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ORIGINAL PAPER

LAST DECADE OF GREEN LOGISTICS WITH MULTIPLE MODES OF TRANSPORTATION: A LITERATURE REVIEW

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ABSTRACT. Background: Transportation systems with multiple modes are effective, economical, and also offer environmental benefits. This paper summarizes the contributions of multimodal and intermodal transportation systems to the progress in green logistics from 2012 to 2022. A literature survey was conducted to determine the characteristic problems in developing sustainable logistics as well as the techniques and approaches to solve them. The study identified research gaps, and the outcomes will provide a reference for researchers in future work. Published work regarding environmental issues, mode combinations, problem formulations, and solution approaches were evaluated. Research gaps were also identified, and the main requirements for future research were proposed. It was shown that intermodal and multimodal transportation problems in the field of green logistics have received substantial attention in existing literature. However, this is the first literature review of the topic that has considered the body of literature published in the last decade.

Methods: The researchers conducted a literature survey to gather relevant information on the topic, based on searching and reviewing academic papers, research articles, conference proceedings, and other publications related to multimodal and intermodal transportation systems and their impact on green logistics from 2012 to 2022. The phases of research method followed data collection, data evaluation, identification of research gaps, proposal of main requirements, and offering valuable insights for future research endeavors.

Results: The result of this study highlights the key findings, such as increasing focus on environmental consideration in multiple mode of transportation, lack of studies on uncertainty, utilizing sophisticated solution techniques, the need for different mode combinations, and integrating technological developments to the transportation systems.

Conclusions: This study shows that while there is a rich body of literature on multimodal and intermodal transportation systems, the focus has predominantly been on economic rather than environmental sustainability. Future research should prioritize environmentally sustainable multi/intermodal transportation systems, exploring multi-objective planning, integrating different vehicle types, and improving meta-heuristics to tackle real-world logistics challenges.

Keywords: Environmental impact of transportation, Multimodal transportation systems, Intermodal transportation systems, Green logistics, Comprehensive literature review

INTRODUCTION

Supply chain activities, logistics, and transportation phases all have a carbon footprint. The United States Environmental Protection Agency [EPA 2021] has reported that carbon dioxide (CO_2) emissions mainly originate from transportation, industrial, commercial, and residential sources. Awareness of environmental activities in the supply chain requires effective transportation planning within the network, and a low carbon footprint should be ensured for all operations. There is currently competition among companies over the development of sustainable logistics strategies. Environmental issues, social responsibility, and customer intentions have placed pressure on companies to increase their green logistics activities. Each mode of transport causes different carbon emissions. The carbon emission unit used by the greenhouse gas (GHG) Protocol is 0.2, 0.05, and 0.0275 for road, sea, and rail transport, respectively [GHG Protocol 2020]. Vehicle weights, road slope, and vehicle and ship speeds are ignored in the calculations for 100 km. As shown in the graphs in Figure 1, the carbon

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emissions increase linearly as the weight of the transported load increases. The mode of transport that caused the most carbon emissions was road transport, while rail transport was the most environmentally sustainable mode of transport.

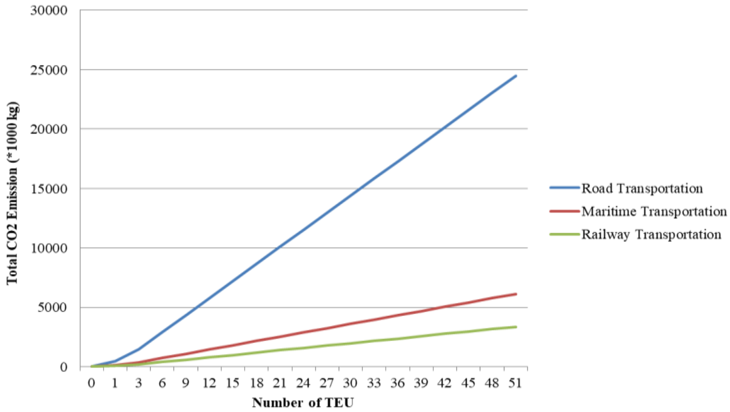

Fig. 1. CO_2 emissions of different modes of transport in freight transportation [Source: The authors].

Because of the growth in international trade and the increasing demand for international logistics, the use of more than one transportation mode has become essential for logistics service providers in intercontinental freight transportation. As shown in Figure 1, avoiding road transport in freight transportation understandably produces more sustainable solutions from the perspective of the environment, and mode combinations can generate environmentally sustainable services. According to [Sahin et al. 2014], combining road or railway transportation with a seaway is more economical over long distances than road-rail combinations. It is obvious that cost analyses considering sea-road, road-rail, sea-rail, and road-sea-rail combinations can vary based on the technical and operational parameters for different transportation systems. Researchers have discussed the modal shifts required for a greener logistics system and have listed case-by-case consequences [Eng-Larsson and Kohn 2012, Sahin et al. 2014, Islam et al. 2020, Basallo-Triana et al. 2021].

Although many literature surveys have been conducted regarding optimization problems or strategic planning for multimodal and intermodal transportation, hardly any literature surveys have investigated green concerns. This paper presents a comprehensive overview of the multimodal transportation systems in terms of environmental sustainability for the first time.

The aim of the study was to summarize the current green multimodal and intermodal transportation literature and to identify any research gaps in this field regarding published articles related to the problem from 2012 to 2022. The study approached the research from a green and sustainable logistics perspective. The following research questions were addressed to achieve the objective of this research:

1. What are the main issues that need to be examined regarding the environmental impacts of multiple modes of transportation systems?

2. How can we determine which of the mode combinations considered in existing studies of multiple modes of transportation systems has the minimal environmental impact?

3. How do researchers formulate models to study multiple modes of transportation system, and which approaches have been most widely applied to provide solutions?

4. What are the gaps in the literature that offer potential research opportunities?

The remainder of the paper is organized as follows. Section 2 describes the methodology used to conduct the study. Section 3 presents an overview of the literature. Section 4 reviews the available research to identify research gaps and future research directions, while Section 5 presents the study conclusions and summarizes the paper.

MATERIALS AND METHODS

Using the realist literature review method to identify and systematically evaluate the relevant literature, we provide a comprehensive review analysis of the available literature on green logistics with multiple modes of transportation of the last decade. Research materials are gathered by searching one or more databases and are qualitatively brought together in the review. The research was conducted in three phases. The first phase established a data collection protocol as shown in Figure 3. The second phase classified the studies that were identified, and the final phase identified gaps in the literature and recommended future research directions. First, a comprehensive search of papers was carried out with specific keywords in the ScienceDirect, Web of Science (WoS), and Scopus databases. More than ten thousand articles were found on those topics. This review focused on multiple modes of transportation systems to provide effective solutions in terms of green and environmentally sustainable freight logistics, as discussed in the introduction. Thus, the filtering criteria consisted of the following thematic keywords within the 'title': ("multimodal transportation" OR "intermodal transportation ") AND ("green multimodal transportation" OR "green intermodal transportation") AND ("sustainable multimodal transportation" OR "sustainable intermodal transportation"). The search was refined to the last decade to obtain current studies of green and sustainable multiple modes of transportation systems to obtain the latest findings from the current literature. Papers published before 2012 were therefore excluded. Many of the studies discarded were largely unrelated to the specific subject area and were limited in scope. For example, articles that focused on synchro-modal transportation and real-time fleet tracking were excluded, as were any non-peer reviewed papers. Another exclusion criterion was language, with the search protocol limited to English. Only papers categorized as (Research Area = Transportation and logistics) in academic journals were included. Our research predominantly included freight transportation rather than public transportation. Recent literature with case studies was emphasized to investigate practical examples, depending on their relevance in the research domain. Duplicated works were also excluded. As a result of this exclusion procedure, a total of 76 papers were analysed.

The aim of the filtering process was to identify research limitations and gaps in the literature in the context of green multimodal and intermodal transportation systems. For this purpose, the most relevant studies were briefly examined using a theoretical framework based on the most common characteristics, such as objectives, data collection, and solution methodologies applied to problems in the last decade.

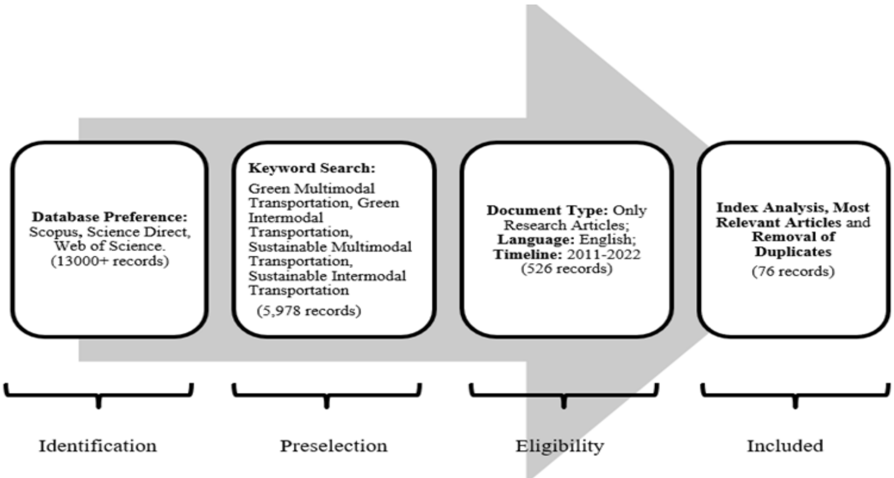

Fig. 2. Data collection protocol in this research.

RESULTS

To start our literature survey, we searched for existing literature surveys of multimodal transportation systems. We found five comprehensive literature surveys in which researchers investigated the existing literature on multimodal and intermodal transportation systems using freight planning, network design, and optimization techniques. Table 1 summarizes the scope of the previous literature and illustrates the differences with our research. [Lam and Gu 2013] addressed the future research directions for intermodal container flows in port hinterlands. [Elbert et al. 2020 and SteadieSeifi et al. 2014] identified the traditional strategic, tactical, and operational levels of planning and design required for a multimodal transportation system to ensure sustainable and reliable freight transportation. [Baykasoğlu et al. 2019] presented a structured overview of how the optimal solutions to multimodal transportation problems can be obtained. [Archetti et al. 2022] summarized the optimization techniques used in multimodal and intermodal operations as strategic/tactical and operational. A review of the effects of mode choices on environmental sustainability in freight transportation with more than one mode of transport was presented in the literature for the first time [Bask and Rajahonka 2017]. This study and ours were similar in that both examined multiple modes of freight transportation in terms of their sustainability and green logistics.

Table 1. Summary of previous literature review studies.

Reference	Type of	Scope	Timeline	N.of articles
Lam and Gu (2013)	Intermodal	Literature Review Container Flow Optimization	1972-2012	50
SteadieSeifi et al. (2014)	Multimodal	Literature Review of Freight Transportation Planning	2005-2014	78
Bask and Rajahonka (2017)	Both	The Role of Environmental Sustainability in Mode Choice	1970-2017	33
Baykasoğlu et al. (2019)	Multimodal	Literature Review of Freight Transportation Planning	1959-2017	283
Elbert et al. (2020)	Multimodal	Literature Review of Tactical Network Design	2008-2020	60
Archetti et al. (2022)	Multimodal	Literature Review of Optimization	1996-2020	111
This Study	Both	Literature Review of Multimodal and Intermodal Transportation Systems with Green Concerns	2012-2022	76

The distinguishing feature of our study was that it did not focus only on mode selection, but also provided a general perspective on environmental sustainability studies conducted during the last ten years. Although there have been many literature surveys of green or sustainable logistics and multimodal transportation systems, our study was the first literature survey to combine these subjects to consider the environmental sustainability of multimodal and intermodal transportation systems. As shown in Figure 3, environmental awareness became prominent in 2020. Although the number of such publications decreased in 2021, we noticed that publications investigating green and sustainable freight transportation in multimodal and intermodal transportation systems increased over time; however, there were fluctuations in the trend line.

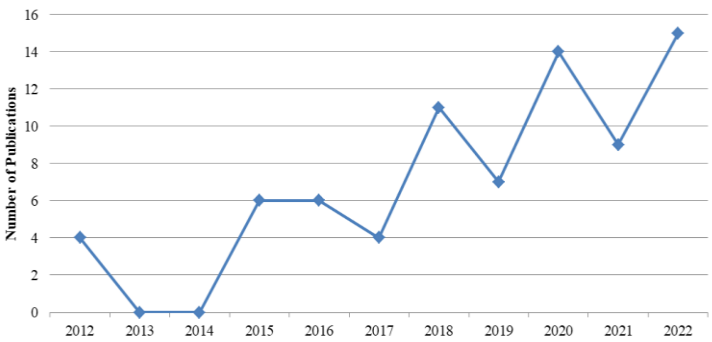

Fig. 3. Number of publications per year.

The European Commission has approved a set of policies to enable Europe's economy and society to become "climate-neutral", i.e., zero GHG emissions, by adopting step-by-step targets until 2050 [European Commission 2020]. We believe that the benefits of mode combination in freight transportation, especially after the European Green Deal is finalized, will be discussed more in the literature going forward. Figure 4 shows that Transportation Research Part E had the most publications in this area. Transportation Research Part D and Sustainability had the second-highest number of publications, with the Journal of Cleaner Production ranking third. The following part of this section examines the environmental considerations in multimodal and intermodal transportation systems, mode combinations, model formulations, and solution approaches.

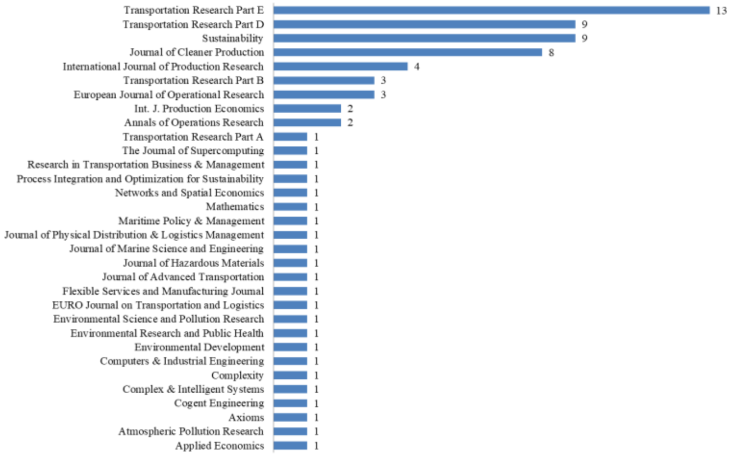

Fig. 4. Publication numbers in academic journals.

Environmental impacts of intermodal and multimodal transportation systems

To ensure greening and sustainability of the supply chain, many studies have considered minimizing the environmental impacts of logistics activities. The United Nations Framework Convention on Climate Change [UNCC 2022] has been preparing yearly Climate Action Pathways with the aim of shifting to more environmentally sustainable and low-carbon public and freight transportation modes. Removing the dependency on road transportation will play a crucial role in meeting the zero-carbon target, especially in freight transportation [European Commission 2020, EEA 2023]. To meet the decarbonization target, logistics service providers have taken action with combined transportation systems to reduce carbon emissions by a reasonable rate, compared with road transportation [MSC Shipping Company 2022, NovaTrans Greenmodal Transport Solutions 2022]. The best way to meet this target is to promote multimodal and intermodal transportation with sea and rail freight modes [EPA 2021, Rail Market News 2022].

The environmental impact of logistics activities is not limited to only GHG emissions. The other significant issues are water and air pollution, toxic waste disposal, and inefficient energy usage [OECD 2021]. However, we observed that these impacts were rarely discussed in the green logistics literature. The most reliable and efficient transportation systems need to be improved in terms of all their environmental impacts. The common environmental impacts in the existing literature were described using the terms "reducing risk", "greening concerns", and "sustainability". In the existing sustainable multimodal and intermodal transportation literature, we observed that mode choice affects sustainability when establishing green transportation. The undesired effects of road-only transportation can be eliminated by clearly switching the transportation mode throughout the system. Additionally, environmental sustainability is directly related to economic and social sustainability and vice versa. Existing studies have shown that it is possible to reduce emission rates if transportation plans include low-emission modes, compared to road-only freight transportation. There is a strong relationship between distance and carbon emissions. One likely explanation for this finding is that combinations of seaway and railway transportation are much more effective for long distance transport because of the high-volume loading capacity and lower fuel costs when trains and ships are used for freight transportation. Studies of hazmat transportation planning are common in the risk-related sustainability literature, and they play a vital role in social and environmental sustainability. For this reason, researchers have considered effective mode combinations and network design to reduce total transportation risks and the related costs.

Table 2 summarizes the general environmental impacts and gives the definitions used in the papers. As can be seen in the table, the common goal of all studies was to provide sustainability using any means of green transportation and therefore minimize the impact on the environment.

Table 2. Environmental impacts in papers.

Studies Focused on Impacts on the Environment	**References**
Green Network Design *(strategic planning that aims to reduce carbon emissions)*	Bauer et al. [2010], Bouchery and Fransoo [2015], Inghels et al. [2016], Lam and Gu [2016], Demir et al. [2016], Ji and Luo [2017], Dai et al. [2018], Jiang et al. [2020], Yang et al. [2021], Farazmand et al. [2022], Ibnoulouaf et al., [2022]
Green Routing in Transportation *(defining effectives routes by minimizing carbon emissions)*	Zhang M et al. [2015], Sun et al. [2018], Heinold and Meisel [2020], Sun [2020], Wang Q et al. [2020] Ziaei and Jabbarzadeh [2021], Choudhary et al., [2022], Qi et al. [2022]
Green Logistics *(planning eco-friendly logistics services)*	Bitzan and Keeler [2011], Eng-Larsson and Kohn [2012], Kengpol and Tuammee [2015], Kirschstein and Meisel [2015], Rudi et al. [2016], Hrušovský et al. [2018], Palmer et al. [2018], Zhao et al. [2018], Zhou et al. [2018], Demir et al. [2019], Dükkancı et al. [2019], Heinen and Mattioli [2019], Aksoy and Durmuşoğlu [2020], Li and Su [2020], Sun et al. [2021], Wang C. et al. [2020], Wang W. et al [2020], Shoukat [2022]
Sustainable Transportation *(enhancing energy-efficiency and environmental sustainability in transportation, any means of green transportation)*	Lammgard [2012], Baykasoglu and Subulan [2016], Woodburn [2017], Göçmen and Erol [2018], Resat and Türkay [2019], Martinez-Lopez et al. [2018], Kumar and Anbanandam [2020], Martinez-Lopez and Chica [2020], Ge et al. [2020], Cannas et al. [2020], Tamannaei et al. [2021], Golnar and Beškovnik [2022], Ko et al. [2022], Okyere et al. [2022]
Sustainable Network Design *(strategic planning for environmental sustainability)*	Stenius et al. [2018], Maiyar and Thakkar [2019], Tadic et al. [2019], Maiyar and Thakkar [2020], Wang et al. [2021], Mohri and Thompson [2022], Taheri and Tamannaei, [2022], Wang C et al. [2022]
Other Environmental Impact	Zanin et al. [2012], Nesheli et al. [2017], Heinold and Meisel [2018], De Miranda Pinto et al. [2018], Pizzol [2019], Zhang X et al. [2019], Wang W et al. [2020], Ardliana et al., [2022], Guo et al. [2022]
Risk *[Hazardous Materials Transportation- HazMat)*	Xie et al. [2012], Assadipour et al. [2015], Mohammadi et al. [2017], Ke [2020], Fattahi and Behnamian [2021], Li S et al. [2021]

Mode Combinations

Mode choice and mode combinations are the elements determining the greenness of the freight transportation network. Characteristics such as transit time, transportation cost, operational cost, and environmental performance vary from mode to mode. Once the size and type of transportation unit have been chosen, mode choice or mode combinations must be determined. Table 3 summarizes the different mode combinations in the literature. The road-rail combination is the most widely studied combination of transportation modes because these transportation modes are easy to combine. Connections with intermodal ports enable sea-rail intermodality to be designed. Because door-to-door deliveries are made possible by trucks, road-rail-sea combinations accurately reflect real logistics problems.

Table 3. Mode combinations in multimodal and intermodal transportation literature.

Mode Combinations	Reference	
	Multimodal Transportation Network	**Intermodal Trasnportation Network**
Road-Rail	Xie et al. [2012], Palmer et al. [2018], Zhang X et al. [2019], Jiang et al. [2020], Ziaei and Jabbarzadeh [2021], Farazmand et al. [2022], Ko et al. [2022]	Bitzan and Keeler [2011], Lammgard [2012], Eng-Larsson and Kohn [2012], Assadipour et al. [2015], Kirschstein and Meisel [2015], Heinold and Meisel [2018], De Miranda Pinto et al. [2018], Göçmen and Erol [2018], Sun et al. [2018], Maiyar and Thakkar [2019], Ke [2020], Sun [2020], Kumar and Anbanandam [2020], Heinold and Meisel [2020] , Cannas et al. [2020], Maiyar and Thakkar [2020], Fattahi and Behnamian [2021], Li S et al. [2021], Sun et al. [2021], Tamannaei et al. [2021], Ardliana et al., [2022], Ibnoulouaf et al. [2022], Mohri and Thompson [2022], Shoukat [2022], Taheri and Tamannaei [2022]
Road – Sea	Yang et al. [2021]	Pizzol [2019], Dong et al. [2020], Martínez-López and Chica [2020], Wang W. et al [2020]
Road – Inland Water	Inghels et al. [2016]	Wang et al. [2021]
Rail – Sea	Woodburn [2017]	Zhao et al. [2018], Aksoy and Durmuşoğlu [2020], Ge et al. [2020], Golnar and Beškovnik [2022]
Rail – Inland Water		Hrušovský et al. [2018]
Rail – Air		Zanin et al. [2012], Li Z et al. [2021]
Road – Rail – Sea	Wang C et al. [2020], Wang Q et al. [2020], Okyere et al. [2022], Qi et al. [2022]	Rudi et al. [2016], Baykasoglu and Subulan [2016], Lam and Gu [2016], Ji and Luo [2017], Resat and Türkay [2019]
Road – Rail – Inland Water	Zhang M et al. [2015], Guo et al. [2022]	Demir et al [2016], Demir et al [2019]
Road – Rail – Air	Li Z et al. [2021]	
Road – Inland Water – Sea		Dai et al. [2018]
Road – Rail – Sea – Pipeline	Wang C et al. [2022]	
Unspecified	Kengpol and Tuammee [2015], Mohammadi et al. [2017], Nesheli et al. [2017], Zhou et al. [2018], Dükkancı et al. [2019], Heinen and Mattioli [2019], Li and Su [2020]	Bouchery and Fransoo [2015], Chen and Wang [2016], Martinez-Lopez et al. [2018], Stenius et al. [2018],Tadic et al [2019]

The majority of the literature considering multimodal and intermodal transportation includes the most common mode combination of rail-road, as well as road-sea, rail-sea, and sometimes inland water transportation. However, future studies need to consider more than two transportation modes, such as road-rail-sea. Because of the model complexity, there have only been a few studies of combinations with air transport.

Model Formulations and Solution Approaches

Logistics service providers and managers have focused on reducing logistics costs because of the vital role they play in economic systems. Based on environmental impacts, many studies have developed mathematical models with green objective functions. Problems with environmental considerations have generally developed for more than one objective function, as shown in Figure 5.

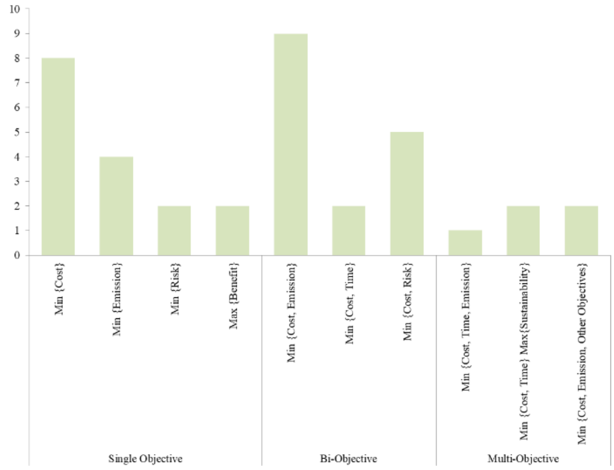

Fig. 5. Objective types.

The traditional objective function considered the economic aspects of logistics. Several studies have considered environmental effects to be a cost objective or constraint. One of the trends appearing in several studies of multi/intermodal transportation problems has been the introduction of environmental concerns as a secondary objective [e.g., Shoukat 2022, Taheri and Tamannaei 2022, Wang C. et al. 2022] to reflect applications in the real transport chain.

Multi-objective mathematical programming problems have been developed for green multimodal or intermodal transportation systems. In terms of sustainable intermodal transportation, multi-objective models with more than two objective functions have been developed to optimize the competition criteria defined by managers [Bouchery and Fransoo 2015, Baykasoğlu and Subulan 2016, Martinez-López et al. 2018, Heinold and Meiser 2020, Wang et al. 2021]. The competitiveness in terms of sustainability can be explained as improved load planning mechanisms, better service selection, and optimized intermodal routes for door-to-door transport. The objective functions can vary according to the decision-makers constrained by environmental issues [Mohri and Thompson 2022]. Table 4 details the objective structure of these modelling studies.

DISCUSSION

This section discusses some challenging issues in the available research regarding the environmental impacts of multimodal and intermodal transportation. The remaining part of this section highlights the potential research directions through the research gaps.

Research Gaps and Potential Opportunities for Future Studies

Many researchers have focused on carbon emissions; however, logistics activities also have other harmful effects on the environment. Future studies should therefore explore effective methods to handle other negative externalities, such as water, air, and noise pollution, or fuel and energy consumption.

For research question 2, the most widely studied and preferred mode combination in multimodal and intermodal transportation systems is the road–rail combination because it is more practical than the other combinations. There is a lack of research on the integration of waterways and airway transportation. The combination of three transportation modes, i.e., road, rail, and sea, is more effective as the transportation distance gets longer. The literature has not discussed air transportation with road, rail, or maritime transportation. In green transportation networks in which multiple transportation modes are used, attention needs to be given to strategic and operational problems where air transportation is included. Despite recent technological developments indicating the integration of automated and unmanned vehicles into intermodal air transportation planning [Archetti et al. 2022], there is a knowledge gap in the current literature regarding the incorporation of air transportation in combined transportation systems. Although this could theoretically provide effective solutions for decision-makers, it will also be directly applicable to real-life problems. For this reason, following and integrating technological developments into transportation systems is important. Mode synchronization and the integration of Logistics 5.0 applications require more attention for combined transportation systems. Therefore, machine learning and data mining for logistics management have become important topics in operations research.

Table 4. Objective structures by paper.

Objective Structure	Reference	Goal
Single – objective	Xie et a. [2012]	Min Total Link Risk associated with Operational Cost
	Rudi et al. [2016]	Min # of Full Truckload with GHG Emission
	Demir et al. [2016], Zhao et al. [2016], Hrušovský et al. [2018]	Min Total Weighted Cost
	Inghels et al. [2016], Ibnoulouaf et al. [2022], Okyere et al. [2022], Qi et al. [2022]	Min Total Cost associated with Environmental Cost
	Mohammadi et al. [2017]	Min Total Risk
	Zhang X et al. [2019]	Max Benefits of Railway Transportation
	Dükkancı et al. [2019], Li and Su [2020], Yang et al. [2021]	Min Total Emission
	Maiyar and Thakkar [2020]	Min Total Relative Regret
	Wang W et al. [2020], Ardliana et al. [2022], Taheri and Tamannaei [2022]	Min Total Cost
	Li Z et al. [2021]	Min Total Transportation Cost
	Mohri and Thompson [2022]	Max Government's Profit
Bi – objective	Lam and Gu [2016]	Min Total Unit Cost of Container Flow Min Total Transit Time
	Ji and Luo [2017]	Min Total Cost Min Maximum Flow Time
	Assadipour et al. [2015], Ke [2017], Li S et al. [2021]	Min Total Cost Min Risk
	Dai et al. [2018], Zhou et al. [2018], Demir et al. [20199, Maiyar and Thakkar [2019], Resat and Türkay [2019], Dong et al. [2020], Sun [2020], Wang Q et al. [2020], Farazmand et al. [2022], Shoukat [2022]	Min Total Cost Min Total Emission
	Fattahi and Behnamian [2021]	Min Total Cost Min Population Exposure
	Ziaei and Jabbarzadeh [2021]	Min Total Cost Min Total Risk with Carbon Emission
Bi – level	Zhang M et al. [2015]	Min Transhipment Cost Min Service Cost
	Jiang et al. [2020]	Max Total Flow Min Total Cost
Multi – objective	Bouchery and Fransoo [2015]	Min Total Cost Min Carbon Emission Min Modal Shift
	Baykasoğlu and Subulan [2016]	Min Total Transportation Cost Min Total Transit Time Min Total CO_2 Emission
	Ko et al. [2022]	Min Transportation Cost Min Social Cost Min environmental Cost
	Wang C et al. [2022]	Max Profit Max Energy Security Min Emission

It was also important to consider the formulation of problems and the proposed solutions in the published studies. There is an additional need for the diversification of model structures to obtain multi-objective models with different objective functions such as maximizing profit, service level, and vehicle utilization, while minimizing travel time, total distance, lead time, and environmental impact.

The number of studies based on real-life applications has grown over time, but the proposed formulations and solution techniques may be specific and inapplicable. Therefore, practical scenarios, formulations, and solutions are required to tackle real business problems. Additionally, considering the pollution routing, uncertainty in weather conditions, capacity, and emission rates some degree of scaling is required. Researchers should also focus on fleet deployment, repositioning, replacement, and sizing. These strategies will reflect real business problems if they are combined with different types of uncertainty and risk.

In addition to these knowledge gaps and future research directions, there were limitations to our study that could also provide opportunities for future research. To summarize the latest developments in green combined transportation, we considered only papers published in the last ten years (2012–2022), which obviously excluded papers published before 2012. This search excluded books, chapters, conference proceedings, and articles that were not in English, but they may still be relevant studies. Considering the review's findings on the trends and research gaps in the available literature, answers can be provided to the initial research questions; however, additional information may also be available. This study collected data from the aforementioned databases using criteria established to ensure the quality of the content. This might have resulted in some data loss due to the exclusion of studies not indexed in the databases.

Most of the available studies focused on network design rather than routing problems. Regarding research question 3, the findings indicated that routing decisions or fleet planning models should be explored. Most of the approaches taken in the studies reviewed focused on multi-objective optimization techniques. However, the proposed formulations and solution techniques were often specific and inapplicable. For real-world applications, more sophisticated methods, such as practical scenarios, formulations, and solution techniques that can tackle real business problems need to be developed. This would enable research question 4 to be fully answered.

We observed that researchers have mainly focused on time uncertainty in transportation planning (i.e., transit, arrival, or departure times). Most of the reviewed studies published in the last five years showed an increasing interest in studying uncertainty in multimodal transportation systems. Only a few studies have considered uncertainty in demand, capacity, and risk. We also noticed that studies considering uncertainty have proposed fuzzy, stochastic, or robust optimization techniques according to the problem structure. Researchers have generally developed the chance-constraint method and sample average approximation (SAA) in addition to metaheuristics in stochastic cases, while some authors have developed fuzzy optimization techniques in fuzzy cases. Simulations, fuzzy optimization, and robust optimization techniques are generally used to handle uncertainty parameters.

Furthermore, it is necessary to use metaheuristics to solve operational decisions such as location, routing, and scheduling problems, which are NP-hard problems, especially at large scales and in a reasonable time. Figure 6 shows the solution methods presented in the reviewed literature. Because the complexity of the problem increases for large-scale real-life transportation problems, the development of sophisticated solution methodologies is required.

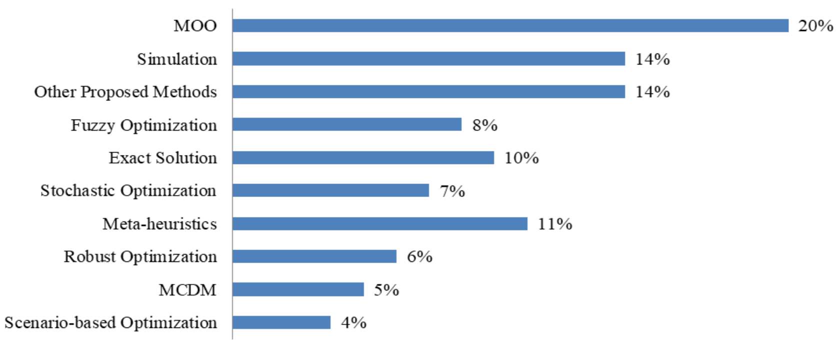

Fig. 6. Solution methods.

We conclude that there is a need for a massive computational effort due to the complexity of the problem. Combined transportation system planning problems are classified as NP-hard problems. Due to the natural consequences of problem complexity, metaheuristics, and hybrid heuristics, they are often proposed in studies for especially large-scale problems.

CONCLUSIVE REMARKS

Capturing and interpreting the trade-offs among economic, environmental, and social consequences is critical for designing and managing an efficient transportation system. Thus, researchers, policy-makers, and practitioners have paid increasing attention to the environmental advantages of transportation systems with multiple-transportation modes. In this paper, we reviewed the proposed multiple modes of transportation systems with a focus on their environmental impacts. There is a rich body of literature reviewing multimodal and intermodal transportation systems because researchers have typically paid more attention to economic than environmental sustainability. There is a need for review studies focusing on environmentally sustainable multimodal or intermodal transportation systems. We also focused on the research gaps to develop a theoretical framework for future green multimodal and intermodal transportation systems. Our study revealed that researchers and practitioners are willing to consider environmental sustainability goals because transportation activities are the leading GHG emitter. To address the research gaps summarized above, future studies should consider multi-objective transportation planning that combines different vehicle types, such as integrating air transportation with the combination of road and seaway transportation. The various uncertain parameters should also be resolved by improving meta-heuristics for large-scale real-case logistics problems. Developing technologies in the logistics sector with new strategies regarding environmental concerns in logistics is another interesting research direction for future studies.

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