Partnerships: Information standards foster collaboration among supply chain partners, especially during challenging times. When organizations effectively communicate using standardized methods, they can work together to solve problems, building trust and strengthening the entire supply chain.
  - Shared Resources and Information: Enhanced communication allows organizations to share resources and information during difficult times. For example, during a pandemic, companies may collaborate in managing inventory, pooling resources to ensure the smooth delivery of essential goods to customers. This is achieved through transportation route optimization and transportation consolidation.

The improved flow of information through information standards such as EDI, GS1, and XML plays a crucial role in reducing risks in the supply chain. These standards streamline real-time information exchange, enhance data accuracy, and foster collaboration, ultimately contributing to the creation of a more resilient and agile supply chain capable of handling complex and unforeseen challenges. Strategic collection, processing, and analysis of data sets enable businesses to gain valuable insights and conclusions that help them make better decisions, improve their products and services, and increase their competitiveness (Nowik, 2018, p. 117).

Standardization of information flow in the supply chain

Standardization of information flow among partners in the supply chain is essential for increasing operational efficiency, strengthening collaboration, and minimizing errors throughout the supply chain. In today's global and integrated market, where many stakeholders must work seamlessly together, consistent and clear communication methods ensure that all partners are aligned and can collaborate effectively. The main benefits of standardizing communication include (Szydło, 2020, pp. 42-51):

- **Increased Efficiency:** Standardized communication protocols streamline information exchange, minimizing delays and misunderstandings. When partners adopt common standards, data can be processed more quickly, leading to more efficient decision-making and more flexible operations throughout the supply chain.
- **Strengthening Collaboration:** The success of supply chain management relies on strong collaboration among partners. Standardized communication creates a common understanding, enabling the execution of joint projects, knowledge exchange, and coordinated actions. This approach fosters innovation, more flexible problem-solving, and the creation of a resilient supply chain.
- **Reduction of Errors and Misunderstandings:** Differences in communication protocols among partners increase the risk of errors and misunderstandings. Standardized formats, terminology, and processes mitigate these risks, creating a common understanding and improving data accuracy across the supply chain.
- **Cost Savings:** Inefficiencies in communication lead to increased costs associated with errors, delays, and additional resources needed to resolve issues. Standardization of communication helps companies avoid these costs by improving the efficiency of information exchange, resulting in lower overall expenses and better resource utilization.
- **Better Data Integration:** Seamless integration of data from various sources is crucial for effective supply chain management and analysis. Standardized communication simplifies data exchange, making it easier for partners to access and utilize information. This enables more accurate forecasting, better inventory management, and improved overall performance.
- **Compliance and Risk Management:** Standardized communication helps meet regulatory requirements through clear protocols that ensure all partners are informed and compliant with legal requirements. This compliance reduces the risk of legal issues and supports the building of a positive image for the entire supply chain.

The standardization of communication among partners in the supply chain is no longer just a best practice but a necessity in today's business environment. By increasing efficiency, collaboration, and data accuracy, organizations can enhance supply chain performance, reduce costs, and ultimately deliver greater value to customers. Implementing standardized communication practices is a strategic decision that brings long-term benefits for all stakeholders, positioning organizations for success in a competitive market.

Examples of implementing standards in risk management

*Walmart and EDI*Walmart, a leader in retail logistics, utilizes Electronic Data Interchange (EDI) to streamline processes within its supply chain. By employing EDI for order processing and inventory management, Walmart achieves high data accuracy in inventory records, reducing stockouts and improving order fulfillment rates. The standardization of EDI allows Walmart to mitigate risks associated with inventory inaccuracies and disruptions in the supply chain.

*Coca-Cola and GS1*Coca-Cola applies GS1 standards for product identification and tracking throughout its supply chain. By implementing GS1 barcodes, Coca-Cola effectively manages inventory and ensures consistent product identification across distribution channels. This level of operational transparency enables the company to respond quickly to changes in demand and risks within the supply chain.

*Maersk and XML*Maersk, a global leader in logistics and shipping, uses XML for data exchange in its logistics operations. XML standards improve the accuracy of shipping documents and facilitate seamless integration with partners and customers. This standardization reduces documentation errors and aids in quick decision-making, helping Maersk manage risks associated with delivery delays and compliance issues.

The integration of EDI, GS1, and XML in risk management enhances data accuracy, minimizes errors, and increases operational transparency in logistics. These standards enable better decision-making, strengthen collaboration, and allow organizations to respond swiftly to potential threats. Successful implementations of these standards by companies like Walmart, Coca-Cola, and Maersk demonstrate how valuable these tools are in creating resilient supply chains capable of overcoming complex global challenges.

Future trends and developments

Evolution of information standards

As the logistics industry continues to evolve in response to digital transformation, information standards such as Electronic Data Interchange (EDI), GS1, and XML are adapting to the demands of a rapidly changing landscape. The integration of these standards in a digitized logistics ecosystem is crucial for enhancing efficiency, accuracy, and collaboration. This section discusses the future of these information standards and the new technologies that complement them, such as artificial intelligence (AI) and blockchain (Czaplewski & Rydzkowski, 2021, pp. 29-32).

The future of EDI, GS1, and XML in a digitized logistics ecosystem

1. **Increased Integration with Digital Platforms**. As logistics operations become increasingly digitized, the future of EDI, GS1, and XML lies in their seamless integration with various digital platforms, including cloud-based systems and Internet of Things (IoT) applications. Such integration will enable real-time data exchange and enhance visibility throughout the supply chain, allowing stakeholders to make better decisions based on accurate and up-to-date information.
2. **Greater Flexibility and Adaptability**. The logistics industry is experiencing rapid changes, including shifts in consumer behavior, market demands, and regulatory requirements. EDI, GS1, and XML standards will evolve toward greater flexibility and adaptability, allowing organizations to easily modify their processes and data formats in response to new challenges. This adaptability will be crucial for maintaining a competitive edge in a dynamic environment.
3. **Enhanced Data Interoperability**. As logistics networks become increasingly complex, ensuring data interoperability between different systems and platforms will be critical (Bianco et al., 2021, p. 174). Future iterations of EDI, GS1, and XML will focus on improving compatibility with various technologies, enabling

smoother communication and data exchange among different partners, software systems, and geographical regions.

4. **Focus on Data Security and Compliance**. With the growing reliance on digital communication, the need for strengthened data security and compliance measures is increasing. Future developments in information standards will likely focus on data protection, ensuring that sensitive information is exchanged securely while complying with regulations. This emphasis on security and compliance will help build trust among stakeholders and protect organizations from potential data breaches.

Next-generation technologies supporting information standards

1. Artificial Intelligence (AI)
   - Data Analysis and Predictive Modeling: AI technologies can analyze vast amounts of data generated by EDI, GS1, and XML standards to identify trends, patterns, and anomalies. This capability allows organizations to leverage predictive analytics for better forecasting and decision-making, enhancing their ability to respond to market changes and potential disruptions.
   - Automated Communication: AI-driven chatbots and virtual assistants can facilitate communication between supply chain partners by automating routine inquiries and information requests. Such automation improves efficiency and reduces employee workload, allowing them to focus on more strategic tasks.
2. Blockchain Technology
   - Increased Transparency and Traceability: Blockchain provides a decentralized ledger that securely and transparently records transactions. By integrating blockchain with information standards such as GS1, organizations can achieve full traceability of products throughout the supply chain, enhancing accountability and reducing the risk of fraud or errors.
   - Smart Contracts: Blockchain enables the use of smart contracts, which are self-executing agreements with the terms of the contract directly written into code. These contracts can automate processes such as payment approvals and order fulfillment based on defined conditions, streamlining operations and reducing potential disputes between partners.
3. Internet of Things (IoT)
   - Real-Time Data Collection: IoT devices, such as sensors and RFID tags, can collect real-time data on inventory levels, shipment conditions, and equipment performance. Integrating this data with EDI, GS1, and XML standards allows organizations to enhance operational efficiency and their ability to respond to changes in the supply chain.
   - Predictive Maintenance: IoT technology can also support predictive maintenance of logistics equipment by monitoring performance and predicting failures before they occur. This capability minimizes downtime and ensures smooth operations, reducing the risk of disruptions.

The impact of technological advancements on risk management

Technological advancements are transforming the landscape of risk management in logistics, offering innovative tools and methodologies that improve forecasting, analysis, and overall operational resilience. Automation, machine learning, and data analytics are key technologies driving this transformation. This section explores their role in enhancing risk management practices and examines future opportunities for improving risk management in logistics through integrated digital systems.

Automation, machine learning, and data analytics are revolutionizing forecasting and analysis in logistics, enabling organizations to increase accuracy, streamline processes, and make informed decisions by leveraging vast amounts of real-time data.

Discussion

The findings of this study align with and further reinforce the conclusions of several previous studies regarding the importance of information exchange standards in logistics. For instance, the work of Brahami et al. (2022, pp. 30-45) highlights the critical role of forecasting in logistics, emphasizing that accurate predictions help organizations manage supply and demand fluctuations. Our findings echo this by showing that standards like EDI, GS1, and XML improve forecasting accuracy and inventory management, thus supporting better decision-making.

Similarly, the research of Adeitan et al. (2021, pp. 317-326) points to the competitive advantage gained through effective information management. This article confirms that using standardized data formats significantly enhances data flow between supply chain partners, leading to more efficient operations and reduced risks. In addition, the article supports the findings of Malik et al. (2024, pp. 1-17), who noted that better information exchange fosters stronger collaboration and improves risk management in the supply chain.

Furthermore, the results align with the conclusions of Kiba-Janiak & Tronina (2017), who discussed the importance of forecasting in minimizing supply chain disruptions. Our analysis suggests that the adoption of information standards not only aids in predicting demand but also helps companies proactively respond to unforeseen disruptions, such as those caused by natural disasters or political instability. By improving transparency and streamlining communication, these standards enable logistics companies to mitigate the risks discussed in earlier research and maintain operational resilience in the face of an unpredictable market environment.

Limitations

This study focuses on the dairy sector in a developing economy, which may limit its generalizability to other industries or regions. Additionally, the reliance on survey data may introduce biases or limitations in capturing the full spectrum of supply chain risks. The study does not explore the role of emerging technologies like AI or blockchain in mitigating risks within the supply chain.

Direction for future research

Future studies could extend the research to other industries or advanced economies to validate the findings across diverse contexts. Additionally, exploring the impact of digital tools, such as AI and blockchain, on risk management and supply chain integration would provide valuable insights.

Conclusion

Effective forecasting and analysis, combined with the implementation of information standards, are key elements in reducing risks in the logistics and supply chain sector. By leveraging advanced technologies such as automation, machine learning, and data analytics, organizations can increase the accuracy of their forecasts, enabling them to anticipate potential disruptions and respond proactively. Information standards, such as EDI and GS1, facilitate seamless data exchange and communication among supply chain partners, ensuring consistency and reducing the likelihood of errors and misunderstandings. Together, these elements create a robust framework that enhances operational resilience and supports informed decision-making.

Adopting standardized communication systems is crucial for organizations aiming to improve efficiency and minimize risks in logistics. Standardization promotes transparency, enables real-time data sharing, and increases collaboration among partners, ultimately leading to more effective risk management. By ensuring that all stakeholders operate based on the same communication protocols and data formats, organizations can streamline their operations, reduce errors, and swiftly respond to changes in the supply chain landscape. The significance of these standards cannot be overstated, as they provide the foundation for reliable and effective communication in an increasingly complex global market.

The future of risk management in logistics is on the brink of significant transformation, driven by continuous technological advancement and the ongoing development of information standards. As organizations increasingly adopt integrated digital systems, the potential for advanced data analytics, real-time monitoring, and forecasting capabilities will grow, further strengthening risk management practices. The evolution of information standards will play a crucial role in this transformation, ensuring that communication remains fluid and effective across various technologies and platforms. By embracing these changes, organizations can build more resilient supply chains, ready to tackle future challenges and uncertainties while delivering value to customers and stakeholders.

References

Adeitan, A.D., Aigbavboa, C., Adeitan, A.D., & Adewole, A.O. (2021). *Influence of effective and new information flow on logistics management*. In *Lecture Notes in Computer Science,* 12520.

Ali, A., Mahfouz, A., & Arisha, A. (2017). Analysing supply chain resilience: integrating the constructs in a concept mapping framework via a systematic literature review. *Supply Chain Management, International Journal*, 22(1).

Andiyappillai, N., & Prakash, T. (2020). Latest developments in logistics and supply chain systems implementations. *International Research Journal on Advanced Science Hub*, 2(3), 12-17. DOI: 10.47392/irjash.2020.18.

Bartkowiak, P., & Rutkowski, I.P. (2018). Implementation of the IMZD Approach (IMZD as the Integrative Maturity Capability Model) in the Performance of a New Product Process. *Journal of Management and Financial Sciences*, 11(31).

Baptiste, P. (ed.). (2019). The social acceptability issues that can be expected in logistics. *Proceedings of the 2019 International Conference on Industrial Engineering and Systems Management, IEMS 2019*. Shanghai, 25-27 September 2019.

Bianco, I., Ilin, I., & Iliinsky, A. (2021). Digital technology risk reduction mechanisms to enhance ecological and human safety in the Northern Sea route for oil and gas companies. In: *E3S Web of Conferences*, 258, 06047. DOI: 10.1051/e3sconf/202125806047.

Cao, Q., Schniederjans, D., & Schniederjans, M. (2017). Establishing the use of cloud computing in supply chain management. *Operations Management Research*, 10(1-2). DOI: 10.1007/s12063-017-0123-6.

Chaudhary, K., Chaudhary, G., & Khari, M. (2023). Applying game theory models for risk management in supply chain networks. *American Journal of Business and Operations Research*, 10(1), 42-52. DOI: 10.54216/AJBOR.100104.

Chen, L., Zhao, X., Tang, O., Price, L., Zhang, S., & Zhu, W. (2017). Supply chain collaboration for sustainability: A literature review and future research agenda. *International Journal of Production Economics*, 194. DOI: 10.1016/j.ijpe.2017.04.005.

Colla, E., & Dupuis, M. (2002). Research and managerial issues on global retail competition: Carrefour/Wal Mart. *International Journal of Retail & Distribution Management*, 30(2).

Czaplewski, J., & Rydzkowski, M. (2021). *Zarządzanie łańcuchem dostaw w dobie cyfryzacji*. Wydawnictwo Naukowe PWN.

Duda, A. (2016). Modelowanie i prognozowanie ekonometryczne w logistyce przedsiębiorstwa. *Systemy Logistyczne Wojsk. Zeszyty Naukowe Instytutu Logistyki Wydziału Logistyki Wojskowej Akademii Technicznej*, 44.

Dong, M., Fang, Y., & Straub, D. (2017). The impact of institutional distance on the joint performance of collaborating firms: The role of adaptive interorganizational systems. *Information Systems Research*, 28(2). DOI: 10.1287/isre.2016.0675.

Dziurny, A. (2019). Determinanty bezpieczeństwa ekonomicznego w logistyce. *Gospodarka Materiałowa i Logistyka*, 10.

Francik, K., & Pudło, M. (2016). Znaczenie systemów realizacji produkcji jako element zarządzania ryzykiem. In: L. Kiełtyka, W. Jędrzejczyk, P. Kobis (eds.), *Wyzwania współczesnego zarządzania. Kreowanie kapitału intelektualnego organizacji*. Warszawa: Towarzystwo Naukowe Organizacji i Kierownictwa.

GS1 Poland (2022). Standardy GS1: Zastosowanie w logistyce i zarządzaniu łańcuchem dostaw. Warszawa: GS1 Polska.

Herold, D.M., Nowicka, K., Pluta-Zaremba, A., & Kummer, S. (2021). COVID-19 and the pursuit of supply chain resilience: Reactions and "lessons learned" from logistics service providers (LSPs). *Supply Chain Management*, 26(6), 702-714. DOI: 10.1108/SCM-09-2020-0439

Jedliński, M., & Marzantowicz, Ł. (2017). Wpływ niepewności i nieprzewidywalności na procesy logistyczne. *Problemy Transportu i Logistyki*, 33.

Kiba-Janiak, M., & Tronina, P. (2017). Wpływ systemów telematycznych na usprawnianie łańcuchów dostaw. *Zeszyty Naukowe Politechniki Śląskiej, Organizacja i Zarządzanie*, 103.

Kasza, S., Romaszewski, A., Kopański, Z., Uracz, F., Furmanik, F., Dyl, S., & Tabak, J. (2018). Wielokierunkowe wykorzystanie Big Data. *Journal of Clinical Healthcare*.

Konecka, S. (2015). *Ryzyko zakłóceń w zarządzaniu łańcuchem dostaw*. Rozprawa doktorska, Uniwersytet Ekonomiczny w Poznaniu, Poznań.

Maciąg, A., Pietroń, R., & Kukla, S. (2013). *Prognozowanie i symulacja w przedsiębiorstwie*. Warszawa: PWE.

Machniewski, S. (2023). Praktyczne zastosowanie Big Data i analizy danych w biznesie. https://www.money.pl [29.06.2023].

Malik, T., Hassan, S.M., & Tufail, M. (2024). The impact of supply chain risk and supply chain integration on organizational performance: Evidence from the dairy sector of a developing economy. *Brazylian Journal of Operations & Production Management*, 21(1), 1682.

Menaouer, B., Abdeldjouad, F.Z., Sabri, M., Semaoune, K., & Matta N. (2022). Forecasting supply chain demand approach using knowledge management processes and supervised learning techniques. *International Journal of Information Systems and Supply Chain Management*, 15(1).

Nowik, M. (2018). Big Data innowacją w logistyce i zarządzaniu łańcuchem dostaw. *Zeszyty Naukowe Szkoły Głównej Gospodarstwa Wiejskiego w Warszawie, Ekonomika i Organizacja Logistyki*, 3(3).

Nyszk, W. (2021). Logistyka czynnikiem tworzenia konkurencyjności przedsiębiorstwa. *Gospodarka Materiałowa i Logistyka*, 3, 37-45.

Radhakrishnan, A., Davis, J., Sridharan, S., Moore, D., & David, D. (2017). The impact of inter organizational information systems-enabled external integration on capabilities of buyer supplier dyads. *European Management Journal*, 36(4). DOI: 10.1016/j.emj.2017.09.006.

Sulewski, P. (2017). Ryzyko w logistyce i sposoby jego minimalizacji. *Ekonomika i Organizacja Logistyki*, 2(4), 71-83. DOI: 10.22630/EIOL.2017.2.4.37

Szydło, M. (2020). *Standaryzacja w logistyce*. Wydawnictwo C.H. Beck.

Vickery, T.A. (2021). EDI, GS1 and XML Standards in Supply Chain Management: Enhancing Operational Transparency and Risk Management. *Journal of Supply Chain Systems*, 32(4).

Chapter 14

INTEGRATION OF TECHNOLOGICAL INNOVATIONS WITH RENEWABLE ENERGY SOURCES IN THE CONSTRUCTION INDUSTRY

Jakub Semrau[1], Anna Horzela-Miś[2]

[1] Silesian University of Technology, Faculty of Logistics, Poland
Jakub.Semrau@polsl.pl ORCID 0000-0002-4894-7792
[2] Silesian University of Technology, Faculty of Management, Poland
Anna.Horzela-Mis@polsl.pl ORCID 0000-0003-2345-9861

Abstract: The aim of this chapter is to develop a model for integrating technological innovations with renewable energy sources in the construction industry, taking into account key aspects of energy efficiency and sustainable development. The chapter examines modern technologies such as building management systems, the Internet of Things, and solutions related to renewable energy sources, including photovoltaic installations and wind farms. The proposed model, divided into five stages – from planning and design to monitoring and optimization – aims to streamline the process of implementing innovations in the construction sector. Research based on literature analysis and case studies demonstrates that the integration of these technologies contributes to improving the energy efficiency of buildings and supports the achievement of long-term sustainable development goals, while also promoting more eco-friendly and cost-effective construction solutions.

Keywords: energy efficiency, integration of technologies, renewable energy sources, sustainable construction

Introduction

The contemporary construction industry faces significant challenges related to the necessity of adapting to new sustainability standards and reducing its environmental impact (Charani Shandiz et al., 2021). Increasing regulatory requirements for greenhouse gas emission reductions, along with social and economic pressures to implement more efficient energy solutions (Diab et al., 2015), compel the construction industry to seek innovative methods to improve energy efficiency and reduce the consumption of natural resources (Hawila et al., 2022). In the context of global efforts to combat climate change, the integration of renewable energy sources (RES) in the construction sector has become a key element of sustainable development strategies (Davino et al., 2022).

For several decades, renewable energy technologies such as photovoltaic panels, wind turbines, and geothermal systems have played an increasingly important role in generating energy for buildings (He et al., 2022). However, renewable energy sources alone are not sufficient to achieve the ambitious goals related to carbon neutrality (Pejović et al., 2021). Collaboration between these technologies and innovative technological solutions is essential (Austin et al., 2022) to support energy management, optimize consumption, and automate construction processes. Technological innovations such as the Internet of Things (IoT), artificial intelligence (AI), 3D printing, and advanced energy management systems (EMS) enable the full integration of renewable energy sources in the design, construction, and operation of buildings (Selvan et al., 2023).

The integration of technological innovations with renewable energy sources in construction has significant potential to contribute to the achievement of several key sustainable development goals (Levesque et al., 2019). Primarily, it enables effective reduction of CO_2 emissions by decreasing the reliance of buildings on traditional, high-emission energy sources such as coal, natural gas, and oil. Utilizing clean energy from RES, including solar, wind, and geothermal energy, leads to a substantial reduction in the carbon footprint of buildings throughout their lifecycle – from construction and operation to eventual demolition (Magrini et al., 2020).

Another significant benefit of integrating new technologies with renewable energy sources is the reduction of operational costs. Modern energy management systems, such as Energy Management Systems (EMS) and Building Management Systems (BMS), allow for the optimal control of a building's energy consumption, thereby minimizing energy waste and operational expenses (Østergaard et al., 2020; Su & Wang, 2012). For instance, smart lighting and heating, ventilation, and air conditioning (HVAC) systems integrated with IoT sensors can adjust their operation based on the actual needs of users, eliminating unnecessary energy usage (Afsharpanah et al., 2022a). Additionally, energy storage systems, such as advanced batteries, can store excess energy generated by photovoltaic installations or wind turbines and use it during peak demand periods, further reducing costs associated with purchasing energy from the grid.

It is also worth emphasizing that integrating innovative technologies with renewable energy sources significantly enhances the comfort of building users. Intelligent environmental management systems allow for the creation of conditions perfectly tailored to individual preferences by automatically adjusting temperature, air quality, lighting, and other parameters. This not only achieves greater energy efficiency but also improves the quality of life and health of those in the building. An example would be HVAC systems with air quality monitoring functions that automatically adjust ventilation based on carbon dioxide levels or humidity, which has a direct impact on the health and comfort of users (Reddy et al., 2024).

Thanks to advanced technologies, it is possible to design so-called smart buildings that not only manage energy efficiently but also dynamically adapt to changing external and internal conditions. These systems use data from IoT sensors to monitor energy consumption, temperature, lighting, humidity, and other parameters in real time. Artificial intelligence algorithms analyze this data and make decisions to optimize the operation of various building systems, leading to minimized energy loss and maximized effective use of energy (De León et al., 2021).

As a result, the integration of technological innovations with renewable energy sources not only contributes to more sustainable development but also significantly transforms how buildings operate, turning them into autonomous energy units that intelligently respond to user needs and changing environmental conditions (Karlessi et al., 2017). This holistic approach to building design and operation has the potential to become the foundation of future cities, where sustainable development and energy efficiency will be core values (Wu & Skye, 2021).

The aim of the article is to develop a model for integrating technological innovations with renewable energy sources in the construction sector, which takes into account energy efficiency and supports sustainable development. The focus is on reviewing modern technologies and their applications across various stages of building design, construction, and operation. The article also discusses examples of practical applications of technological innovations combined with renewable energy sources that are already contributing to achieving sustainability in construction. In this way, the article seeks to provide readers with both theoretical foundations and practical aspects of integrating technology with renewable energy sources, which represents one of the most significant challenges and, at the same time, one of the greatest opportunities for the contemporary construction industry.

Literature review

The integration of technological innovations and renewable energy sources in the construction sector is an area of growing interest both in the academic community and among practitioners (Østergaard et al., 2021). The literature shows an increasing number of studies focused on the implementation of modern technologies, such as energy management systems, the Internet of Things, and renewable energy sources, including photovoltaic panels, wind systems, and energy storage technologies (Davi et al., 2016). In the context of construction, these technologies have the potential not only to enhance energy efficiency but also to reduce the negative environmental impact of buildings, which is crucial for achieving sustainable development (Laski & Burrows, 2017).

The literature on renewable energy sources emphasizes that technologies such as photovoltaic panels and wind farms are fundamental to achieving sustainable energy development in construction (Lin et al., 2020). Specifically, research on the use of photovoltaics in zero-energy buildings demonstrates (Belussi et al., 2019) that by integrating renewable energy sources with intelligent energy management systems, it is possible not only to achieve energy self-sufficiency but also to generate excess energy that can be fed back into the power grid (Sun et al., 2023).

Another significant area of research is green building, which involves designing buildings with the goal of minimizing their environmental impact. The literature cites numerous examples of environmental certifications, such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method), which provide frameworks for designing and constructing sustainable buildings (Ahmed et al., 2022). These certifications assess buildings in terms of energy efficiency, material use, water management, and user comfort, significantly contributing to their popularity in the construction sector worldwide.

In the context of modern technologies in construction, literature increasingly addresses issues related to the automation of energy management processes. Building Management Systems (BMS), supported by the Internet of Things, enable real-time monitoring and optimization of energy consumption, which is a crucial element for managing building energy efficiency. These technologies allow for the adjustment of energy use based on weather conditions, user activity, and other environmental factors, leading to reductions in operational costs and carbon dioxide emissions (Jensen et al., 2017).

Based on the literature analysis, it can be concluded that the integration of renewable energy sources with modern energy management technologies in buildings is crucial for the future of sustainable construction. In particular, many authors highlight the lack of guidelines, models, or legal frameworks that facilitate the harmonious integration of these technologies to maximize the benefits of their implementation (Kapsalis et al., 2024). Therefore, this chapter proposes an original Model for Integrating Technological Innovations with Renewable Energy Sources, which incorporates the latest technological advancements and sustainable building practices.

In summary, the existing literature provides a solid theoretical and empirical foundation for the development and advancement of integrated technological solutions in construction that support sustainable development and energy efficiency.

Research methodology

In this chapter, a literature analysis method was used as the primary research tool to develop a model for integrating technological innovations with renewable energy sources in the construction sector. This method allowed for an in-depth examination of existing scientific research and case studies related to technological innovations and their application in construction, as well as the implementation of renewable energy sources in the context of energy efficiency and sustainable development.

The literature analysis focused on identifying key technologies used in construction, such as Building Management Systems (BMS), the Internet of Things (IoT), intelligent energy management systems, and modern renewable energy technologies, including photovoltaic and wind farms. The review of research enabled the identification of significant trends and challenges associated with the implementation of these technologies, which served as the basis for developing the original integration model.

A key stage of the research process was to understand how these technologies can be effectively integrated with renewable energy sources in buildings to enhance their energy efficiency, minimize CO_2 emissions, and support long-term sustainability. The model was developed based on a synthetic analysis of previous research, incorporating stages of technological innovation implementation such as planning and analysis, system design, implementation, monitoring and optimization, and evaluation and maintenance.

The developed model for integrating technological innovations with renewable energy sources is based on a systemic approach that takes into account each of the mentioned stages of the technology and renewable energy integration process. Each stage has been thoroughly discussed based on available research and examples of practical implementations. This model aims not only to identify best practices in the area of technological innovation integration but also to present a comprehensive approach to energy optimization in construction, considering the requirements of modern sustainable development.

The results of the literature analysis, along with conclusions drawn from the conducted case studies, led to the creation of a structural model that can be used as a tool to support decision-makers in the process of designing, constructing, and managing energy-efficient buildings fully integrated with renewable energy technologies.

Sustainable technologies and innovations in construction

The development of modern technologies and the growing demand for sustainable development in the construction industry have led to the necessity of integrating renewable energy sources with innovative technological solutions (Bhattacharya et al., 2023). To understand the full scope of this integration, it is essential to analyze the theoretical foundations related to renewable energy sources, technological innovations in construction, and the impact of these changes on energy efficiency and sustainable development. Key concepts include not only the renewable energy sources themselves but also the new technologies that enable their full integration with buildings and other infrastructure elements (Ma et al., 2023).

Renewable energy sources

Renewable energy sources are natural resources that are replenished in short cycles and serve as alternatives to conventional fossil fuels (Ullah et al., 2021). The main types of renewable energy sources used in the construction sector include:

– Solar Energy – Most commonly used in the form of photovoltaic energy, it involves converting sunlight directly into electricity using photovoltaic panels (Barakat et al., 2020). Photovoltaic cells made from semiconductor materials like silicon absorb photons from sunlight, which induces the flow of electrons, generating direct current (DC) that can then be converted into alternating current (AC) suitable for powering buildings (Sinha & Chandel, 2016). This technology is widely used in both small, residential installations and large photovoltaic farms that supply energy to entire regions. In addition to PV systems, there is also solar water heating technology, which utilizes solar energy to heat domestic water in residential and commercial buildings (Shi et al., 2022). Solar collectors, typically mounted on roofs, absorb radiation and transfer heat to a medium such as water or glycol, which then feeds into heating systems (Hernández-Callejo et al., 2019). Solar energy stands out due to its exceptional availability, as the sun is an almost unlimited energy source, and technologies based on this energy are increasingly affordable and efficient (IEA, 2023). Moreover, these systems can be relatively easily integrated into buildings in the form of panels on roofs, facades, or even within building infrastructure, making solar energy a highly flexible solution. It is a key renewable energy source that enhances the energy efficiency of buildings, reduces their reliance on conventional energy sources, and lowers greenhouse gas emissions, which has a direct impact on combating climate change (Aldhshan et al., 2021).

- Wind Energy – one of the oldest forms of renewable energy, used for centuries, ranging from simple windmills to advanced modern wind turbines (Palraj & Rajamanickam, 2020). The kinetic energy of the wind is converted into electrical energy using wind turbines, which consist of a rotor, generator, and control systems. In the context of construction, wind turbines can be integrated on roofs or near buildings, especially in areas with favorable wind conditions (Zhang et al., 2023). For small wind turbines installed on buildings, their efficiency depends on local wind conditions such as wind speed and direction, as well as the height and location of the building (Kaewunruen et al., 2018). The use of small wind turbines is particularly popular in buildings located in suburban and rural areas (Arnfield, 2003), where space around buildings allows for effective wind energy exploitation (Wang et al., 2021). The application of such solutions in buildings enables on-site electricity production, reducing the demand for grid energy and supporting the building's energy autonomy (Kwok & Hu, 2023).
- Geothermal Energy – utilizes heat stored within the Earth's interior for the production of thermal and electrical energy (Gaur et al., 2021). In buildings, the technology primarily used involves heat pumps that convert geothermal heat into heating energy (Palmero-Marrero et al., 2020; Shah et al., 2022). Geothermal systems are particularly beneficial in buildings with high energy demands, such as commercial, industrial, or multi-family residential properties, where the ability to harness ground heat yields significant savings (Bae & Nam, 2022). Additionally, geothermal installations have a long lifespan and can operate for decades without major upgrades, making them a long-term investment (Lee et al., 2022; Osman et al., 2023).
- Biomass – a renewable energy source derived from organic materials, including both plant products (e.g., wood, agricultural residues, forest waste) and organic waste (e.g., municipal or agricultural waste) (Zhu et al., 2020). In the construction sector, biomass is primarily used for heat production through combustion in dedicated heating systems, such as biomass boilers (Behzadi et al., 2023). The advantage of using biomass in buildings also includes the potential to utilize local resources, which reduces transportation costs and supports the local economy (Yang et al., 2022). Biomass boilers are used in both residential and commercial buildings, particularly in rural areas where access to organic raw materials is easier (Rahman et al., 2015).
- Hydropower Energy – although often associated with large hydropower plants, in the context of construction, the use of micro and small hydropower systems can be considered. These systems can be integrated with local energy systems, particularly in buildings located near rivers and other watercourses. Hydropower is characterized by high conversion efficiency, but its application in buildings is limited to areas with access to watercourses with appropriate flow rates. When integrating micro-hydropower plants with building systems, significant reductions in energy costs can be achieved, especially in rural and mountainous areas (Panagopoulos, 2021).

Each of the presented renewable energy sources has specific applications in the construction sector, which depend on local climatic, topographical, and technological conditions. However, the key aspect is their integration with innovative technological systems, which enables the maximum utilization of their potential.

Modern technologies in construction sector

The development of innovative technologies is a key element in integrating renewable energy sources in construction. The concept of technological innovations refers to the introduction of new technical and organizational solutions that enable more efficient resource management, as well as the reduction of operational costs and environmental impact. Among the key technologies supporting the integration of renewable energy sources in construction are:

- Internet of Things (IoT) refers to a network of interconnected sensors and devices that enable the collection and processing of data related to various aspects of building operations, such as energy consumption, weather conditions, and user preferences (Ramamurthy & Jain, 2017). In the context of integrating renewable energy sources, IoT plays a crucial role by allowing more efficient management of renewable systems (Kelly et al., 2013). For example, data from sensors on sunlight levels can automatically regulate the operation of photovoltaic systems, while information about energy demand in different parts of the building allows for the optimization of heating, ventilation, and lighting systems. IoT also enables remote control of these systems, which not only enhances user comfort but also leads to significant energy savings (Di Francia, 2017).
- Energy Management Systems (EMS) are advanced digital platforms that enable the monitoring, controlling, and optimizing of energy consumption in buildings (Thirunavukkarasu et al., 2022). Utilizing real-time data collected from IoT sensors, EMS analyze the current operational conditions of systems and the building's energy demand. This allows for dynamic adjustment of energy use in response to changing external and internal conditions (Zia et al., 2018). Consequently, EMS effectively manage intermittent renewable energy sources, such as solar and wind energy, which are subject to significant variability due to weather conditions (Venayagamoorthy et al., 2016). Advanced algorithms within EMS can predict when and to what extent energy should be stored or consumed, contributing to the reduction of losses and increasing the efficiency of renewable energy utilization (Li et al., 2023).
- Building Information Modeling (BIM) is a digital modeling technology that enables the creation of precise, three-dimensional models of buildings at every stage of their lifecycle – from design, through construction, to operation and demolition (Sanhudo et al., 2018). BIM allows for precise planning of the integration of renewable energy sources in construction projects, optimizing both construction costs and subsequent building operations (Succar, 2009). Through detailed energy simulations, BIM can predict the building's energy consumption behavior, facilitating decisions on the placement of photovoltaic panels, and systems for heating or cooling based on renewable energy. This tool is a key element of sustainable design, reducing errors during the construction phase and lowering operational costs thereafter (Tobias & Vavaroutsos, 2009).

- Artificial Intelligence (AI) is a crucial component of modern energy management systems in buildings, supporting energy consumption analysis and prediction processes (Singh et al., 2021). AI enables the optimization of various building systems, such as HVAC and lighting systems, allowing for better adjustment of device operations to changing conditions and user needs. AI algorithms can analyze meteorological data and information about the availability of energy from renewable sources to predict when and in what quantities energy will be required. As a result, heating, cooling, and lighting systems can be managed more efficiently, minimizing energy consumption during periods of low demand and maximizing its use when available from renewable sources (Abualigah et al., 2022).
- 3D printing technology is gaining significance in the construction sector, offering new possibilities for sustainable design and building realization. 3D printing allows for the creation of optimized building structures that feature improved thermal insulation, greater strength, and easy integration with renewable energy systems, such as photovoltaic panels (Bos et al., 2016). Buildings constructed using 3D printing can be designed in a way that minimizes energy and construction material usage, thereby reducing the carbon footprint. Additionally, the precise control of the construction process enables better utilization of space and materials, lowering operational costs and enhancing the energy efficiency of buildings (Sanguinetti et al., 2019).
- Building Management Systems (BMS) are advanced building automation systems that integrate various elements of building infrastructure, such as HVAC systems, lighting, and security, into a unified management system. BMS enables centralized monitoring and control of all building systems, which enhances energy efficiency and improves user comfort (Mujumdar & Agarwal, 2024). BMS systems are essential in modern buildings that utilize renewable energy sources, as they allow for real-time monitoring of energy production and consumption and dynamic adjustment of system parameters based on the availability of renewable energy (Taboada et al., 2024).
- HVAC systems (Heating, Ventilation, Air Conditioning) play a crucial role in managing indoor climate, handling heating, ventilation, and air conditioning (Afsharpanah et al., 2022b). In the context of integrating renewable energy sources, modern HVAC systems can be powered by renewable sources such as solar energy or geothermal energy. By integrating with building management systems and IoT technologies, HVAC systems can be automatically adjusted to current energy needs and weather conditions, which enhances their efficiency and reduces energy consumption (Jouhara & Yang, 2018).

Green building and environmental certifications

The concept of green building is an approach to the design, construction, and operation of buildings that emphasizes minimizing the negative impact on the natural environment. It involves efficient management of resources such as energy, water, and materials, and promotes the reduction of emissions and waste generated during the construction and operation of buildings (Cabeza & Chàfer, 2020). A key aspect of this concept is the integration of renewable energy sources and innovative energy management technologies, which enables greater energy efficiency and sustainable use of buildings by their occupants and users. To promote and assess sustainable building practices, several certification systems have been developed over the years, serving as standards for evaluating buildings based on their environmental impact. The most well-known of these are LEED, BREEAM, and Passivhaus, each of which has unique criteria and requirements.

LEED is an international green building certification system developed by the U.S. Green Building Council (USGBC). It is one of the most recognized and widely used systems in the world, assessing buildings based on energy efficiency, water usage, indoor environmental quality, building materials, and innovation in design (Gurgun et al., 2016). The LEED system awards points for meeting various criteria, and buildings can receive different levels of certification – from the basic LEED certification to LEED Silver, LEED Gold, and the highest level, LEED Platinum. In the context of renewable energy sources, LEED encourages the use of renewable energy technologies such as photovoltaic panels, heat pumps, and solar water heating systems to reduce conventional energy consumption. LEED-certified buildings must also meet high standards of energy efficiency, resulting in lower operational costs and reduced carbon emissions (Sabapathy et al., 2010).

BREEAM is a British environmental assessment system for buildings, and it is one of the oldest and most frequently used certification systems in the world. Developed by the Building Research Establishment (BRE), BREEAM evaluates buildings based on criteria such as energy and water consumption, pollution emissions, indoor environmental quality, innovation, and impact on local ecosystems (Rebelatto et al., 2024). The BREEAM system awards points in various categories, and buildings can receive certificates ranging from "Pass" to "Outstanding". Like LEED, BREEAM promotes the use of renewable energy sources and innovative technologies such as Energy Management Systems and the Internet of Things. An important aspect of BREEAM assessment is the building's energy efficiency and its ability to adapt to climate changes. Consequently, buildings certified under BREEAM are more sustainable and have a smaller carbon footprint. BREEAM also places significant emphasis on the health and comfort of occupants, which is achieved through improvements in indoor air quality and optimal use of natural light (Cordero et al., 2019).

The Passivhaus standard, developed in Germany, is one of the most demanding building design systems focused on energy efficiency. It emphasizes minimizing energy consumption for heating and cooling by employing high-quality insulation, windows with low thermal transmittance, and heat recovery ventilation systems. Buildings designed to the Passivhaus standard are characterized by extremely low energy consumption, often not exceeding 15 kWh/m^2 per year for heating purposes, achievable through precise design and integration with renewable energy sources such as heat pumps and photovoltaic systems (Moreno-Rangel, 2021). Passivhaus also focuses on minimizing heat loss by eliminating thermal bridges and utilizing natural heat gains from solar radiation. As a result, these buildings are not only energy-efficient but also provide high user comfort, contributing to improved quality of life for residents.

The Passivhaus standard is recognized as one of the most effective methods for reducing energy consumption in residential and commercial buildings, and its popularity is growing in the context of global efforts to reduce greenhouse gas emissions (Rangel et al., 2020).

Real-world implementation of technological innovations

Contemporary construction, in the era of technological advancement and increasing environmental protection requirements, increasingly utilizes advanced technological innovations and renewable energy sources. These innovations introduce new standards for the design, management, and operation of buildings, moving towards sustainable development. This section will present specific examples of technological applications in construction that effectively combine modern technical solutions with renewable energy sources. These examples include both actual buildings and pilot projects that illustrate the practical possibilities of technology integration.

Zero-energy buildings

Zero-energy buildings (ZEB) are structures that produce at least as much energy as they consume, and in some cases, can even generate surplus energy (Settino et al., 2020). A key component in such buildings is the integration of photovoltaic systems, which enable the generation of electrical energy from solar radiation (André et al., 2022). These systems often work in conjunction with heat recovery technologies from ventilation and heating systems (heat exchangers), which help minimize energy losses. Additionally, smart energy management systems monitor real-time energy consumption and production, automatically adjusting the operation of devices and optimizing energy use (Charron, 2008).

An example of a technologically advanced building integrated with renewable energy sources is The Edge in Amsterdam, which is considered one of the most energy-efficient office buildings in the world (Evola et al., 2014). This building has been designed to maximize energy efficiency and minimize environmental impact. It utilizes photovoltaic panels that provide electricity, meeting a significant portion of the building's power needs. The LED lighting systems employed are controlled by intelligent sensors that analyze the presence of people in rooms and the level of natural light, automatically adjusting the lighting intensity (Torcellini et al., 2006). This optimization of electrical lighting consumption significantly reduces operational costs.

The extensive system BMS at The Edge monitors all aspects of the building's operation, from temperature and ventilation to energy and water usage, allowing for dynamic adjustments of individual systems (Minelli et al., 2024). The building also features heat recovery technologies, which contribute to efficient thermal management. Together, these solutions not only minimize energy consumption but also significantly enhance user comfort through intelligent resource management (Carpino et al., 2023).

Another example is the Bullitt Center in Seattle, regarded as one of the most environmentally friendly commercial buildings in the world. The Bullitt Center was designed with the goal of minimizing its carbon footprint and aiming to be energy-

-positive, meaning it generates more energy than it consumes (European Parliament, 2018). The building features an extensive array of photovoltaic panels that meet the building's entire electrical energy needs. The rooftop panels not only power all the building's systems but also allow for the storage of excess energy.

It is also worth noting that the Bullitt Center utilizes advanced water systems, including rainwater collection and filtration systems, as well as on-site sewage treatment. This allows the building to function in full harmony with the natural water cycle, without relying on municipal water resources. These measures, combined with energy-efficient heating and cooling systems, enable the Bullitt Center to achieve a positive energy balance, positioning it among the most sustainable buildings in the world (Erba et al., 2019).

Both The Edge and the Bullitt Center are exemplary models of integrating modern technologies with renewable energy sources, demonstrating how innovative solutions can not only reduce energy consumption but also enhance the efficiency and comfort of building occupants.

Smart cities

The concept of smart cities involves the broad integration of advanced technologies, including renewable energy sources, to enhance energy efficiency, resource management, and the quality of life for residents (Batty et al., 2012). In such cities, smart energy management systems play a crucial role by enabling dynamic monitoring and optimization of energy use on a city-wide scale (Sabory et al., 2021). IoT technology facilitates the connection and management of various urban infrastructure systems, such as street lighting, public transportation, and even waste management (Al-Badi & Al-Saadi, 2020).

Masdar City in the United Arab Emirates is one of the most ambitious and innovative smart city projects in the world, designed with the goal of achieving full carbon neutrality. The city was created as an experimental hub that combines modern technologies with the idea of sustainable development (Janajreh et al., 2013). A key feature of Masdar City is its extensive photovoltaic farms, which provide electricity to the entire urban infrastructure. These farms, in conjunction with other renewable energy sources such as wind turbines and heat recovery technologies, enable efficient energy resource management, eliminating the need for fossil fuels.

One of the most innovative solutions in Masdar City is its advanced energy management system, which monitors energy consumption in real-time, analyzing data and adjusting the operation of devices, lighting, and ventilation systems based on user needs. The use of smart sensors and IoT systems enables automatic management of the city's infrastructure, leading to a significant reduction in energy consumption. The city also features integrated electric transport systems, including autonomous vehicles, which further reduce greenhouse gas emissions. Masdar City is also an example of sustainable urban design. Buildings are designed to maximize the use of natural light and wind, reducing the need for artificial lighting and air conditioning. Additionally, the city's infrastructure is adapted to desert conditions, which minimizes water consumption and ensures efficient use of natural resources (Griffiths & Sovacool, 2020).

Similar initiatives are developing in Europe, where cities like Copenhagen and Barcelona are pioneers in implementing smart technological solutions that support sustainable development (Ferrara, 2015). Copenhagen, with its plan to achieve carbon neutrality by 2025, has introduced smart energy consumption monitoring systems, as well as integrated district heating networks powered by renewable energy sources. The city is also a leader in the use of electric public transport and bicycles as primary means of transportation. Meanwhile, Barcelona is implementing smart street lighting systems equipped with motion sensors and monitoring air quality and temperature, adjusting lighting based on environmental conditions, which significantly reduces energy consumption.

These smart city projects demonstrate how innovative technologies can support the development of sustainable urban spaces, minimizing environmental impact and enhancing the quality of life for residents.

Photovoltaic and wind farms in the industrial sector

Solar and wind farms are key elements in the global energy transition, providing clean energy on a large scale. Through the integration of advanced monitoring, management, and optimization technologies, it is possible to enhance the operational efficiency of these installations. Modern wind and solar farms utilize IoT systems for real-time monitoring of wind turbines and solar panels, allowing for predictive maintenance, reduction in operational costs, and maximization of energy performance (López et al., 2020).

A prime example of effective integration of innovative technologies with renewable energy sources is the Hornsea One project in the United Kingdom. Currently the largest offshore wind farm in the world, it is located in the North Sea and consists of hundreds of wind turbines that together supply electricity to millions of households in the UK (Yaouba et al., 2022). Advanced real-time data analysis algorithms play a crucial role in the operational efficiency of this farm. This technology monitors the performance of each turbine, analyzing weather conditions, wind speed, and other parameters, allowing for optimization of turbine operation, reduction of mechanical wear, and minimization of downtime due to failures or maintenance. In this way, Hornsea One achieves high energy efficiency while providing stable and reliable energy supply to the grid (Dröes & Koster, 2021).

Equally impressive are the massive photovoltaic installations in China, such as the solar farms in Qinghai Province. Located on vast desert areas, these installations not only generate billions of kilowatt-hours of energy annually but also integrate advanced weather monitoring and energy management systems. Sophisticated monitoring technologies enable the prediction of changes in sunlight and other atmospheric conditions, allowing for dynamic adjustments in farm operations and minimizing energy losses. Additionally, these farms are equipped with advanced energy storage systems that allow for the storage of excess solar energy during periods of high sunlight, which can then be used during peak demand, even at night or on cloudy days. Such technologies ensure stable energy supplies and minimize the impact of variable weather conditions on farm efficiency (Vinod et al., 2018).

Projects like Hornsea One and the photovoltaic farms in China are excellent examples of how modern technologies, combined with renewable energy sources, can contribute to creating a more sustainable and efficient global energy sector.

Modular construction

Modular construction, based on prefabricated modules, is gaining increasing popularity as an efficient and sustainable solution in the construction industry. Thanks to the use of prefabrication technology, it is possible to quickly erect buildings while minimizing construction waste and energy consumption. Prefabricated modules are often designed to integrate renewable energy sources and energy-saving systems, such as photovoltaic panels, heat recovery ventilation systems, and advanced thermal insulation systems (Romero Quidel et al., 2023).

One of the pioneers in modular construction is the company Katerra, which utilizes advanced energy-efficient technologies and renewable energy sources in its projects. Katerra creates prefabricated passive houses that feature exceptionally low energy requirements due to the use of innovative insulation materials and advanced energy management systems. These buildings are designed to minimize heat loss, resulting in significantly lower energy consumption for heating and cooling (Agha et al., 2021).

In Europe, companies like Scandic Modular are developing similar projects, combining modern technologies with innovations in building materials. Their passive houses are designed to minimize environmental impact while providing high living comfort for residents. By integrating renewable energy sources and efficient energy management systems, these projects support sustainable development and represent the future of modern energy-efficient construction (Zukowski, 2022).

The examples presented above demonstrate that integrating innovative technologies in construction not only transforms the industry but also contributes to more efficient energy management, reduced operational costs, and decreased CO_2 emissions.

Integration of technological innovations

The integration of technological innovations in the construction sector is a crucial step towards achieving sustainability and energy efficiency. This process goes beyond simply implementing modern technologies, encompassing their harmonious integration with existing building and management systems. In practice, effective integration of technological innovations requires a complex approach that considers various aspects of a building's operation as well as its impact on the environment and its users. To address this, based on literature analysis and existing solutions in sustainable construction and technological innovations, the authors have proposed an original model for integrating technological innovations with renewable energy sources in the construction industry, which is illustrated in Figure 14.1. This model reflects a comprehensive process for implementing modern technologies in the construction sector, including the use of renewable energy sources, energy management, and optimization of building operations to enhance their energy efficiency.

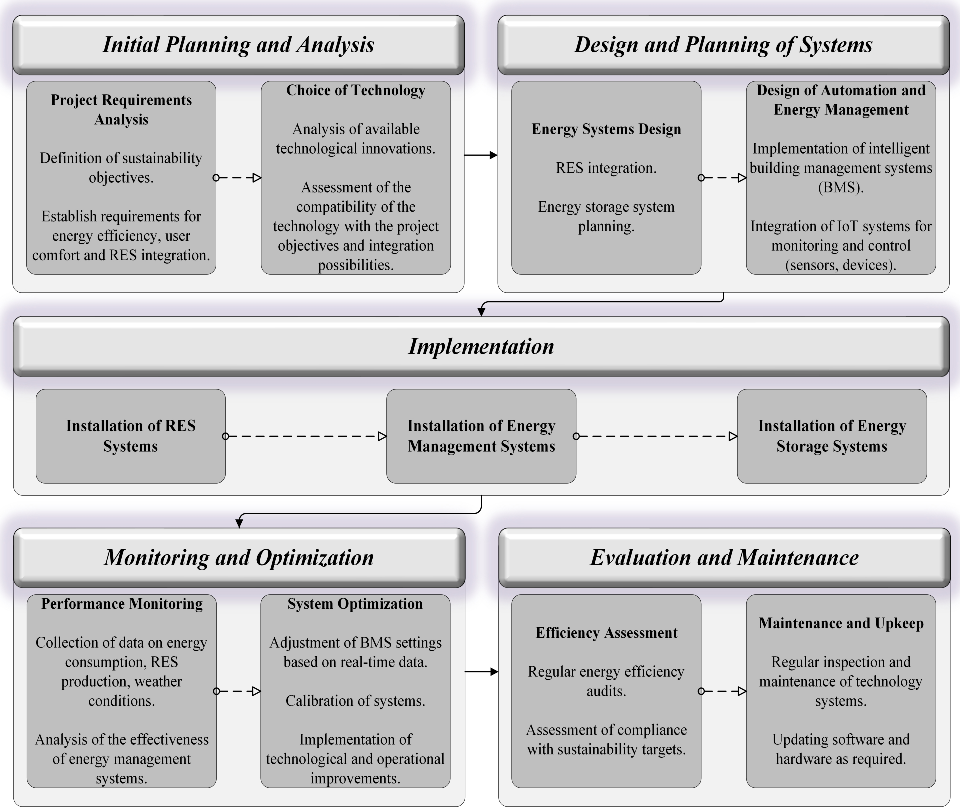


Figure 14.1. Model of integrating technological innovations with renewable energy sources in the construction industry

Source: Own study.

The model consists of five key phases aimed at ensuring effective integration of innovations and renewable energy sources throughout the building's lifecycle: initial planning and analysis, design and planning of system, implementation, monitoring and optimization, and evaluation and maintenance. Each phase addresses different aspects of the construction process, from strategic planning and system implementation to long-term operation and maintenance.

Initial planning and analysis

This phase begins with a detailed analysis of project requirements, where goals related to sustainability are defined, and criteria for energy efficiency, user comfort, and integration of renewable energy sources are established. Key to this phase is making an informed choice of technologies, based on an analysis of available technological innovations such as intelligent BMS systems, IoT, and energy storage systems. An evaluation of the alignment of these technologies with project goals and their integration capabilities is also conducted.

Design and planning of systems

In this phase, the actual design of energy systems begins, including the integration of renewable energy sources such as photovoltaic panels, wind turbines, or solar collectors, as well as planning for energy storage systems, e.g., batteries or fuel cells. The design of automation and energy management involves implementing intelligent building management systems that enable monitoring and optimization of energy consumption, as well as integrating IoT systems for monitoring and controlling building systems.

Implementation

The third phase of the model involves the physical installation of renewable energy systems, such as photovoltaic panels, wind turbines, and energy storage systems, which are directly integrated with the building infrastructure. An important aspect of this phase is also the installation of energy management systems, such as intelligent systems BMS, and IoT technologies, which enable real-time control and optimization of energy consumption. The implemented technologies are then configured to ensure their maximum efficiency and compatibility with the rest of the building infrastructure.

Monitoring and optimization

After the implementation phase, the performance monitoring phase begins. Data on energy consumption, renewable energy production, and weather conditions are collected and analyzed to assess the effectiveness of the energy management systems. System optimization is based on this data, allowing for real-time adjustments, such as modifying BMS settings or calibrating energy storage systems.

Evaluation and maintenance

The final phase of the model is the evaluation of the installed systems' effectiveness, which includes regular energy audits and assessment of compliance with the established sustainability goals. Key aspects of this phase also involve maintenance and upkeep of the technological systems, including regular technical inspections and updates to software and hardware as needed. Such maintenance ensures the long-term high efficiency of the building's technology and energy performance.

The proposed model for integrating technological innovations with renewable energy sources in the construction industry serves as a comprehensive tool for effective implementation and management of modern technologies within the sector. It addresses not only technical aspects but also environmental and economic factors, making it a foundation for future innovations and sustainable development in the construction industry.

Discussion

The integration of technological innovations in construction is a key element in achieving sustainable development and improving energy efficiency within the sector. Examples such as zero-energy buildings, smart cities, and modular construction demonstrate that applying modern technologies and renewable energy sources is not only feasible but also profitable and beneficial for both the environment and users. The introduction of photovoltaic panels, intelligent energy management systems, and solutions like BMS systems or IoT enables the maximization of energy efficiency and the minimization of environmental impacts.

However, a major challenge remains the degree of integration of these innovations at a global scale. While pilot projects and examples of leading buildings or cities show the feasibility of such innovations, widespread adoption requires further investment, the development of legal frameworks, and increased education and awareness among developers and investors. Furthermore, the scalability and localization of these solutions will require careful consideration of legal, financial, and educational barriers. Addressing these barriers will be essential for promoting broader adoption and ensuring the long-term success of such systems.

Additionally, continuous evaluation of the effectiveness of these technologies, as well as their adaptation to local climatic and social conditions, will be crucial for their successful implementation. The proposed model for integrating technological innovations with renewable energy sources provides a foundation for this transformation, though further research is needed to refine and adapt the model to different regional contexts and challenges. Further investigation is also needed to explore the scalability of proven solutions, ensuring that they can be applied to diverse geographic, economic, and regulatory environments.

In summary, the integration of technological innovations with renewable energy sources is essential for transforming the construction sector toward a more sustainable, energy-efficient, and environmentally friendly approach. Continued research and the expansion of proven solutions will be critical for achieving these goals on a global scale.

Conclusion

In this chapter, a broad spectrum of issues related to the integration of innovative technologies and renewable energy sources in the construction industry has been analyzed, presenting a multi-faceted approach to the topic. The initial discussions focused on introducing the concept of sustainable development and energy efficiency, emphasizing that the development of green building practices and environmental certifications form the foundation of modern design and management strategies for buildings.

Subsequent chapters focused on modern technologies in the construction industry, such as intelligent energy management systems, the Internet of Things, and advanced monitoring and optimization tools. The focus was on how these solutions can support both the operational efficiency of buildings and their sustainability. The benefits of integrating these technologies were analyzed, emphasizing the need for proper planning, design, and implementation to maximize benefits and minimize risks.

The examples presented in the chapter, such as The Edge in Amsterdam, Bullitt Center in Seattle, and Hornsea One, illustrate how innovative technologies can be effectively integrated into buildings and infrastructure. Additionally, the discussion of smart cities, such as Masdar City, demonstrates the potential for larger-scale implementation of sustainable technologies that can transform the functioning of entire cities.

The proposed model for integrating technological innovations with renewable energy sources in the construction industry presents a comprehensive approach to implementing modern technologies in this sector. This model consists of several key stages, starting with the initial planning and analysis phase, followed by system design and planning, implementation, and monitoring and optimization, and ending with regular evaluation and maintenance of technological systems. Such a structure enables the harmonious integration of innovative solutions with existing building systems, supporting not only energy efficiency but also the long-term sustainable operation of buildings.

In summary, this article highlights the crucial role of integrating technological innovations and renewable energy sources in the future of construction. Modern buildings and cities must not only meet the increasing demands for energy efficiency but also address the challenges associated with climate change. The proposed model, based on real project examples and an analytical approach, indicates the significant potential of modern technologies in shaping a sustainable future. Integrating technology and renewable energy sources is not just a technical requirement but also a necessity for buildings and cities to meet the challenges of the present and future, while simultaneously ensuring comfort, efficiency, and ecological responsibility.

References

Abualigah, L., Zitar, R.A., Almotairi, K.H., Hussein, A.M., Abd Elaziz, M., Nikoo, M.R., & Gandomi, A.H. (2022). Wind, solar, and photovoltaic renewable energy systems with and without energy storage optimization: A survey of advanced machine learning and deep learning techniques. *Energies*. DOI: 10.3390/en15020578.

Afsharpanah, F., Mousavi Ajarostaghi, S.S., & Arıcı, M. (2022a). Parametric study of phase change time reduction in a shell-and-tube ice storage system with anchor-type fin design. *Int. Commun. Heat Mass Tran.* DOI: 10.1016/j.icheatmasstransfer.2022.106281.

Afsharpanah, F., Pakzad, K., Mousavi Ajarostaghi, S.S., & Arıcı, M. (2022b). Assessment of the charging performance in a cold thermal energy storage container with two rows of serpentine tubes and extended surfaces. *J. Energy Storage*. DOI: 10.1016/j.est.2022.104464.

Agha, A., Shibani, A., Hassan, D., & Zalans, B. (2021). Modular construction in the United Kingdom housing sector: Barriers and Implications. *Journal of Architectural Engineering Technology*. DOI: 10.4172/2168-9717.1000236.

Ahmed, T., Ge, J., Peng, W.C., Yan, B.T., & Tee, S. (2022). Assessment of the renewable energy generation towards net-zero energy buildings: a review. *Energy Build*. DOI: 10.1016/j.enbuild.2021.111755.

Al-Badi, A.H., & Al-Saadi, S.N. (2020). Toward energy-efficient buildings in Oman. *Int. J. Sustain. Energy*. DOI: 10.1080/14786451.2019.1685521.

Aldhshan, S.R.S., Maulud, K.N.A., Jaafar, W.S.W.M., Karim, O.A., & Pradhan B. (2021). Energy consumption and spatial assessment of renewable energy penetration and building energy efficiency in Malaysia: a review. *Sustainability*. DOI: 10.3390/su13169244.

André, M., Kamimura, A., Bavaresco, M., Giaretta, R.F., Fossati, M., & Lamberts, R. (2022). Achieving mid-rise NZEB offices in Brazilian urban centres: a control strategy with desk fans and extension of set point temperature. *Energy Build*. DOI: 10.1016/j.enbuild.2022.111911.

Arnfield, A.J. (2003). Two decades of urban climate research: A review of turbulence. exchanges of energy and water, and the urban heat island. *Int. J. Climatol*. DOI: 10.1002/joc.859.
Austin, M.C., Solano, T., Tejedor-Flores, N., Quintero, V., Boya, C., & Mora, D. (2022). *Bio-inspired Approaches for Sustainable Cities Design in Tropical Climate.* In Bionics and Sustainable Design. DOI: 10.1007/978-981-19-1812-4_11.
Bae, S., & Nam, Y. (2022). Economic and environmental analysis of ground source heat pump system according to operation methods. *Geothermics*. DOI: 10.1016/j.geothermics. 2022.102373.
Barakat, S., Ibrahim, H., & Elbaset, A.A. (2020). Multi-objective optimization of grid-connected PV-wind hybrid system considering reliability, cost, and environmental aspects. *Sustain. Cities Soc.* DOI: 10.1016/j.scs.2020.102178.
Batty, M., Axhausen, K.W., Giannotti, F., Pozdnoukhov, A., Bazzani, A., Wachowicz, M., Ouzounis, G., & Portugali, Y. (2012). Smart cities of the future. *Eur. Phys. J.* DOI: 10.1140/epjst/e2012-01703-3.
Behzadi, A., Thorin, E., Duwig, C., & Sadrizadeh, S. (2023). Supply-demand side management of a building energy system driven by solar and biomass in Stockholm: A Smart integration with minimal cost and emission. *Energy Convers. Manag*. DOI: 10.1016/j.enconman.2023.117420.
Belussi, L., Barozzi, B., Bellazzi, A., Danza, L., Devitofrancesco, A., Fanciulli, C., Ghellere, M., Guazzi, G., Meroni, I., Salamone, F., Scamoni, F., & Scrosati, C. (2019). A review of performance of zero energy buildings and energy efficiency solutions. *J. Build. Eng*. DOI: 10.1016/j.jobe.2019.100772.
Bhattacharya, S., Goswami, A., & Sadhu, P.K. (2023). Design, development and performance analysis of FSPV system for powering sustainable energy based mini micro-grid. *Microsyst. Technol*. DOI: 10.1007/s00542-023-05457-2.
Bos, F., Wolfs, R., Ahmed, Z., & Salet, T. (2016). Additive manufacturing of concrete in construction: Potentials and challenges of 3D concrete printing. *Virtual and Physical Prototyping*. DOI: 10.1080/17452759.2016.1209867.
Cabeza, L.F., & Chàfer, M. (2020). Technological options and strategies towards zero energy buildings contributing to climate change mitigation: a systematic review. *Energy Build.* DOI: 10.1016/j.enbuild.2020.110009.
Carpino, C., Loukou, E., Austin, M.C., Andersen, B., Mora, D., & Arcuri, N. (2023). Risk of fungal growth in nearly zero-energy buildings (nZEB). *Buildings*. DOI: 10.3390/buildings13071600.
Charani Shandiz, S., Rismanchi, B., & Foliente, G. (2021). Energy master planning for net-zero emission communities: state of the art and research challenges. *Renew. Sustain. Energy*. DOI: 10.1016/j.rser.2020.110600.
Charron, R. (2008). A review of design processes for low energy solar homes. *Open House Int*. DOI: 10.1108/OHI-03-2008-B0002.
Davi, G.A., Caamano-Martín, E., Rüther, R., & Solano, J. (2016). Energy performance evaluation of a net plus-energy residential building with grid-connected photovoltaic system in Brazil. *Energy Build*. DOI: 10.1016/j.enbuild.2016.03.058.
Davino, G., Longobardi, E., Meglio, A., & Dallari, A. (2022). Formisano, Seismic energy upgrading of an existing brick masonry building by a cold-formed steel envelope system. *Buildings*. DOI: 10.3390/buildings12111918.
De León, L., Austin, M.C., Carpino, C., & Mora, D. (2021). Towards zero energy districts developments base on bioclimatic strategies: a numerical study in a developing country. *E3S Web of Conferences*. DOI: 10.1051/e3sconf/202131202017.
Di Francia, G. (2017). The development of sensor applications in the sectors of energy and environment in Italy. 1976-2015. *Sensors*. DOI: 10.3390/s17040793.
Diab, F., Lan, H., Zhang, L., & Ali, S. (2015). An environmentally-friendly tourist village in Egypt based on a hybrid renewable energy system – Part Two: a net zero energy tourist village. *Energies*. DOI: 10.3390/en8076945.

Dröes, M.I., & Koster, H.R.A. (2021). Wind turbines, solar farms, and house prices. *Energy Policy*. DOI: 10.1016/j.enpol.2021.112327.
Erba, S., Pagliano, L., Shandiz, S.C., & Pietrobon, M. (2019). Energy consumption, thermal comfort and load match: study of a monitored nearly Zero Energy Building in Mediterranean climate. *IOP Conf. Ser. Mater. Sci. Eng*. DOI: 10.1088/1757-899X/609/6/062026.
European Parliament (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources. *Official Journal of the European Union*. PE/48/2018/REV/1.
Evola, G., Margani, G., & Marletta, L. (2014). Cost-effective design solutions for low-rise residential Net ZEBs in Mediterranean climate. *Energy Build*. DOI: 10.1016/j.enbuild.2013.09.026.
Ferrara, R. (2015). The smart city and the green economy in Europe: A critical approach. *Energies*. DOI: 10.3390/en8064724.
Gaur, A.S., Fitiwi, D.Z., & Curtis, J. (2021). Heat pumps and our low-carbon future: A comprehensive review. *Energy Res. Soc. Sci*. DOI: 10.1016/j.erss.2020.101764.
Griffiths, S., & Sovacool, B.K. (2020). Rethinking the future low-carbon city: Carbon neutrality, green design, and sustainability tensions in the making of Masdar City. *Energy Research & Social Science*. DOI: 10.1016/j.erss.2019.101368.
Gurgun, A.P., Polat, G., Damci, A., & Bayhan, H.G. (2016). Performance of LEED Energy Credit Requirements in European Countries. *Procedia Engineering*. DOI: 10.1016/j.proeng.2016.11.641.
Hawila, A.A.W., Pernetti, R., Pozza, C., & Belleri, A. (2022). Plus energy building: operational definition and assessment. *Energy Build*. DOI: 10.1016/j.enbuild.2022.112069.
He, Y., Chu, Y., Song, Y., Liu, M., Shi, S., & Chen, X. (2022). Analysis of design strategy of energy efficient buildings based on databases by using data mining and statistical metrics approach. *Energy Build*. DOI: 10.1016/j.enbuild.2021.111811.
Hernández-Callejo, L., Gallardo-Saavedra, S., & Alonso-Gómez, V. (2019). A review of photovoltaic systems: Design, operation and maintenance. *Solar Energy*. DOI: 10.1016/j.solener.2019.06.017.
IEA. (2023). *Funding for Thin Film Technologies for Solar PV – Policies*. https://www.iea.org/policies/13275-fundingfor-thin-film-technologies-for-solar-pv.
Janajreh, I., Su, L., & Alan, F. (2013). Wind energy assessment: Masdar City case study. *Renewable Energy*. DOI: 10.1016/j.renene.2012.09.025.
Jensen, S.Ø., Marszal-Pomianowska, A., Lollini, R., Pasut, W., Knotzer, A., Engelmann, P., Stafford, A., & Reynders, G. (2017). IEA EBC Annex 67 Energy Flexible Buildings. *Energy Build*. DOI: 10.1016/j.enbuild.2017.08.044.
Jouhara, H., & Yang, J. (2018). Energy efficient HVAC systems. *Energy Build*. DOI: 10.1016/j.enbuild.2018.09.001.
Kaewunruen, S., Rungskunroch, P., & Welsh, J. (2018). A digital-twin evaluation of net zero energy building for existing buildings. *Sustainability*. DOI: 10.3390/su11010159.
Kapsalis, V., Maduta, C., Skandalos, N., Wang, W., Bhuvad, S.S., D'Agostino, D., Ma, T., Raj, U., Parker, D., Peng, J., & Karamanis, D. (2024). Critical assessment of large-scale rooftop photovoltaics deployment in the global urban environment. *Renew. Sustain. Energy*. DOI: 10.1016/j.rser.2023.114005.
Karlessi, T., Kampelis, N., Kolokotsa, D., Santamouris, M., Standardi, L., Isidori, D., & Cristalli, C. (2017). The concept of smart and NZEB buildings and the integrated design approach. *Procedia Eng*. DOI: 10.1016/j.proeng.2017.04.294.
Kelly, S.D.T., Suryadevara, N.K., & Mukhopadhyay, S.C. (2013). Towards the implementation of IoT for environmental condition monitoring in homes. *IEEE Sens. J.* DOI: 10.1109/JSEN.2013.2263379.
Kwok, K.C.S., & Hu, G. (2023). Wind energy system for buildings in an urban environment. *J. Wind Eng. Ind. Aerodyn*. DOI: 10.1016/j.jweia.2023.105349.
Laski, J., & Burrows, V. (2017). *From Thousands to Billions. Coordinated Action towards 100% Net Zero Carbon Buildings By 2050*. World Green Building Council.

Lee, M., Kim, J., Shin, H.H., Cho, W., & Kim, Y. (2022). CO_2 emissions and energy performance analysis of ground-source and solar – assisted ground-source heat pumps using low-GWP refrigerants. *Energy*. DOI: 10.1016/j.energy.2022.125198.

Levesque, R.C., Pietzcker, G., & Luderer, G. (2019). Halving energy demand from buildings: the impact of low consumption practices. *Technol. Forecast. Soc. Change*. DOI: 10.1016/j.techfore.2019.04.025.

Li, Y., Han, M., Shahidehpour, M., Li, J., & Long, C. (2023). Data-driven distributionally robust scheduling of community integrated energy systems with uncertain renewable generations considering integrated demand response. *Appl. Energy*. DOI: 10.1016/j.apenergy.2023.120749.

Lin, Y., Zhong, S., Yang, W., Hao, X., & Li, C.Q. (2020). Towards zero-energy buildings in China: a systematic literature review. *J. Clean. Prod*. DOI: 10.1016/j.jclepro.2020.123297.

López, M., Rodríguez, N., & Iglesias, G. (2020). Combined floating offshore wind and solar PV. *J. Mar. Sci. Eng.* DOI: 10.3390/jmse8080576.

Ma, Z., Awan, M.B., Lu, M., Li, S., Aziz, M.S., Zhou, X., Du, H., Sha, X., & Li, Y. (2023). An overview of emerging and sustainable technologies for increased energy efficiency and carbon emission mitigation in buildings. *Buildings*. DOI: 10.3390/buildings13102658.

Magrini, G., Lentini, S., Cuman, A., & Bodrato, L. (2020). From nearly zero energy buildings (NZEB) to positive energy buildings (PEB): the next challenge - the most recent European trends with some notes on the energy analysis of a forerunner PEB example. *Developments in the Built Environment*. DOI: 10.1016/j.dibe.2020.100019.

Minelli, F., Ciriello, I., Minichiello, F., & Agostino, D.D. (2024). From net zero energy buildings to an energy sharing model – the role of NZEBs in renewable energy communities. *Renew. Energy*. DOI: 10.1016/j.renene.2024.120110.

Moreno-Rangel, A. (2021). Passivhaus. *Encyclopedia*. DOI: 10.3390/encyclopedia1010005.

Mujumdar, P., & Agarwal, S. (2024). *Integrating Building Management Systems in High-Rise Structures using Building Information Modeling*. Proceedings of the International Conference of Contemporary Affairs in Architecture and Urbanism-ICCAUA. DOI: 10.38027/ICCAUA2024IN0320.

Osman, A.I., Chen, L., Yang, M., Msigwa, G., Farghali, M., Fawzy, S., Rooney, D.W., & Yap, P-S. (2023). Cost, environmental impact, and resilience of renewable energy under a changing climate: a review. *Environ. Chem. Lett*. DOI: 10.1007/s10311-022-01532-8.

Østergaard, P.A., Duic, N., Noorollahi, Y., & Kalogirou, S. (2021). Recent advances in renewable energy technology for the energy transition. *Renew. Energy*. DOI: 10.1016/j.renene.2021.07.111.

Østergaard, P.A., Duic, N., Noorollahi, Y., Mikulcic, H., & Kalogirou, S. (2020). Sustainable development using renewable energy technology. *Renew. Energy*. DOI: 10.1016/j.renene.2019.08.094.

Palmero-Marrero, A.I., Gomes, F., Sousa, J., & Oliveira, A.C. (2020). Energetic analysis of a thermal building using geothermal and solar energy sources. *Energy Rep*. DOI: 10.1016/j.egyr.2020.11.268.

Palraj, M., & Rajamanickam, P. (2020). Motion control of a barge for offshore wind turbine (OWT) using gyrostabilizer. *Ocean Eng*. DOI: 10.1016/j.oceaneng.2020.107500.

Panagopoulos, A. (2021). Water-energy nexus: desalination technologies and renewable energy sources. *Environ Sci Pollut Res*. DOI: 10.1007/s11356-021-13332-8.

Pejović, B., Karadźić, V., Dragaśević, Z., & Backović, T. (2021). Economic growth, energy consumption and CO_2 emissions in the countries of the European Union and the Western Balkans. *Energy Rep*. DOI: 10.1016/j.egyr.2021.05.011.

Rahman, H., Sharif, M.R., Ahmed, R., Nijam, T., & Shoeb, M.A. (2015). *Designing of biomass based power plant for residential building energy system*. In: 2015 International conference on Electrical Engineering and Information Communication Technology (ICEEICT). DOI: 10.1109/ICEEICT.2015.7307366.

Ramamurthy, A., & Jain, P. (2017). *The Internet of Things in the Power Sector: Opportunities in Asia and the Pacific*. Asian Development Bank: Mandaluyong. DOI: 10.22617/WPS178914-2.

Rangel, A.M., Sharpe, T., McGill, G., & Musau, F. (2020). Indoor air quality in passivhaus dwellings: A literature review. *Int. J. Environ. Res. Public Heal*. DOI: 10.3390/ijerph17134749.

Rebelatto, B.G., Salvia, A.L., Brandli, L.L., & Leal Filho, W. (2024). Examining Energy Efficiency Practices in Office Buildings through the Lens of LEED, BREEAM, and DGNB Certifications. *Sustainability*. DOI: 10.3390/su16114345.

Reddy, V.J., Hariram, N.P., Ghazali, M.F., & Kumarasamy, S. (2024). Pathway to sustainability: An overview of renewable energy integration in building systems. *Sustainability*. DOI: 10.3390/su16020638.

Romero Quidel, G., Soto Acuña, M.J., Rojas Herrera, C.J., Rodríguez Neira, K., & Cárdenas-Ramírez, J.P. (2023). Assessment of modular construction system made with low environmental impact construction materials for achieving sustainable housing projects. *Sustainability*. DOI: 10.3390/su15108386.

Sabapathy, A., Ragavan, S.K.V., Vijendra, M., & Nataraja, A.G. (2010). Energy efficiency benchmarks and the performance of LEED rated buildings for information technology facilities in Bangalore, India. *Energy and Buildings*. DOI: 10.1016/j.enbuild.2010.07.014.

Sabory, N.R., Senjyu, T., Danish, M.S.S., Hosham, A., Noorzada, A., Amiri, A.S., & Muhammdi, Z. (2021). Applicable smart city strategies to ensure energy efficiency and renewable energy integration in poor cities: Kabul case study. *Sustainability*. DOI: 10.3390/su132111984.

Sánchez Cordero, A., Gómez Melgar, S., & Andújar Márquez, J.M. (2019). Green building rating systems and the new framework level(s): A critical review of sustainability certification within Europe. *Energies*. DOI: 10.3390/en13010066.

Sanguinetti, P., Almazam, K., Humaidan, O., & Colistra, J. (2019). *Evaluating the potential of high performance concrete 3D-printing for zero energy homes*. Proceedings of the 16th IBPSA Conference. DOI: 10.26868/25222708.2019.211155.

Sanhudo, L., Ramos, N.M.M., Martins, J.P., Almeida, R.M.S.F., Barreira, E., Simões, M.L., & Cardoso, V. (2018). Building information modeling for energy retrofitting – A review. *Renewable and Sustainable Energy Reviews*. DOI: 10.1016/j.rser.2018.03.064.

Selvan, S.U., Saroglou, S.T., Mosca, F., Tyc, J., Joschinski, J., Calbi, M., Vogler, V., Weisser, W., Grobman, J.Y., & Barath, S. (2023) *Multi-species Building Envelopes: Developing a multi-criteria design decision-making methodology for cohabitation.* In Proceedings of the Human-Centric, Proceedings of the 28th International Conference of the Association for Computer-Aided Architectural Design Research in Asia. DOI: 10.52842/conf.caadria.2023.2.643.

Settino, J., Carpino, C., Perrella, S., & Arcuri, N. (2020). Multi-objective analysis of a fixed solar shading system in different climatic areas. *Energies*. DOI: 10.3390/en13123249.

Shah, A.R., Krarti, M., & Huang, J. (2022). Energy performance evaluation of shallow ground source heat pumps for residential buildings. *Energies*. DOI: 10.3390/en150 31025.

Shi, S., Sun, J., Liu, M., Chen, X., Gao, W., & Song, Y. (2022). Energy-saving potential comparison of different photovoltaic integrated shading devices (PVSDs) for single-story and multi-story buildings. *Energies*. DOI: 10.3390/en15239196.

Singh, O., Yadav, M., Yadav, P., & Rishiwal, V. (2021). *3 AI-based renewable energy with emerging applications.* Introduction to AI Techniques for Renewable Energy System. DOI: 10.1201/9781003104445-3.

Sinha, S., & Chandel, S.S. (2016). Analysis of fixed tilt and sun tracking photovoltaic-micro wind based hybrid power systems. *Energy Convers. Manag*. DOI: 10.1016/j.enconman.2016.02.056.

Su, W., & Wang, J. (2012). Energy management systems in microgrid operations. *Electr. J*. DOI: 10.1016/j.tej.2012.09.010.

Succar, B. (2009). Building information modelling framework: a research and delivery foundation for industry stakeholders. *Autom Constr*. DOI: 10.1016/j.autcon.2008.10.003.

Sun, B., Gao, K., Liu, S., Wei, Q., & Wang, H. (2023). Assessing the performance and economic viability of solar home systems: a way forward towards clean energy exploration and consumption. *Renew. Energy*. DOI: 10.1016/j.renene.2023.03.009.

Taboada, A., Yetongnon, K., & Nicolle, C. (2024). Smart buildings: A comprehensive systematic literature review on data-driven building management systems. *Sensors*. DOI: 10.3390/s24134405.

Thirunavukkarasu, G.S., Seyedmahmoudian, M., Jamei, E., Horan, B., Mekhilef, S., & Stojcevski, A. (2022). Role of optimization techniques in microgrid energy management systems – A review. *Energy Strategy Rev*. DOI: 10.1016/j.esr.2022.100899.

Tobias, L., & Vavaroutsos, G. (2009). *Retrofitting office buildings to be green and energy-efficient: optimizing building performance, tenant satisfaction, and financial return*. Washington, DC: Urban Land Institute.

Torcellini, P., Pless, S., & Deru, M. (2006). *National renewable energy laboratory*. Pacific Grove, California presented at ACEEE Summer Study.

Ullah, K.R., Prodanovic, V., Pignatta, G., Deletic, A., & Santamouris, M. (2021). Technological advancements towards the net-zero energy communities: a review on 23 case studies around the globe. *Sol. Energy*. DOI: 10.1016/j.solener.2021.06.056.

Venayagamoorthy, G.K., Sharma, R.K., Gautam, P.K., & Ahmadi, A. (2016). *Dynamic energy management system for a smart microgrid.* IEEE Trans. Neural Netw. Learn. Syst. DOI: 10.1109/TNNLS.2016.2514358.

Vinod, K.R., & Singh, S.K. (2018). Solar photovoltaic modeling and simulation: As a renewable energy solution. *Energy Reports*. DOI: 10.1016/j.egyr.2018.09.008.

Wang, B.H., Klemes, J.J., Malasek, J., Hemza,l M., Liang, Y.T., & Zeng, M. (2021). A novel turbine ventilator with a damper regulator to adjust exhausted air for energy-saving in buildings. *J. Build Eng*. DOI: 10.1016/j.jobe.2020.102141.

Wu, W., & Skye, H.M. (2021). Residential net-zero energy buildings: review and perspective. *Renew. Sustain. Energy Rev*. DOI: 10.1016/j.rser.2021.110859.

Yang, C.W., Kwon, H., Bang, B., Jeong, S., & Lee, U.D. (2022). *Role of biomass as low-carbon energy source in the era of net zero emissions*. Fuel. DOI: 10.1016/j.fuel.2022.125206.

Yaouba, Bajaj, M., Welba, C., Bernard, K., Kitmo, Kamel, S., & El-Naggar, M.F. (2022). An experimental and case study on the evaluation of the partial shading impact on PV module performance operating under the sudano-sahelian climate of cameroon. *Front. Energy Res*. DOI: 10.3389/fenrg.2022.924285.

Zhang, Z., Liu, X., Zhao, D., Post, S., & Chen, J. (2023). Overview of the development and application of wind energy in New Zealand. *Energy Built Environ*. DOI: 10.1016/j.enbenv.2022.06.009.

Zhu, Y., Li, W., Li, J., Li, H., Wang, Y., & Li, S. (2020). Thermodynamic analysis and economic assessment of biomass-fired organic rankine cycle combined heat and power system integrated with CO_2 Capture. *Energy Convers. Manag*. DOI: 10.1016/j.enconman.2019.112310.

Zia, M.F., Elbouchikhi, E., & Benbouzid, M. (2018). Microgrids energy management systems: A critical review on methods, solutions, and prospects. *Appl. Energy*. DOI: 10.1016/j.apenergy.2018.04.103.

Zukowski, M. (2022). A small modular house as a response to the energy crisis. *Energies*. DOI: 10.3390/en15218058.