Transportation Research Part E 194 (2025) 103915

Contents lists available at ScienceDirect

Transportation Research Part E

journal homepage: www.elsevier.com/locate/tre

Operational synchromodal transport planning methodologies: Review and roadmap[☆]

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ARTICLE INFO

Keywords:
Synchromodal transport planning
Operational planning
Multi-criteria optimization
Dynamic optimization
Collaborative planning

ABSTRACT

This review aims to explore the potential for synchromodal transport planning at the operational level. Synchromodal transport planning involves the optimization of the movement of freights across multiple transport modes, with the objective of minimizing cost, improving efficiency, and promoting sustainability. Through this review, we provide a roadmap for methodological developments in the area of operational synchromodal transport planning research. The roadmap provides a comprehensive categorization of different fields and their trends. The fundamentals of synchromodal transport planning are evolved to more flexible planning approaches that take practical considerations and multiple objectives into account. Dynamic planning is evolving to become more adaptive and resilient to changing environments. Finally, collaborative planning will continue to integrate both vertical and horizontal collaboration with distributed optimization approaches. With dynamic and collaborative approaches considering preferences, the full potential of synchromodal transport planning can be unlocked towards efficient and sustainable freight transportation.

1. Introduction

In order to mitigate climate change, different countries and regions have put forward initiatives to use intermodal transport. The goal of the European Commission is to transition 30% of the freight transportation that currently takes place on roads to more environmentally friendly modes, such as rail and inland waterways, by the year 2030. The Commission aims to increase this percentage to 50% by the year 2050 (European Commission, 2011). China has announced a policy named “Carbon Peak and Carbon Neutrality” with the goal of achieving a peak in carbon emissions by 2030 and carbon neutrality by 2060. As a part of this policy, the annual volume of container transportation through rail and ship should increase by 15% between 2021 and 2025 (State Council of China, 2021a,b). However, the current state of intermodal transport is still challenged by various barriers to its utilization, such as a lack of flexibility, delays due to uncertainty in travel time, and the absence of cooperation among stakeholders (Vural et al., 2020). Transport companies continue to heavily rely on road transportation, while the shift towards rail and water transportation modes has been slow and limited in adoption (Dong et al., 2018).

[☆] This work is supported by National Natural Science Foundation of China (52402521, 52232011, and 52372306) and Hebei Natural Science Foundation, PR China (G2024105007). This work is partly co-funded by the European Union (ERC, ADAPT-OR, No 101117675). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them.

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https://doi.org/10.1016/j.tre.2024.103915
Received 18 July 2024; Received in revised form 21 September 2024; Accepted 3 December 2024

To achieve the operational and sustainability objectives of stakeholders in transport and logistic fields, the concept of synchromodal transport is proposed as an evolution of intermodal transport (Verweij, 2011; Behdani et al., 2014; Tavasszy et al., 2017). Synchromodal transport is defined as a flexible transport planning system that emphasizes dynamic adaptation of transport modes and routes based on current conditions and collaborations among various stakeholders including shippers, carriers, and synchromodal transport operators (SteadieSeifi et al., 2014; Ambra et al., 2019; Giusti et al., 2019b; Zhang, 2023). This approach allows for the alignment of multiple objectives and preferences, such as cost efficiency, time, reliability, and sustainability, optimizing the use of transportation resources and infrastructure in a coordinated manner (Verweij, 2011; Behdani et al., 2014; Tavasszy et al., 2017; Sakti et al., 2023). Synchromodal transport offers multiple benefits in terms of resource utilization, reliability, cost savings, flexibility, and environmental impacts (Dong et al., 2018). These benefits are achieved by combining different modes of transport, reducing empty runs and providing alternative routes, allowing carriers to quickly respond to changes in demand or disruptions in the supply chain, and using more sustainable modes of transport. Synchromodal transport has been studied in the context of transport networks in different regions and countries, including Europe (Qu et al., 2019; Hrušovskỳ et al., 2021), China–Europe (Guo et al., 2021, 2024), and the United States (Farahani et al., 2023).

To achieve synchromodal transport, scholars have studied it from different perspectives, such as business, legal barriers, physical infrastructure, digital planning tools, awareness, and implementation (Rentschler et al., 2022). Synchromodal transport planning consists of planning at strategic, tactical, and operational levels (SteadieSeifi et al., 2014). Strategic-level planning deals with long-term decisions related to investments in transportation infrastructure, such as building or expanding networks. Tactical-level planning concerns optimization by utilizing the existing infrastructure, such as choosing services and transportation modes, allocating capacities, and planning itineraries and frequency. Operational-level planning focuses on the real-time management of transportation services, considering the dynamic and uncertain nature of transportation demand and addressing any issues that arise in real-time. It involves making quick decisions on transportation modes, routes, and resource allocation to meet the actual demand. It is considered to be the most complex among the three levels as it involves dealing with real-time requirements of multiple parties and requires the use of advanced algorithms to make accurate and efficient decisions.

Despite the growing number of publications on Operational Synchromodal Transport Planning (OSTP), there is no systematic review on this emerging topic. This may be due to the interdisciplinary nature of OSTP, which involves considerations such as transportation & logistics science, operations research, and multi-agent systems (Tavasszy et al., 2017; SteadieSeifi et al., 2014; Sakti et al., 2023). Therefore, this study conducts a systematic and interdisciplinary review to provide the state of the art and future research trends for researchers and engineers from diverse backgrounds. This review focuses on OSTP. For the literature at strategic and tactical levels, we suggest the reviews conducted by SteadieSeifi et al. (2014) and Elbert et al. (2020).

The stakeholders involved in synchromodal transport planning are outlined in Section 1.1. Understanding the roles and interests of these stakeholders is crucial as it sets the stage for delving into the operational planning problems, discussed in Section 1.2. These problems highlight the core challenges and opportunities that define the operational dynamics within synchromodal transport systems. Following this, Section 1.3 presents a methodological framework, offering a detailed view of the approaches and techniques employed to address these operational challenges. In Section 1.4, we illustrate the contributions of this review, articulating the advancements and insights it adds to the existing body of knowledge. Lastly, Section 1.5 provides an outline of this review.

1.1. Stakeholders in operational synchromodal transport planning

As shown in Fig. 1, the stakeholders in synchromodal transport include shippers, synchromodal transport operators (e.g., freight forwarders), carriers, and terminal operators. Shippers are the entities that initiate the transport of goods and may have their own priorities in terms of time, cost, service quality, and reliability. Synchromodal transport operators are intermediaries that coordinate the movement of goods between different modes of transportation. Carriers are responsible for the physical movement of goods and may have different objectives and preferences based on their business model and the type of goods they are transporting. To achieve these objectives, research in intermodal transport has gained attention from various domains, including transportation, logistics, real-time control, and operations research.

1.2. Operational planning problems

Operational planning includes activities such as routing and scheduling vehicles, optimizing the flow of goods through the transportation network, and coordinating the use of different modes of transportation, which is crucial for achieving the efficiency and sustainability benefits of synchromodal transport and for meeting the needs of stakeholders. Table 1 reviews explanatory research on synchromodal transport and summarizes the critical success factors of synchromodal transport planning, including mode-free booking, integrated planning, flexible planning, dynamic planning, collaborative planning, and preference-based planning. Other critical success factors not in operational transport planning, including trust among stakeholders, information and communication technologies (ICT) and intelligent transportation system (ITS) technologies, physical infrastructure, legal and political framework, mental shift, service cost, and pricing (Agbo et al., 2017; Giusti et al., 2019b), are not considered in the review. Mode-free booking, integrated planning and flexible planning are prerequisites of other critical success factors. Below are explanations of the critical success factors we consider:

1. **Mode-free booking:** Shippers in synchromodal transport cede modal control to the synchromodal transport operator or carrier, allowing for flexibility in mode choice based on shipper needs and real-time availability (Zhang et al., 2022d,b;

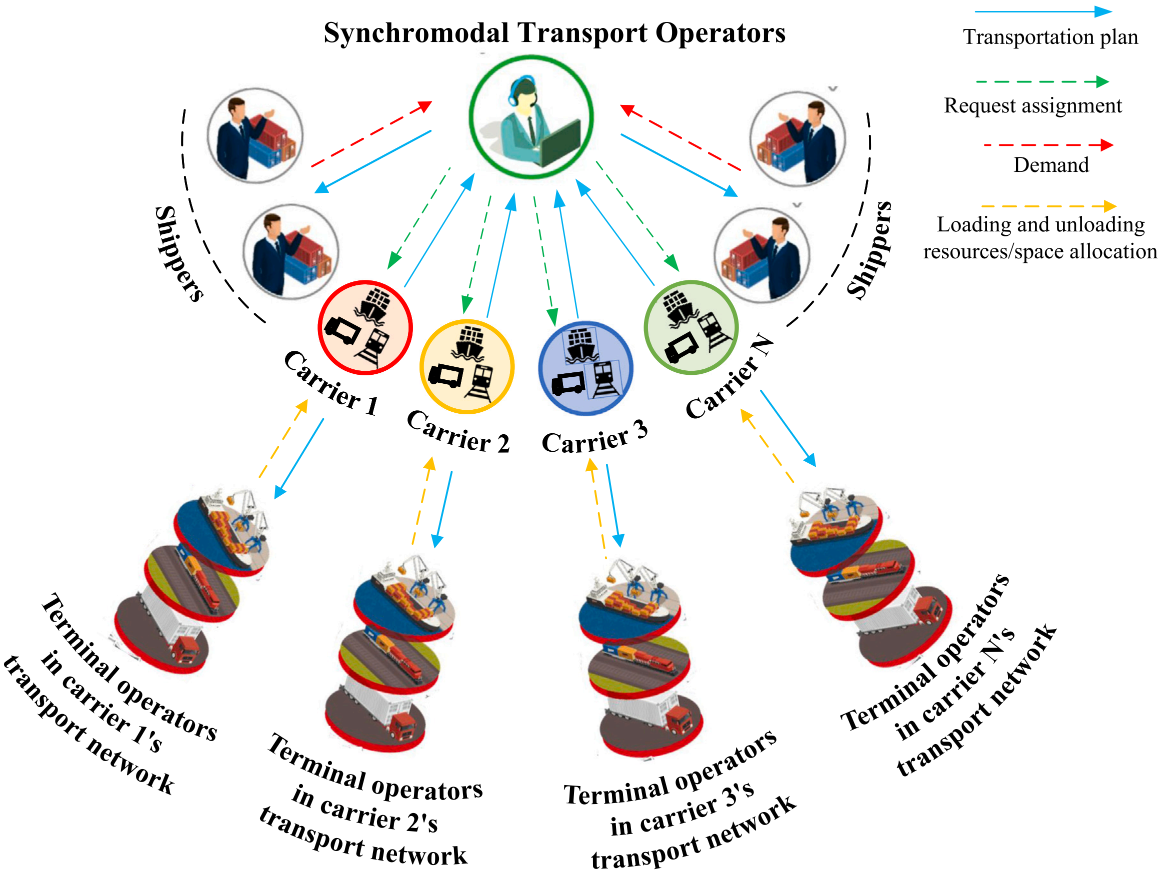


Fig. 1. Stakeholders in operational synchromodal transport planning.

Table 1

Critical success factors of synchromodal transport planning in the literature.

article	Mode-free booking	Integrated planning	Flexible planning	Dynamic planning	Collaborative planning	Preference-based planning
Behdani et al. (2014)	✓	✓	✓	✓	✓	
Van Riessen et al. (2015a)		✓	✓	✓		
Pfoser et al. (2016)	✓	✓		✓	✓	✓
Tavasszy et al. (2017)	✓	✓	✓	✓	✓	✓
Agbo et al. (2017)	✓	✓		✓	✓	✓
Guo et al. (2017)	✓	✓	✓	✓	✓	
Giusti et al. (2019b)	✓	✓	✓	✓	✓	✓
Pfoser et al. (2021)	✓	✓		✓	✓	
Acero et al. (2022)	✓	✓	✓			

Behdani et al., 2014; Khakdaman et al., 2020). Without mode-free booking, shippers' choices on specific modes limits the ability of the synchromodal transport operator or carrier to make adjustments based on real-time availability and operational requirements.

2. **Integrated planning:** Integrated planning is the process of optimizing transportation by considering all modes and resources in the entire network, it is more efficient than only scheduling specific routes and modes for each individual connection (Pfoser et al., 2021).
3. **Flexible planning:** The ability to adapt to changing demands and disruptions requires the use of flexible services in synchromodal transport. Flexibility in routes and schedules can help to avoid idle capacity and ensure that vehicles are utilized according to actual demand and preferences of shippers (Zhang et al., 2022b).
4. **Dynamic planning:** In static and deterministic planning, all information required for the problem is assumed to be known beforehand and collected a priori. However, in practical scenarios, the data may be highly dynamic, and not available in advance. Dynamic planning is critical for ensuring the efficient operation and reducing costs associated with disruptions and delays (Qu et al., 2019).

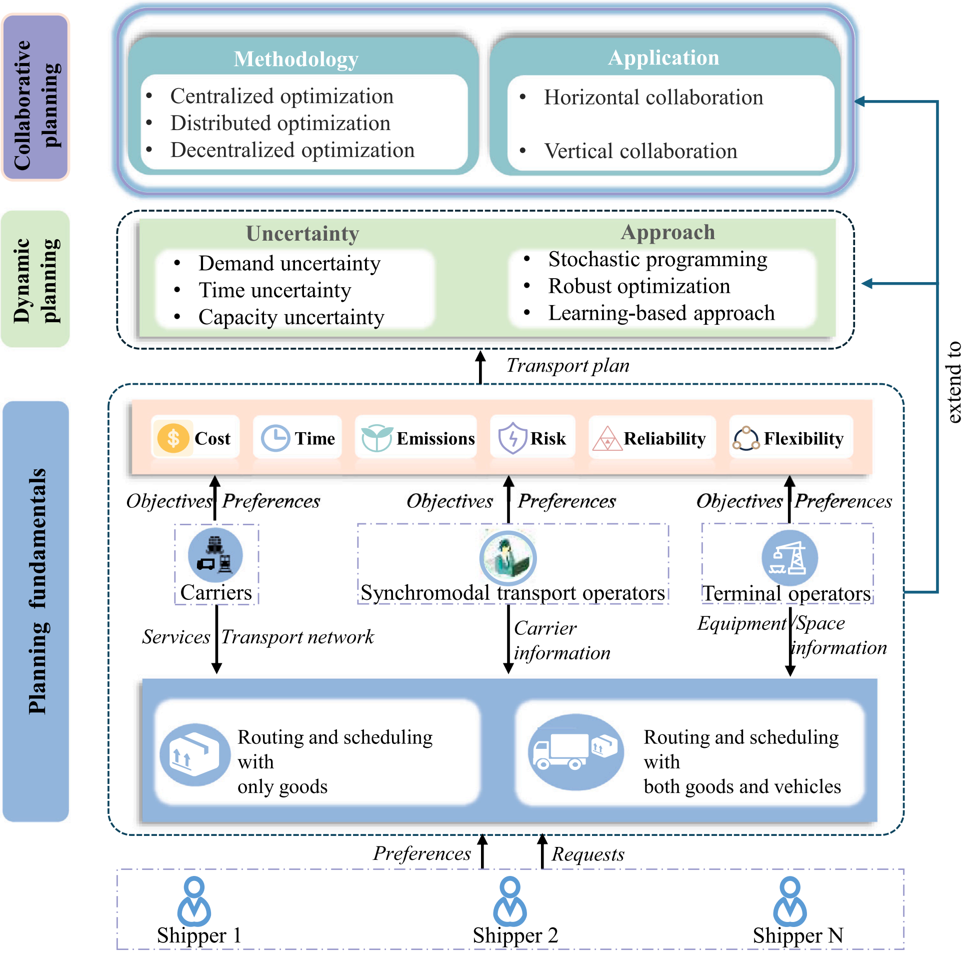


Fig. 2. Framework of operational synchromodal transport planning.

5. **Preference-based planning:** In synchromodal transport planning, there are various stakeholders involved, each with its own objectives and preferences. It is hard to satisfy all objectives of stakeholders because some objectives may conflict with each other. The integration of the objectives and preferences of stakeholders is essential for the successful planning of synchromodal transport.
6. **Collaborative planning:** Inefficient use of resources is a major concern in synchromodal transport as it can lead to increased costs and decreased performance. Effective collaboration among stakeholders is essential to optimize resource allocation and enhance operational efficiency. Companies can establish collaborations to jointly plan their logistics operations to utilize resources, which drives prices down and results in reduced profit margins. Collaborations not only increase efficiency but also contribute to environmental objectives by mitigating CO_2 emissions and reducing congestion, which are significant issues caused by transportation activities (Ballot and Fontane, 2010).

1.3. Methodological framework

Drawing on identified critical success factors, we have developed a methodological framework for achieving the OSTP, as shown in Fig. 2. This framework highlights the importance of planning fundamentals, dynamic planning under uncertainty, and collaborative planning, as essential methodologies for the successful implementation of OSTP.

The planning fundamentals studies focuses on the basic principles and methodologies of synchromodal transport planning. It can focus on routing and scheduling for goods alone or both goods and vehicles. Fundamental planning also takes into account the diverse objectives and preferences of various stakeholders. This category is crucial for understanding the foundational concepts that support all other planning strategies, emphasizing the importance of a solid theoretical base for practical application.

The ability to respond to uncertainty in dynamic planning has grown into a essential capability in synchromodal transport. The uncertainty in the transport network includes travel time, service time, and demand uncertainties. To deal with uncertainty, techniques such as stochastic programming, robust optimization, and re-planning, need to be developed. Dynamic planning needs to incorporate preferences, as the adopted strategy under uncertainty is influenced by individual preferences. For instance, in the event of disruptions, a carrier who prioritizes cost optimization may choose a waiting strategy, whereas a carrier who values time efficiency may opt for alternative transport modes and routes. These preferences need to be integrated into the dynamic planning process to ensure effective decision-making in uncertain conditions.

In order to ensure the long-term profitability of the overall system, synchromodal transport planning needs to consider stakeholders' preferences that are by nature heterogeneous and vague. Shippers and carriers are the primary stakeholders in synchromodal transport that should be considered. Heterogeneous preferences refer to the fact that different carriers and shippers may have different needs and preferences, which can be difficult to capture and represent. Vague preferences refer to the fact that carriers and shippers may have imprecise preferences, which can be difficult to quantify and incorporate into transport planning. Considering preferences refers to the ability of the transport service to meet the specific needs, wishes, and expectations of the shipper or carrier, such as cost, time, reliability, and environmental impact. This can involve trade-offs between competing objectives and balancing heterogeneous preferences of the shipper and carrier.

At the top of the diagram, the focus shifts to methodologies and applications in collaborative transport planning, which needs information sharing among stakeholders to optimize services within the transport network. There are different collaborative planning methodologies with advantages and disadvantages, including centralized, distributed, and decentralized approaches. Based on the characteristics of synchromodal transport, the most suitable approach needs to be selected. In centralized approaches, stakeholders are required to fully disclose information and resources, with control centralized to a single agent. However, in practice, stakeholders may be hesitant to share private information and prefer self-automation. In contrast, decentralized approaches empower stakeholders to make autonomous decisions, but may lack coordination and thus prove less efficient and sustainable than centralized approaches. Distributed approaches offer a compromise, balancing the benefits of centralization and decentralization. In these approaches, stakeholders share limited information on requests and services, with an agent coordinating transport planning. The specific type of collaborative planning implemented can have a significant impact on performance in terms of efficiency, sustainability, and stakeholder satisfaction in synchromodal transport. Different types of collaborative planning need to be developed and the effect on the consideration of preferences needs to be evaluated.

Fundamental planning concepts serve as the foundation for further planning processes. In practice, synchromodal transport planning requires the consideration of both dynamic planning under uncertainty and collaborative planning with other stakeholders. This is particularly relevant in large-scale synchromodal transport, such as global synchromodal transport, where carriers across continents must work together to manage uncertainties in transshipment terminals for seamless transportation (Guo et al., 2021, 2024). This requires knowledge from multiple disciplines, including multi-agent systems and operations research. By combining these approaches, operators and carriers can optimize resource utilization, reduce transportation costs, and improve service levels while minimizing environmental impact.

1.4. State of the art and contributions

The conceptual framework (De Juncker et al., 2017; Lößer, 2021; Suryavanshi, 2022; Pfoser et al., 2021; Sakti et al., 2023), success factors (Pfoser et al., 2016; Agbo et al., 2017) and characteristics of synchromodal transport (Tavasszy et al., 2017; Acero et al., 2022) are widely researched. However, there are few reviews that examine optimization approaches in transport planning. SteadieSeifi et al. (2014) review the multimodal transportation literature from the strategic, tactical, and operational planning levels. They point out that synchromodality is the essence of optimized multimodal transportation planning, considering practical aspects such as collaboration, uncertainty, traffic at terminals or a route, resource limitations, and modal capacities. Archetti et al. (2022) review papers at strategic, tactical, and operational levels across various modes of freight transport, including air, rail, long-haul maritime and waterway, and multimodal transport. Sakti et al. (2023) emphasize that synchronization is central to synchromodality, identifying three types of synchronization (between the three dimensions of synchromodality, between multiple players, and between decision levels) and discussing methods and future research directions to address synchronization challenges in this field. In terms of operational planning, Guo et al. (2017) emphasize multi-objective planning problem and dynamic/real-time routing choice due to the perishable and dynamic characteristics of synchromodal transport in global cold chains. In the enabling optimization technologies, according to Giusti et al. (2019b), operational planning focuses on the optimal allocation of resources over a short time frame, whereas real-time optimization addresses disruptions by swiftly adapting current plans through immediate re-planning. Delbart et al. (2021) review literature on how uncertainties in intermodal and synchromodal transport can be managed, proposing synchromodal transport as a flexible, real-time alternative to traditional intermodal systems and highlighting future research directions to enhance their resilience and efficiency. Rentschler et al. (2022) highlight the benefits of real-time modal switching and flexible transport booking for sustainability, and identifies key future research areas including business models, legal barriers, technological advancements, and awareness.

With the recent surge in the literature on OSTP, it is both timely and crucial to present a comprehensive review of the state of knowledge. This paper contributes to the field by:

1. Providing an extensive literature review: We offer a detailed survey of the existing studies on OSTP, comparing and contrasting various approaches and findings by characteristics and approaches. We also list and discuss the types of methodologies used and their theoretical foundations.

2. Developing a methodological roadmap: Unlike previous reviews, this paper proposes a methodological roadmap that organizes different OSTP research areas—including OSTP fundamentals, dynamic transport planning under uncertainty, and collaborative transport planning—into a coherent framework. This framework not only categorizes various fields within OSTP but also elucidates their relationships and potential synergies, guiding researchers towards comprehensive and integrated future research efforts. In the roadmap, the research evolves towards dynamic and collaborative transport planning that incorporates user preferences.
3. Identifying gaps and future research directions: By synthesizing current studies, we identify and outline critical gaps in the literature, offering future research directions that address these shortcomings. These future research directions are closely related to practical problems, and the advancement of relevant technologies can facilitate the application of synchromodal transport planning approaches.
4. Applying cross-disciplinary techniques: We explore and adapt techniques from other fields, such as the Vehicle Routing Problem (VRP), in novel ways specific to the challenges of synchromodal transport planning. This adaptation goes beyond traditional VRP applications by incorporating real-time data and synchromodal requirements, providing innovative solutions to complex logistical challenges.
5. Practical implications: This review assists transport operators in selecting appropriate methodologies tailored to specific challenges in synchromodal transport, providing practical value alongside academic insights. For example, transport operators seeking to collaborate with other operators can select methodologies from the collaborative transport planning area. This area is further divided based on the desired type of collaboration — horizontal or vertical — with specific approaches provided for each category to effectively address the collaboration objectives.

Compared to recent review papers on operational synchromodal transport planning (Delbart et al., 2021; Rentschler et al., 2022; Sakti et al., 2023), our contributions are unique in providing a structured roadmap and in adapting cross-disciplinary techniques for novel applications in the field.

1.5. Outline of this review

To provide a structured framework for discussing synchromodal transport planning, we extend the foundational classifications by Pillac et al. (2013) with a comprehensive review of recent literature. We also integrate insights from Sakti et al. (2023)'s work, which offers valuable perspectives on emerging approaches and technologies in this domain. Three types of planning will be reviewed, including Planning fundamentals, Dynamic planning, and Collaborative planning. The planning types selected are particularly relevant to current challenges and trends observed in the field (Guo et al., 2024; Zhang et al., 2023, 2022c,a).

Section 2 provides the review methodology. Section 3 focuses on operational synchromodal transport planning fundamentals. Section 4 reviews the approaches and methods used for dynamic optimization and optimization under stochastic information. The previous sections focus on the planning for a single decision-maker in synchromodal transport. Section 5 explores the literature on collaborative transport planning. Summarizing the reviews from Sections 3 to 5, Section 6 outlines a comprehensive roadmap for OSTP. Finally, in Section 7, we provide concluding remarks.

2. Review methodology

Our review specifically focuses on studies that apply operations research methodologies to address OSTP problems in the context of transportation and logistics. Empirical studies that do not address these problems are excluded from our review. For readers interested in empirical studies, we recommend referring to works such as those by Behdani et al. (2014), Van Riessen et al. (2015a), Tavasszy et al. (2017) and Giusti et al. (2019b). The review methodology is shown in Fig. 3. We review journal papers that were published between 2010 and March of 2024, as 2010 is widely recognized as the year when synchromodal transport first appeared in the literature. The databases we use include Web of science, Elsevier ScienceDirect and Google scholar, which cover major journals in transportation and logistics science, operations research, and management science, among others. The scope of this review is limited to papers written in English, with searches conducted on titles, keywords, and abstracts. Articles are meticulously filtered by document type, closely examined for relevance to specific research fields, transport modes considered, and methodologies employed. Used search terms were the combinations of "synchromodality", "synchronization", "integration", "synchromodal transport", "intermodal transport", "multimodal transport", "logistics", "freight", "planning", "optimization", and

1. "routing", "scheduling", "shipment matching", in operational synchromodal transport planning fundamentals;
2. "dynamic", "real time", "uncertainty", "stochasticity" in dynamic planning;
3. "collaboration", "cooperation", "coalition", "decentralized", "distributed" in collaborative planning.

We reviewed the found articles' reference lists and identified additional articles that were relevant to our review. To ensure that we did not miss any relevant studies, we also employed a descendancy approach that involved screening articles that cited the relevant papers we had found. Initially, a total of 504 papers were identified. Following a rigorous filtering process based on relevance, methodology, and focus areas, this number is refined down to 57 key publications for further review. Fig. 3 additionally illustrates a keyword network analysis conducted on the abstracts of the 57 selected publications. Among all keywords, "transport", "intermodal", "synchromodal", "freight", and "planning" are the top five. It also shows that the literature focuses on various themes and terminologies associated with synchromodal transport such as "optimization", "dynamic", "preferences", and "uncertainty".

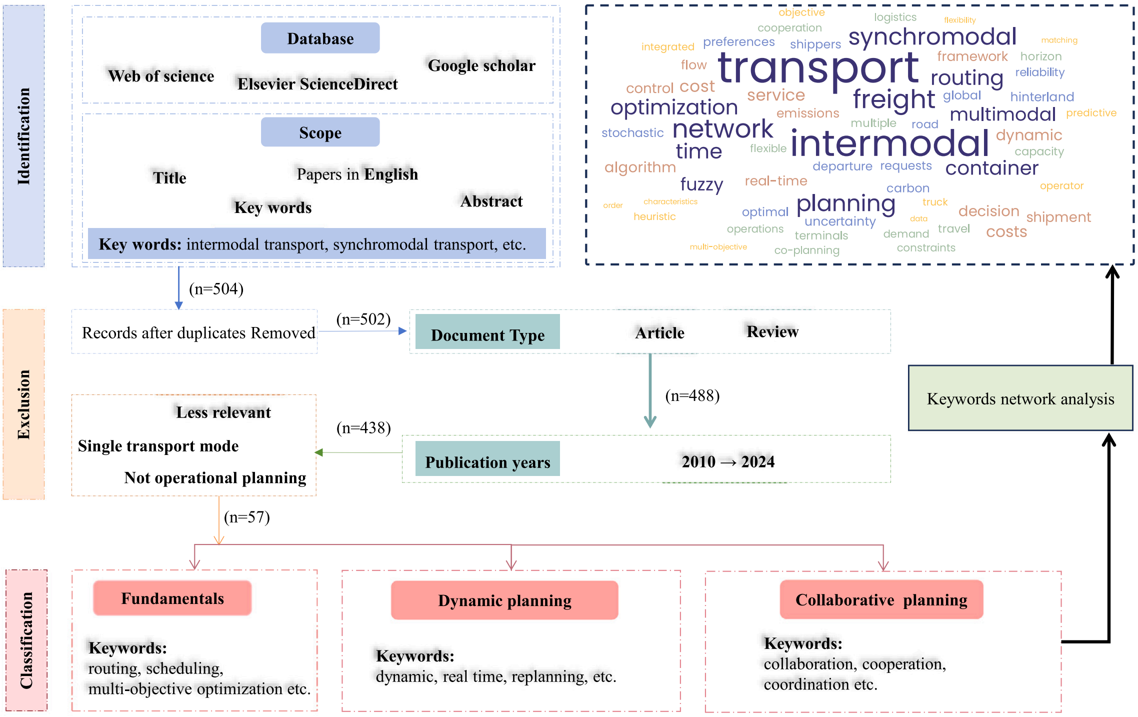


Fig. 3. Review methodology.

Table 2
Journals with more than one paper.

Journal	Number of publications
Transportation Research Part E: Logistics and Transportation Review	7
Transportation Research Part C: Emerging Technologies	5
Computers & Industrial Engineering	4
Flexible Services and Manufacturing Journal	3
Annals of Operations Research	3
Journal of Cleaner Production	3
European Journal of Operational Research	2
Journal of Advanced Transportation	2

2.1. Descriptive analytics

The goal of descriptive analytics is to offer an initial understanding of OSTP, with an aim to gather insights into the primary areas of focus within the literature. A summary of the relevant journals is presented in Table 2, which shows journals that have at least two relevant article published. Seven of the reviewed papers on OSTP are published in Transportation Research Part E: Logistics and Transportation Review, a journal that primarily focuses on the theoretical foundations, mathematical models, and advanced methodologies for solving transportation and logistics problems. In addition, some papers are published in journals that address the development of advanced approaches for decision-making support, such as Computers & Industrial Engineering and Transportation Research Part C: Emerging Technologies. Furthermore, journals that emphasize the development of innovative methodologies, such as the European Journal of Operational Research and Annals of Operations Research, have also published several OSTP papers.

The numbers of OSTP papers published between 2010 and March 2024 are displayed in Fig. 4. We also analyzed the publication trends over time and found that the field of operational synchromodal transport is relatively new. The data indicate that 55% of the articles were published between 2021 and March 2024, highlighting the recent interest in this research area. The proportions of articles on planning fundamentals, dynamic planning, and collaborative planning are 44%, 37%, and 19%, respectively. The research trends of planning fundamentals, dynamic planning, and collaborative planning are also identified, which will be illustrated in later sections. It is worth noting that there are some studies comprised more than one type of planning, and Fig. 4 categorizes the literature into only the main factor considered.

Fig. 5 illustrates the classifications of approaches found in the literature. The “Solver” category pertains to utilizing a commercial solver to tackle the problem, aiming for either an optimal solution or a solution under a computation time limitation. The “Approximate” category includes papers that present an approximate reformulation of the problem due to the original formulation’s

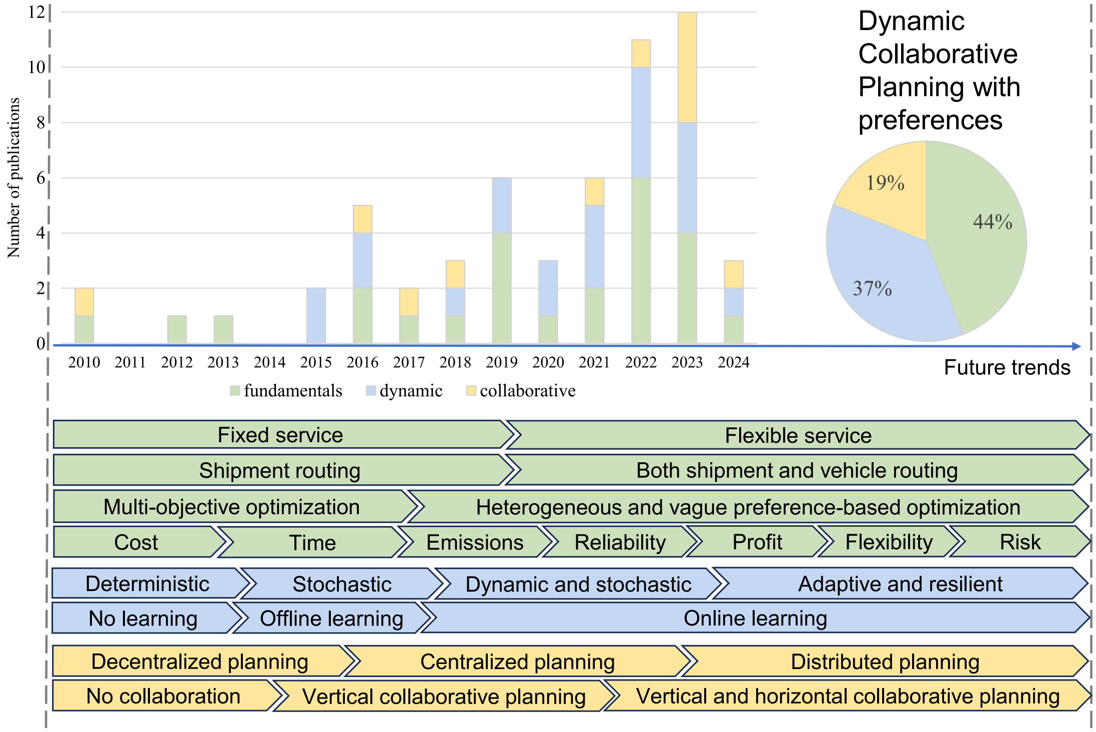


Fig. 4. Number of publications and trends.

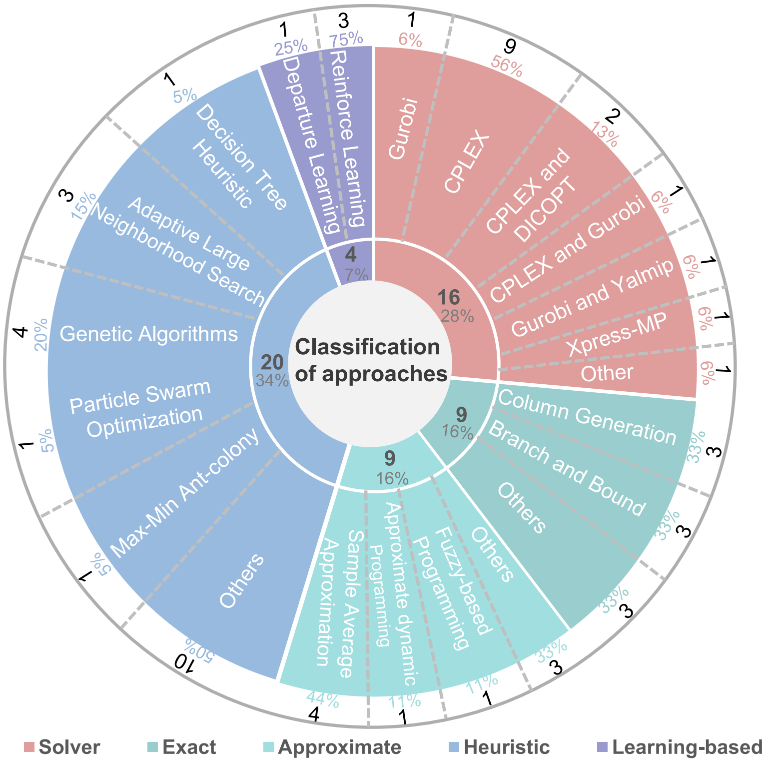


Fig. 5. Classification of approaches in the literature

complexity, often caused by non-convex expressions. These approximations are typically solved with an off-the-shelf solver. Both "Exact" and "Heuristic" categories involve implementing a specialized solution method: "Exact" focuses on solving the problem to optimality, while "Heuristic" seeks near-optimal solutions. The "Learning-based" approaches use machine learning techniques to identify patterns, optimize decision-making processes, or improve the efficiency and accuracy of solving OSTP problems by leveraging data-driven insights and predictive models. When multiple types of approaches are used, we consider the primary methodology employed by the papers. The distribution of these approaches is as follows: heuristic algorithms (34%), solvers (28%), approximate approaches (16%), exact approaches (16%), and learning-based approaches (7%). Among these, the CPLEX solver holds the largest proportion. Additionally, within the heuristic algorithms, the Adaptive Large Neighborhood Search and Genetic Algorithm are the most commonly utilized algorithms.

3. Synchromodal transport planning fundamentals

The fundamental function of operational synchromodal transport planning is to creating a transportation plan based on requests and available services. It forms the basis for dynamic and collaborative planning by providing a foundation for adjusting the transportation plan as needed.

In the literature, research on synchromodal transport planning fundamentals has primarily focused on the use of mathematical models and heuristic algorithms to optimize the routing and scheduling. Section 3.1 reviews studies on planning approaches of vehicles and goods in synchromodal transport. Section 3.2 examines the literature on multi-objective and preference-based transport planning. Section 3.3 reviews the solution methodologies. Section 3.4 provides a summary and proposes research trends.

3.1. Synchromodal transport planning of goods and vehicles

This section initially discusses research focused solely on the planning of goods, as detailed in Section 3.1.1. Subsequently, it reviews studies that consider the planning of both vehicles and goods in Section 3.1.2.

3.1.1. Synchromodal transport planning with only goods

In addressing the complexities of synchromodal transportation, it becomes essential to distinguish between the optimization challenges inherent in long-haul and short-haul transportation. Network flow problems, often closer to long-haul operations, present a critical area for discussion due to their capability to manage large-scale transportation networks and optimize multi-modal and multi-segment flows effectively. Such problems are particularly suited to scenarios in synchromodal logistics, where decisions span across vast geographical areas and involve multiple transportation modes, aligning closely with the dynamics and scale of long-haul transportation operations.

Both link-based and path-based models are used to optimize the transport of containers in the network and solve the network flow problems (Farahani et al., 2023). Link-based models define links as services and match these services with requests (Guo et al., 2020; Demir et al., 2016). Path-based models, on the other hand, have predetermined paths for the transport of containers, which reduces the number of decision variables, leading to greater computational efficiency compared to the link-based models. However, path-based models may also have a higher transport cost compared to link-based models, as the search space is potentially reduced. It should be noted that both link-based and path-based models rely on predefined services, links, or paths with fixed scheduling assumptions.

Mode-free booking allows carriers to make adjustments to the routes and schedules of different modes of transportation like truck and barge depending on the demand and specific situation (e.g., unexpected events or disruptions) without being tied to a predefined mode of transportation (Tavasszy et al., 2017). This flexibility enables the carrier to choose the most efficient and cost-effective mode of transportation for a particular shipment, which is crucial for mode-free booking to be successful. In other words, without the flexibility to adjust routes and schedules, mode-free booking would not be able to fully realize its potential for cost savings and efficiency improvements. Most studies, such as Demir et al. (2016), Qu et al. (2019) and Guo et al. (2020), typically assume that the routes and schedules of services are predetermined and the assignment to those services is optimized with the developed models. This results in a lack of flexibility in synchromodal transport planning, as the services cannot be updated during optimization.

Service flexibility is an emerging core component of logistics services (Khakdaman et al., 2022). Some researchers allow for flexibility in these models, but only in the form of flexible due or departure times (Demir et al., 2016). Some studies have investigated flexible due times and the application of delay penalty (Ghane-Ezabadi and Vergara, 2016; Guo et al., 2020), while others allow for flexible departure times within a defined time window (Moccia et al., 2011; Demir et al., 2016; Hrušovský et al., 2018). Qu et al. (2019) introduce a model for synchromodal transport that combines service rescheduling and shipment rerouting. This model offers two types of flexibility, allowing for the splitting of shipments and buffer times to be added to the departure of services (Qu et al., 2019). However, it is limited as it does not consider changes to pre-planned service routes.

3.1.2. Synchromodal transport planning with both goods and vehicles

When the service is a link or path, shipment routing is considered while vehicle routing is ignored. By nature, synchromodal transport planning involves heterogeneous vehicles differing in speed, capacity, and cost structure. Vehicle routing is crucial for achieving synchromodal transport as it is necessary for flexible routing and scheduling (Larsen et al., 2021). Ignoring vehicle routing limits the potential for flexibility in transport operations. In the literature, several studies extend beyond merely planning the transportation of goods to also include vehicle routing. Some studies consider the routing of trucks (Wolfinger et al., 2019; Larsen et al., 2021). In the studies of Wolfinger et al. (2019), although there is some degree of flexibility in the truck routes, it is limited to the initial and final legs of the transportation process. Additionally, they limit each request to utilize a maximum of one long-haul transport vehicle (ship or train). Larsen et al. (2021) consider simultaneous planning of containers and truck routes, and the barge and train's routing is not considered.

In order to consider vehicle routing, some studies employ methodologies from the VRP field. VRPs have traditionally been associated with short-haul distribution challenges, particularly where fleet management is centralized and the vehicles are owned by the decision-maker. In the context of synchromodal transportation, by incorporating vehicle routing, OSTP optimizes not only the flow of goods but also vehicle allocation and scheduling, leading to significant enhancements in operational efficiency. This holistic approach reduces transportation costs through better vehicle utilization and minimizes environmental impact by reducing unnecessary runs. Additionally, VRP allows for real-time adjustments in routing and mode selection, thereby improving reliability and flexibility in response to dynamic synchromodal transport conditions. Some studies have considered the entire synchromodal transport as a VRP with both fixed services (such as trains) and flexible services (such as trucks) (Zhang et al., 2022b). Zhang et al. (2022b) extend VRP methodologies and modify them to address the unique challenges posed by synchromodal planning, ensuring that their application remains relevant and effective even when scaled to fit the broader logistic frameworks. Building on the foundation established by Zhang et al. (2022b), subsequent studies by Zhang et al. (2022a,d,c) expand the scope to include additional industry stakeholders, such as shippers and freight forwarders.

3.2. Synchromodal transport planning with multiple objectives and preferences

While minimizing cost is the primary objective for most optimization models in the literature, it is essential to consider more comprehensive performance criteria and metrics in practical scenarios. The preferences of stakeholders need to be considered in synchromodal transport planning to determine which modes and routes meet the specific needs and goals of stakeholders. Therefore, it is necessary to develop optimization algorithms that incorporate these factors as either constraints or additional objectives. This review focuses on two important stakeholders in synchromodal transport, i.e., the shipper and carrier (or freight forwarder).

In synchromodal transport planning, both carriers and shippers have objectives such as minimizing cost, time, and emissions, but their preferences may differ, as shown in Fig. 6. Carriers may have different preferences on objectives due to factors like business models, operational strategies, capacity and resources, customer base, geographical location, and routes. Shippers also have various preferences due to factors such as business models, type of goods transported, geographical location, and inventory management. A shipper or carrier may prioritize speed and time over cost savings if the goods being shipped are perishable or time-sensitive. They may also prioritize environmental sustainability and may choose modes of transportation that have a lower carbon footprint. In Fig. 6, Carrier C is more concerned about emissions compared to Carriers A and B. Shipper E regards minimizing emissions as the most important thing, whereas Shipper F wants to transport shipments in a faster way. Apparently, Carrier B and Shipper E have non-aligned objectives. If Carriers B and C serve a request together, they also have conflicts on decisions affecting emissions and time.

The diverse objectives and preferences of shippers and carriers can make synchromodal transport planning a complex and challenging task, as it requires the integration of multiple (possibly conflicting) objectives and preferences into a single optimization model. To address this complexity, some studies have focused on the use of multi-objective optimization and preference-based optimization approaches in synchromodal transport planning. These approaches allow for the consideration of multiple criteria and heterogeneous preferences in the planning process, and provide a means of trade-off analysis and decision-making in the presence of conflicting criteria and preferences.

3.2.1. Multi-objective optimization in synchromodal transport planning

In the field of synchromodal transport planning, multi-objective optimization (MOO) is often used to address problems with multiple conflicting objectives. These objectives can include cost, emission, transport time, and others. There are several multi-objective techniques that exist in the literature, including:

1. Weighted sum method: This method involves assigning weights to each objective and summing them to form a single scalar objective function (Zhang et al., 2022a). This approach assumes that all objectives can be aggregated into a single value.
2. ε-constraint method: This method restricts other objectives in constraints while minimizing or maximizing one objective (Zhang et al., 2020a).
3. Pareto-based approaches: Pareto-optimality is a concept used to describe a set of solutions that are not dominated by any other solution. The non-dominated solution means that it dominates other solutions in at least one objective and there is no other solution that is better than it in all objectives (Zhang et al., 2022a). These approaches aim to find the set of non-dominated solutions, called the Pareto front, which represents the trade-off between multiple conflicting objectives (Sun and Lang, 2015).
4. Goal programming: This method involves setting target values for each objective and minimizing the deviation from these targets (Sun, 2020b). This approach allows for the prioritization of objectives and the specification of tolerances for deviation from the targets.

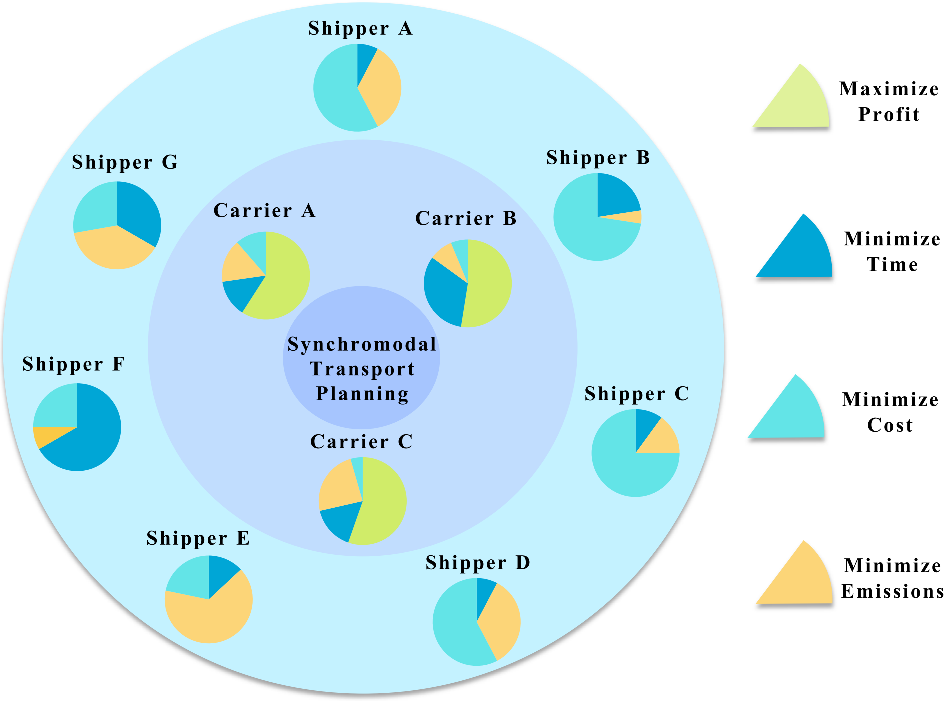


Fig. 6. Carriers and shippers with different preferences in synchromodal transport.

5. Multi-objective evolutionary algorithms: These algorithms use evolutionary computation techniques, such as genetic algorithms, to search for non-dominated solutions in the multi-objective space (Xiong and Wang, 2014).
6. Interactive methods: These methods involve human decision-makers interacting with the optimization process to guide the search towards a preferred solution (Zhang et al., 2020b).

One example of MOO in synchromodal transport planning is the work of Kalinina et al. (2013), who uses the ϵ-constraint method to solve the MOO problem that minimizes cost, emissions, and transport time in transport planning under transport time uncertainty. Another example is the work of Xiong and Wang (2014), who presents a bi-objective multimodal route optimization problem with multiple commodities. The objectives in this problem are total cost and total travel time. The authors use a genetic algorithm to solve the problem and demonstrate the effectiveness of their approach through a case study involving the transportation of hazardous materials.

The objective functions in relevant papers are shown statistically in Fig. 7. Most researchers consider cost and travel time as objective functions and less research considers risk, reliability and flexibility. Particularly, due to the threat of energy overuse and air pollution, there is a rising trend on carbon emissions. Researchers and entrepreneurs are exploring the relationship between transportation and the environment through green synchromodal transport planning to provide practical suggestions for achieving positive environmental effects while meeting economic objectives. Maden et al. (2010) explicitly show that directing vehicles away from congestion, even if it leads to longer travel distances, can be more environmentally friendly. Studies have also highlighted the potential of intermodal freight transport for reducing GHG by utilizing low-emission transport modes (Bauer et al., 2010) and the importance of considering eco-labels as constraints in intermodal transport planning (Zhang et al., 2022c). Despite the growing interest in green synchromodal transport planning in recent years, there is still a need for further research and development in both theoretical contributions and real-world applications.

To effectively optimize fuel efficiency, it is crucial to investigate fuel consumption models across various transportation modes and vehicle types, as factors such as vehicle type, traction type, fuel emission factors, and payload utilization, have a significant impact on the fuel consumption model, Heinold and Meisel (2018). Understanding the factors that impact fuel efficiency is necessary to develop effective strategies for optimization. Routing models have yet to consider certain limitations that exist in practice, such as restrictions on recharging or refueling. The availability and fuel capacity of stations and the uncertain service time can impact the travel time and arrival time at each location. In this context, queuing models can be used to address the service time problem.

3.2.2. Preference-based optimization in synchromodal transport planning

Over the past few years, there has been an increasing interest in incorporating preferences into synchromodal transport planning (Zhang et al., 2020b; Shao et al., 2022; Yang et al., 2023; Li et al., 2024). For instance, Zhang et al. (2022a) use a weight interval method to handle vague preferences of carriers and obtain non-dominated solutions through the Pareto-optimality

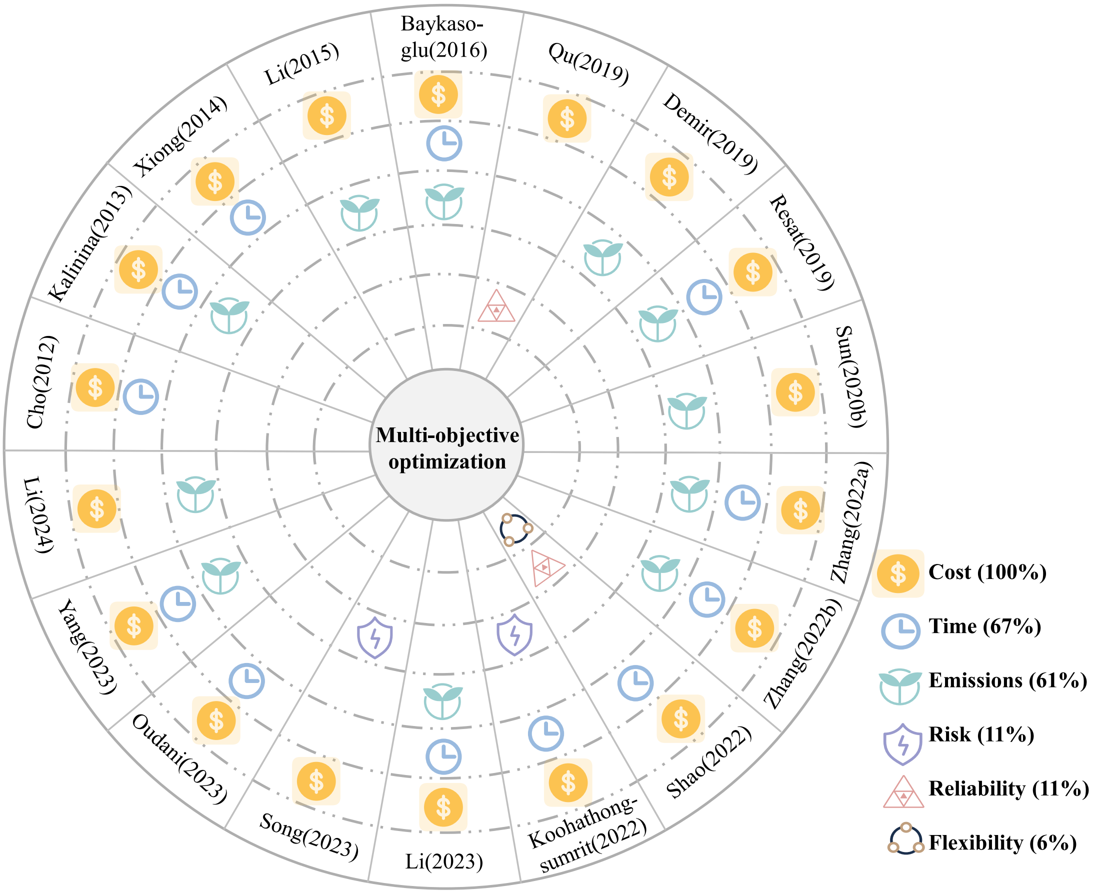


Fig. 7. The objective functions in multi-objective optimization.

approach in a multi-objective setting; Zhang et al. (2022d) consider the heterogeneous and vague preferences of shippers, which are handled by multi-attribute decision making (MADM) and fuzzy set theory, respectively. This is because preferences can play a significant role in determining the efficiency and effectiveness of synchromodal transport systems. Efficient synchromodal transport can move goods from one location to another with minimal resources, while effective synchromodal transport meets the needs and goals of the shippers and carriers. Carriers can design more targeted and effective transport solutions by considering preferences, resulting in reduced waste and better alignment with actual needs. Additionally, considering preferences can improve satisfaction and trust among carriers and shippers, resulting in stronger relationships and greater cooperation among stakeholders, ultimately facilitating the successful implementation of synchromodal transport.

The integration of preferences into transport planning poses a significant challenge, as preferences can be highly heterogeneous and vague. They may be subjective and vary among different shippers and carriers, making it difficult to accurately capture and mathematically model them. In synchromodal transport, shippers may hold conflicting preferences, requiring the carrier to navigate trade-offs among these preferences. There are several approaches to modeling preferences in transport planning. For example, in the weighted sum method, the preferences of the stakeholder are represented as weights for each objective. To handle the heterogeneity, MADM is a method used to evaluate and compare different options or alternatives based on multiple criteria or attributes (Zanakis et al., 1998). In the context of synchromodal transport, time windows are often expressed using ambiguous language, such as “preferred delivery between 2–4 P.M.”. To address the subjective, ambiguous, and vague nature of these statements, the fuzzy set theory is often used to represent preferences in a mathematical way, which can be compared and aggregated by the use of mathematical techniques to find the best solution (Koohathongsumrit and Meethom, 2022).

3.3. Solution methodologies

Synchromodal transport planning is a complex optimization problem that is computationally challenging. Solution methodologies in the VRP domain can inspire several potential opportunities for improving optimization problems in synchromodal transport planning. In VRP, finding a (near) optimal solution usually needs to employ exact or approximate algorithms. Exact algorithms, such as mixed-integer linear programming models (Guo et al., 2020), branch and bound-based approaches (Costa et al., 2019;

Tan and Yeh, 2021), constraint programming (Shaw, 1998), and dynamic programming (Xiao and Konak, 2017), are effective for small-scale problems.

On the other hand, approximate approaches, heuristics algorithms, and meta-heuristic algorithms are commonly used for solving larger-scale problems efficiently. Approximate approaches are about balancing the trade-off between solution quality and computational effort with some optimality guarantees. Heuristic algorithms aim to find a satisfactory solution within a restricted number of iterations (Pisinger and Ropke, 2007). Meta-heuristics refers to intelligent strategies that combine different heuristics for both exploration and exploitation (Tan and Yeh, 2021). By using a combination of techniques, meta-heuristics are able to efficiently search for high-quality solutions in complex problem spaces. Local search-based meta-heuristics, such as Tabu search (Gendreau et al., 1994), simulated annealing (Vincent et al., 2017), variable neighborhood search (Hansen et al., 2019), and large neighborhood search (Zhang et al., 2022b), employ iterative movements from the current solution to a neighboring solution to continuously explore the solution space. Population search-based meta-heuristics, such as genetic algorithms (Baker and Ayechew, 2003) and ant colony optimization (Yu et al., 2009), create and maintain a set of parent solutions to generate and select promising offspring that can potentially improve the quality of the solution. Though meta-heuristics require more computation time than heuristics, they usually produce high-quality solutions. Moreover, hybrid algorithms may offer a suitable approach by combining exact and approximation methods to achieve better solutions (Maden et al., 2010). These algorithms can be applied to synchromodal transport planning to reduce the computation time to obtain transport solutions.

3.4. Summary and future trends

Table 3 summarizes the studies in synchromodal transport planning fundamentals. Flexibility in synchromodal transport planning is important because it allows for the adaptability of the transport plan to changing circumstances and demands. This can include changes in the availability of certain modes of transport, changes in customer requirements or preferences, and disruptions or unexpected events. Flexibility allows for the creation of transport plans that are more resilient to these changes, leading to more efficient and cost-effective transport operations. Additionally, flexibility can help to reduce the amount of unused or underutilized capacity in the transport system, leading to more sustainable transport operations. It is clear that the studies on preferences are still limited. Some studies model preferences but do not consider them for transport planning (Koohathongsumrit and Meethom, 2022; Oudani, 2023; Pamucar et al., 2022). Table 3 illustrates that MOO approaches place the greatest importance on cost, while also considering time and emissions. However, revenue has received relatively little attention in comparison to these factors. There are also important criteria that have been overlooked, such as shipper satisfaction and crew workload. When considering these criteria as attributes in constraints, more than three attributes are usually considered (Zhang et al., 2022e). Most papers consider two or three objectives, while none of them consider many-objective optimization with more than three objectives. Multi-objective optimization problems are rarely addressed using the exact approach from a methodological perspective.

Fig. 8 highlights the trend in synchromodal transport planning fundamentals, as the introduction of flexible services. One way to incorporate flexibility into synchromodal transport planning is through the use of flexible vehicles, such as trucks or barges, that are able to change routes and schedules and adapt to changes in demand and specific situations. In this case, synchromodal transport planning can be regarded as a VRP with capacity, time window, transshipment, and heterogeneous vehicles. However, there are also challenges to achieving flexibility in synchromodal transport planning. One of the main challenges is the need to develop effective optimization algorithms and decision-making frameworks that can handle the large solution space and complex constraints associated with flexible transport operations. This includes the coordination and synchronization between different transport modes, involving both fixed and flexible vehicles, as well as the routing and scheduling for requests and vehicles.

A critical, yet unexplored, area in the study of transportation supply chains is the flexibility of stakeholders concerning various operational factors. Future research should investigate the extent to which stakeholders can adapt to deviations in time accuracy, such as changes in the scheduled arrivals and departures of transport modes. Additionally, the degree of freedom stakeholders possess in selecting transportation modes and paths warrants detailed examination. This line of inquiry could uncover valuable insights into how flexibility of stakeholders impacts the efficiency and resilience of supply chains, potentially leading to more robust transportation systems.

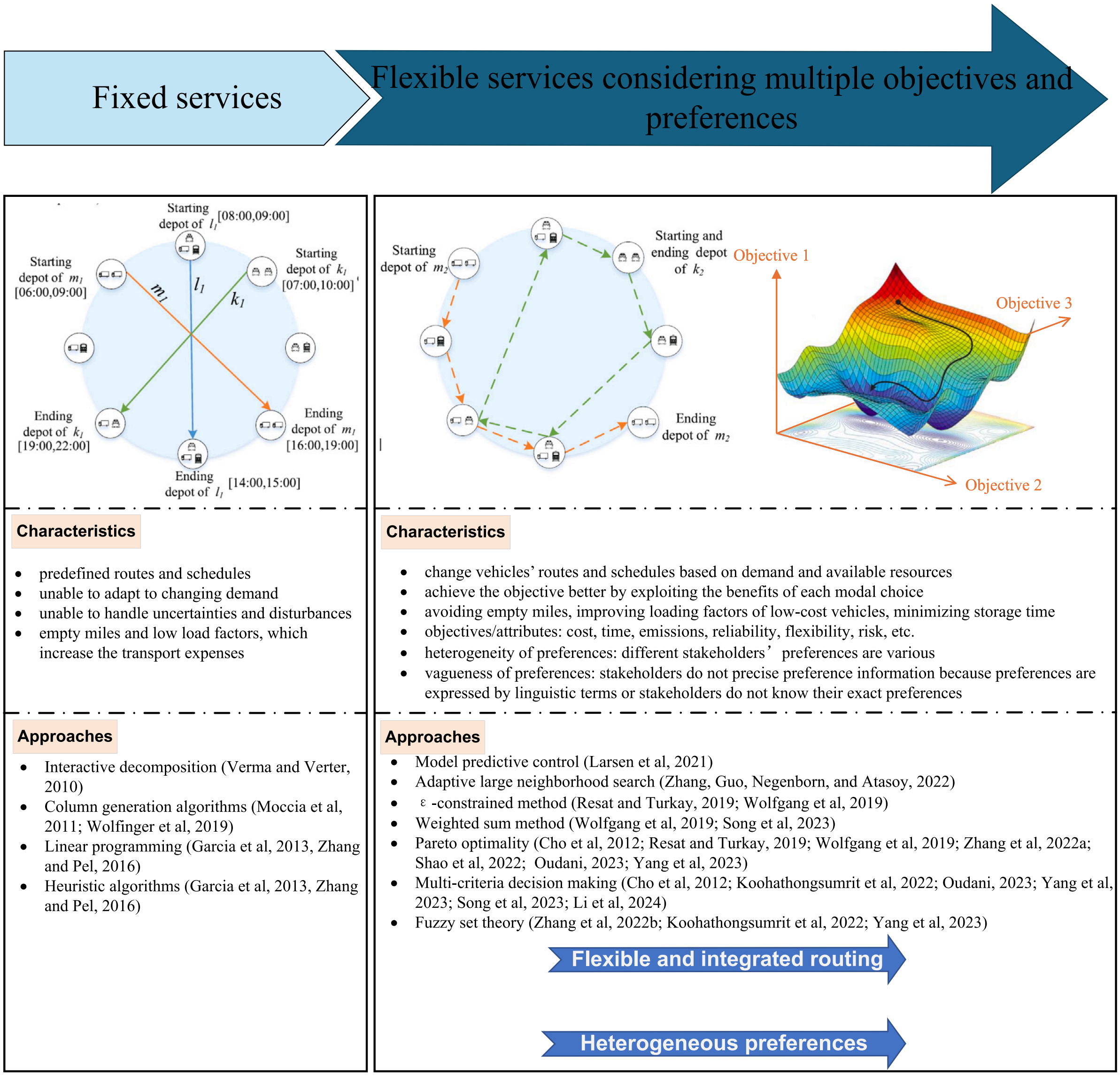
In the field of multi-objective optimization, synchromodal transport planning can learn from a variety of techniques to handle conflicting objectives such as minimizing cost and maximizing service level. These techniques include evolutionary algorithms, such as NSGA-II (Verma et al., 2021), and multi-objective local search methods, such as MOEA/D and MOSA (Qi et al., 2014), which allow for the consideration of multiple objectives and preferences. When the number of objectives exceeds three, the number of non-dominated solutions increases exponentially. This problem is further compounded in synchromodal transport planning, where the objectives are often conflicting and complex, making the optimization process even more challenging. To address this challenge, various approaches in many-objective optimization can be utilized, such as ranking methods (Garza-Fabre et al., 2009), reference point, decomposition-based methods (Han et al., 2019), and niching techniques (Tanabe and Ishibuchi, 2019).

Currently, many approaches rely on either stated preferences, which are explicit declarations of preference made by the shipper, or revealed preferences, which are inferred from historical data on the shipper's past transport decisions. However, both of these methods have limitations and may not accurately reflect the shipper's true preferences in real time. A promising avenue for future research would be to explore ways to incorporate real-time data on the shipper's transport decisions into the planning process, potentially through the use of machine learning techniques, in order to more accurately reflect the shipper's evolving preferences and make more informed transport planning decisions. The field of interactive preference-based optimization also offers a fascinating avenue for research. Recent studies, such as those on interactive fuzzy goal programming in intermodal transport (Baykasoğlu and

Table 3
Summary of the literature review on synchromodal transport planning fundamentals.

Article	Integrated vehicle and shipment routing	Flexible routing	Flexible scheduling	Service	Objectives	Preferences (of whom)	Approach
Verma and Verter (2010)				Path	cost, risk	Vagueness (carrier)	ID
Moccia et al. (2011)			Departure	Path	cost		CGA
Cho et al. (2012)	Barge, train, air	Barge	Due	Path	Cost, time		DP, PO, MAD
García et al. (2013)				Path	Cost		LP, HA
Zhang and Pel (2016)			Wait, departure	Path			LP, HA
Baykasoğlu and Subulan (2016)	Truck, barge, train	Trucks	Wait, departure	Path	Cost, time, emissions	Vagueness (carrier)	FGP
Agbo and Zhang (2017)			Wait, due, departure	Link	Cost		MILP
Wolfinger et al. (2019)	Truck	First- and last-mile trucks	Wait, departure	Vehicle, path	Cost		MILP, CGA
Pérez Rivera and Mes (2019)	Truck	First- and last-mile trucks	Departure	Link, vehicle	Cost		MILP, MDP
Resat and Turkay (2019)			Wait, due	Link	Cost, time, emissions		MILP
Demir et al. (2019)	Truck, inland waterway	Trucks	Wait	Path	Cost, emissions		WS, ε and PO
Sun (2020b)	Truck, train	First- and last-mile trucks	Departure, wait	Path, vehicle	Cost, emissions	Vagueness (carrier)	FGP
Larsen et al. (2021)	Truck	Trucks	Wait, departure, due	Link, vehicle	Cost		MPC
Hosseini and Al Khaled (2021)			Due	Link	Cost		MILP
Zhang et al. (2022b)	Truck, barge, train	Trucks, barges	Departure, due, wait, storage	Vehicle	Cost	Vagueness (carrier)	MILP, ALNS
Zhang et al. (2022a)	Truck, barge, train	Trucks, barges	Wait	Vehicle, link	Cost, time, emissions	Vagueness (carrier)	PO
Zhang et al. (2022d)	Truck, barge, train		Departure time, wait, due	Link, path	Cost, time, emissions, reliability, risk	Heterogeneity, Vagueness (shipper)	MADM and FS
Shao et al. (2022)	Barge, air, train	Barges	Due	Path	Cost, time, flexibility, reliability	Heterogeneity (shipper)	DRSA and PO
Koohathongsumrit and Meethom (2022)	Truck, barge			Path	Cost, time, risk	Vagueness (carrier)	MCDM, FS
Farahani et al. (2023)			Wait, due	Link	Cost		MILP, GA
Oudani (2023)	Road	First- and last-mile		Path, link	Cost, time		PO and MCDM
Yang et al. (2023)	Railway, highway, waterway			Path	Cost, time, emission		FS and PO
Li et al. (2023)	Road, train, air	Road	Transit	Path, link	Cost, time, emission	Vagueness (carrier)	FCCP, GT and WS
Song et al. (2023)	Truck, rail	Trucks	Departure, arrival	Path	cost, risk	Heterogeneity (carrier)	WS, PO
Li et al. (2024)	Railway, road, waterway	Road	Arrival	Path	cost, emission	Vagueness (carrier)	FCCP, PO

ID: Iterative decomposition; CGA: Column generation algorithms; LP: Linear Programming; HA: Heuristic algorithms; MILP: Mixed Integer Linear Programming; MPC: Model predictive control; MDP: Markov Decision Process; ALNS: Adaptive Large Neighborhood Search; GA: Genetic algorithm DP: Dynamic programming; FGP: Fuzzy goal programming; ε: ε-constraint method; PO: Pareto-optimality; DRSA: Dominance-based Rough Set Approach; MCDM: Multi-criteria decision making; MADM: Multi-attribute decision making; FS: Fuzzy set theory; FCCP: Fuzzy chance-constrained programming; WS: Weighted sum method; GT: Game theory



Characteristics

- predefined routes and schedules
- unable to adapt to changing demand
- unable to handle uncertainties and disturbances
- empty miles and low load factors, which increase the transport expenses

Approaches

- Interactive decomposition (Verma and Verter, 2010)
- Column generation algorithms (Moccia et al, 2011; Wolfinger et al, 2019)
- Linear programming (Garcia et al, 2013, Zhang and Pel, 2016)
- Heuristic algorithms (Garcia et al, 2013, Zhang and Pel, 2016)

Characteristics

- change vehicles' routes and schedules based on demand and available resources
- achieve the objective better by exploiting the benefits of each modal choice
- avoiding empty miles, improving loading factors of low-cost vehicles, minimizing storage time
- objectives/attributes: cost, time, emissions, reliability, flexibility, risk, etc.
- heterogeneity of preferences: different stakeholders' preferences are various
- vagueness of preferences: stakeholders do not precise preference information because preferences are expressed by linguistic terms or stakeholders do not know their exact preferences

Approaches

- Model predictive control (Larsen et al, 2021)
- Adaptive large neighborhood search (Zhang, Guo, Negenborn, and Atasoy, 2022)
- ε -constrained method (Resat and Turkay, 2019; Wolfgang et al, 2019)
- Weighted sum method (Wolfgang et al, 2019; Song et al, 2023)
- Pareto optimality (Cho et al, 2012; Resat and Turkay, 2019; Wolfgang et al, 2019; Zhang et al, 2022a; Shao et al, 2022; Oudani, 2023; Yang et al, 2023)
- Multi-criteria decision making (Cho et al, 2012; Koohathongsumrit et al, 2022; Oudani, 2023; Yang et al, 2023; Song et al, 2023; Li et al, 2024)
- Fuzzy set theory (Zhang et al, 2022b; Koohathongsumrit et al, 2022; Yang et al, 2023)

Fig. 8. The trend in research on synchromodal transport planning fundamentals.

Subulan, 2016; Shao et al., 2022), have explored how to optimize by interacting with users. However, while these studies have focused on altering the supply side, the literature on demand nudging-where users' behavior is nudged for specific aims-is relatively scarce. Further investigation in this area could yield valuable tools for sustainable transport by nudging stakeholders' behavior towards more sustainable options.

In urban passenger transport, numerous studies have focused on multimodal transport, addressing challenges similar to those found in synchromodal freight transport, including synchronization of timetables and multi-objective optimization (Cao et al., 2019; Liu et al., 2021). To improve the transfer efficiency between intercity railways and metro systems, Chai et al. (2024a) develop a mixed-integer nonlinear programming (MINLP) model to generate synchronization strategies and optimize scheduling decisions. To address the challenge of long computation times, Chai et al. (2024b) expand upon the work of Chai et al. (2024a), introducing an exact branch-and-cut algorithm that generates (near-)optimal solutions more efficiently. In the model proposed by Chai et al. (2024b), a portion of the vehicle fleet can be dynamically allocated to certain metro trains, enhancing their capacity to accommodate the increased number of passengers transferring from mainline rail trains at transfer hubs. Considering the fixed timetables of public transport and the flexible dispatch of shared mobility, Xia et al. (2024) propose an optimization approach to manage the mismatch between supply and demand. Additionally, research has been conducted on timetable synchronization for buses connecting to/from trains (Takamatsu and Taguchi, 2020) and on joint frequency setting and pricing optimization (Bertsimas et al., 2020). In the context of multi-objective optimization for urban transport planning, Liu and Ceder (2017) propose a multi-criteria optimization framework to synchronize timetables and minimize transfer times in public transport, balancing the interests of both users and operators. For a more comprehensive review on multimodal transport planning, we recommend reading the studies by Kuo et al. (2023) and Liu et al. (2021). In synchromodal transport, synchronization of timetables and conflicting objectives among stakeholders need to be considered and these approaches from urban multimodal transport can be effectively applied.

Besides flexible services and multi-objective optimization, synchromodal transport planning has some practical variants that are often overlooked, including:

1. Synchromodal transport planning with loading: Efficient and cost-effective transport in synchromodal systems, particularly for ships and trains, depends on optimized routing and careful loading. Strategically arranging and ordering freights ensure streamlined unloading, reducing transportation costs. Loading algorithms are essential for determining the best arrangement of freight, considering dimensions and weight distribution (SteadieSeifi et al., 2014; Mantovani et al., 2018).
2. Synchromodal Transport Planning with Open and Closed Routes: Synchromodal transport includes open and closed route types. Open routes allow vehicles to finish their deliveries without returning to the depot, ideal for operators using third-party logistics services (Li et al., 2007). Conversely, closed routes require vehicles to return to the depot, suitable for operators managing their own fleets.
3. Synchromodal Transport Planning with Crew Schedules: Different transport modes and countries have specific regulations impacting schedules (Prescott-Gagnon et al., 2010; Vidal et al., 2014). Integrating vehicle and crew schedules is essential for safety and compliance with regulatory driving hours, crucial in long-haul synchromodal transport.

4. Dynamic transport planning under uncertainty

In synchromodal transportation, dynamic and stochastic planning approaches serve distinct yet complementary roles. Dynamic planning enables real-time adaptation of transport plans to disturbances, leveraging the flexibility of transport operations to respond to immediate changes. Stochastic planning prepares for uncertainties using probabilistic models to address unknowns like demand fluctuations or variable transit times. This paper first introduces uncertainty in synchromodal transport in Section 4.1, then reviews literature on dynamic and stochastic planning approaches in Sections 4.2 and 4.3, respectively. Finally, the summary and future trends are presented in Section 4.4.

4.1. Uncertainties in synchromodal transport

Uncertainty in synchromodal transport planning at the operational level can have significant impacts on the efficiency and effectiveness of the transportation system. There are many sources of uncertainty that can affect the performance of synchromodal transport. These uncertainties include but are not limited to:

1. Demand uncertainty: The amount and type of cargo being transported can vary significantly from one day to the next, making it difficult to accurately predict the resources that will be needed to meet demand. Demand uncertainty can be caused by factors such as market fluctuations, seasonal variability, and disruptions in supply chains (Demir et al., 2016; Guo et al., 2021; Yee et al., 2021).
2. Capacity uncertainty: The availability of transportation resources, such as trucks, ships, and trains, can be affected by factors such as crew availability, maintenance issues, accidents, and natural disasters (Uddin and Huynh, 2019; Sun, 2022).
3. Time uncertainty: Delays and disruptions can occur at any point in the transportation process, affecting the timeliness of deliveries and the overall efficiency of the system. Specifically, it includes:
    (a) travel time uncertainty, which can be caused by factors such as traffic and weather conditions (Demir et al., 2016; Guo et al., 2022a; Yee et al., 2021; Guo et al., 2022b),
    (b) service time uncertainty, which can be caused by factors such as cargo loading and unloading, maintenance of equipment, weather-related issues, and congestion at terminals (Demir et al., 2016).

Such uncertainties can cause delays and disrupt the transportation schedule, leading to unsatisfied customers and financial losses for the transport company, thus it is imperative that these uncertainties be taken into consideration when planning and executing synchromodal transport. Considering these sources of uncertainty is important because it allows transport planners to more accurately predict the resources that will be needed to meet demand, and to develop contingency plans to mitigate the impact of potential delays and disruptions. This can help to ensure that the transportation system is able to effectively meet the needs of its customers, and operate as efficiently as possible.

4.2. Dynamic planning approaches

At the operational level, synchromodal transport must be flexible and responsive to a dynamic environment, necessitating planning that is continuously updated based on real-time information as it becomes available (Yee et al., 2021). Dynamic planning problems in synchromodal transport present new challenges due to the introduction of new elements that add degrees of freedom and make it more difficult to evaluate the merits of a given plan. By providing the ability to dynamically update transport plans in response to disturbances and disruptions, dynamic planning enables synchromodal transportation to consistently and effectively deliver goods and services to their destination in a timely manner.

Dynamic planning is a process that enables real-time adjustments to transportation plans, taking into account the current and expected events. By continuously updating and adapting plans in response to changing circumstances, it is possible to remain flexible and responsive. These adjustments can be made periodically (such as in the case of the rolling horizon approach) (Li et al., 2015; Van Riessen et al., 2016; Zhang and Pel, 2016; Guo et al., 2022a, 2021; Rivera and Mes, 2022) or in real-time (such as in the case of the event-triggered approach) (Zhang and Pel, 2016; Qu et al., 2019). Re-optimization involves generating an initial set of routes at the beginning, followed by periodic or real-time optimization procedures that solve a static problem based on the current state (Chen and Xu, 2006). Periodic optimization may occur at fixed time intervals and real-time optimization is usually triggered by changes in available data.

In the literature, some scholars propose re-planning approaches under unexpected events without explicitly modeling uncertainty, thus solving dynamic and deterministic problems. For example, to handle disruptions, Van Riessen et al. (2015b) assesses the impact and relevance of revised plans, which measure the additional costs incurred and the cost difference between fully revised and locally adjusted plans, respectively. Li et al. (2015) employ a receding horizon control method to redirect intermodal container flows in response to fluctuations in demand and travel time. When changes occur, Qu et al. (2019) re-route shipment flows, reschedule services, and adjust transshipment processes.

4.3. *Stochastic planning approaches*

Transport uncertainties can increase risk and vulnerability (Gendreau et al., 2016). The ability to respond to dynamics and uncertainties is a vital capability in synchromodal transportation (Ferrucci and Bock, 2014). In synchromodal transport, stochastic planning problems can be considered as an extension of deterministic planning problems, where stochastic information is incorporated. Deterministic and stochastic synchromodal transport planning are distinguishable in their fundamental characteristics. Specifically, in deterministic formulations, the decision maker possesses complete information at the planning stage, thus precluding any probability of failure. Conversely, in stochastic formulations, the decision maker must devise a plan with incomplete information about the parameters, which can result in constraint violations once the actual values are obtained. For instance, the actual demand may surpass the capacity of the vehicle. Consequently, in stochastic formulations, the plan may be considered unsuccessful or “fail” when executed with the realized data.

A variety of methods can be employed to handle uncertainty within the framework of dynamic planning, including:

1. Stochastic programming (Demir et al., 2016; Guo et al., 2022a, 2021): Stochastic programming utilizes probability distributions to represent uncertainty in the model and use analytical techniques to integrate stochastic information into the optimization process (Sarasola et al., 2016).
    (a) Chance-constrained approach (Guo et al., 2021): Chance-constrained programming approach is used to solve problems by ensuring that the probability of route failure remains within an acceptable limit, while the associated costs of failures are often disregarded.
    (b) Stochastic programming with recourse approach (Li et al., 2010): The stochastic programming with recourse approach permits route failures but requires the decision-maker to define a course of action to rectify the solution following a failure. This approach optimizes the expected transportation cost, which accounts for both the travel cost and the cost associated with recourse policies.
2. Robust optimization (Li and Chung, 2020): Robust optimization is specifically designed to be robust against potential disruptions or changes in uncertain parameters. This approach involves finding solutions that are robust or resilient to a range of potential outcomes, rather than trying to optimize for a single, most likely scenario. In the context of synchromodal transport, this might involve developing plans that can adapt to a range of different demand and capacity scenarios.

Stochastic modeling-based approaches provide a formal framework for capturing the stochastic nature of the problem but can be complex to formulate and require efficient computation of complex expected values (Li et al., 2010). Sampling-based approaches can be employed within stochastic programming and robust optimization to generate scenarios based on random variable distributions and then solve the problem using a static and deterministic framework. The advantage of sampling-based approaches lies in their simplicity and flexibility with regard to distributional assumptions. However, the downside is the need for a large number of scenarios to represent actuality precisely. Techniques in machine learning are trained based on experience, either online or offline, and update the learned policy to make it more efficient in handling uncertainty. These techniques can be integrated within both stochastic and robust optimization frameworks to enhance the learning and adaptability of the models. In the context of synchromodal transport, the selection of an appropriate approach may depend on different factors, including but not limited to the degree of stochasticity in the input data and the complexity of the problem.

There are studies handling demand uncertainty. Rivera and Mes (2017) suggest a look-ahead planning approach for intermodal long-haul round-trips, considering the demand uncertainty. Travel time uncertainty is a significant factor that affects transportation efficiency. Various methods have been proposed to address uncertainty, including stochastic programming (Demir et al., 2016; Guo et al., 2021), Markov decision processes (Yee et al., 2021), and reinforcement learning (Guo et al., 2021). Some studies also regard travel times of trucks as time-dependent (Guo et al., 2020; Zhang et al., 2022b), as they can result from a variety of factors such as

Table 4
Summary of the literature review on dynamic synchromodal transport planning.

Article	Uncertainty	Re-planning	Learning	Required prior information	Approach
Xu et al. (2015)	Demand			Distribution	SP
Li et al. (2015)		Periodical		–	RHC
Van Riessen et al. (2016)	Demand	Event-trigger	Offline	Historical requests	DT
Demir et al. (2016)	Travel and service time, demand			Distribution	SAA
Hrušovskỳ et al. (2018)	Travel time				HSO
Qu et al. (2019)		Event-trigger		–	MIP
Uddin and Huynh (2019)	Capacity			–	CCP
Sun (2020a)	Demand and capacity			–	FST
Guo et al. (2020)	Demand	Periodical		–	RH
Yee et al. (2021)	Travel time	Periodical		–	MDP
Guo et al. (2021)	Demand and travel time	Periodical		Distribution	RH, SAA, CCP
Hrušovskỳ et al. (2021)	Unexpected events	Event-trigger		–	HSO
Sun (2022)	Capacity and price			–	FST, RPP
Guo et al. (2022a)	Demand	Periodical		Distribution	RH, SAA
Guo et al. (2022b)	Travel time	Periodical	Offline	Distribution	RL
Rivera and Mes (2022)	Demand	Periodical	Offline	Distribution	ADP
Xu et al. (2023)	Travel time			–	FST
Akyüz et al. (2023)	Disruption	Event-trigger		–	CG
Zhang et al. (2023)	Service time	Real-time	Online	None	RL, ALNS
Liu (2023)	Time-varying network		Offline	Dynamic freight train information	HEGA
Alaei et al. (2024)	Disruption	Event-trigger		Initial travel plan	AS

SP: stochastic programming; DT: Decision tree; RHC: Receding horizon control; SAA: Sample average approximation method; HSO: Hybrid simulation and optimization; MIP: mixed-integer programming; CCP: Chance constraint programming; FST: Fuzzy set theory; RH: Rolling Horizon; MDP: Markov decision process; RPP: Robust possibilistic programming; ADP: Approximate dynamic programming; RL: Reinforcement learning; CG: Column generation; ALNS: Adaptive Large Neighborhood Search; HEGA: Hummingbird Evolutionary Genetic Algorithm; AS: Agent-based Simulation
–: not mentioned or no information is required as uncertainty is not taken into account

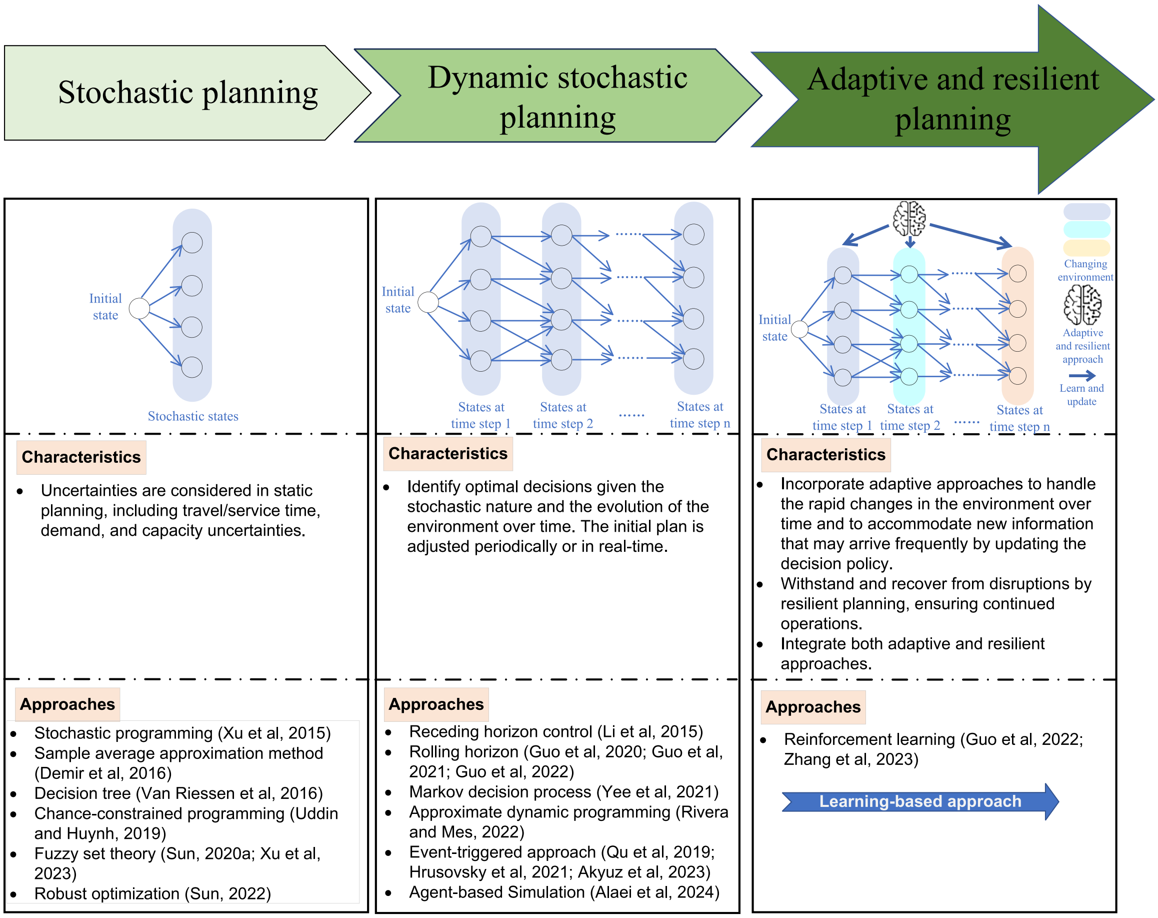
peaking hours and congestion. To model these time-dependent effects, commonly used approaches include travel-time or travel-speed functions (Gendreau et al., 2015). Most existing studies focus on travel time uncertainty on roads, railways, and waterways (Guo et al., 2020, 2021), while service time uncertainty in terminals has not received enough attention. Service time uncertainty at terminals is common due to unexpected events such as equipment failures and severe weather. However, few studies have proposed approaches to handle it (Lemmens et al., 2019).

It is worth noting that stochastic programming and robust optimization typically assume the availability of distribution information on uncertainty and modeling uncertainty through these distributions (Guo et al., 2022a). Similarly, offline machine learning also assumes the availability of such distribution or historic information (Van Riessen et al., 2016). However, in real-world situations, such distributional information may not be available due to various reasons, such as a lack of historical records, difficulty in capturing uncertainty patterns through a specific distribution, or complexity in modeling uncertainty caused by multiple factors. In such cases, online learning may be a suitable solution, because it allows updating the model based on the current observations and it can also adapt to changing conditions, which can reduce the risk of poor performance due to inaccurate assumptions about the uncertainty distribution. Other approaches, such as Fuzzy logic, can also handle uncertainty with limited historical data. For example, Sun (2020a) use fuzzy variables to characterize uncertain information, including demand and capacity.

4.4. Summary and future trends

Table 4 summarizes the literature on dynamic synchromodal transport planning. In the literature, travel time and demand uncertainties have been extensively investigated, however, the service time uncertainty has not been fully addressed. Neglecting service time uncertainty in planning and decision-making can lead to delays and increased costs, negatively impacting the overall performance of synchromodal transport. Service time uncertainty can be influenced by multiple factors and the distribution of service time uncertainty is usually not available, therefore online learning method is needed.

The field of dynamic stochastic planning encompasses both reactive and predictive approaches, which enable planners to respond to changing conditions in real time and anticipate future uncertainties. Reactive approaches respond to changes after they occur. The potential research avenues in reactive solution methods for synchromodal transport lie in devising efficient techniques to enhance system agility, improve solution quality, or tackle higher-dimensional optimization problems. For instance, the application of parallel algorithms and GPU computing for dynamic synchromodal transport planning is not explored in the literature, but could potentially enhance the responsiveness of the solution. Another research opportunity is to explore the potential of policy or value function approximations to optimize the responsiveness of reactive approaches. Upon review of the literature, it is apparent that there is a significant lack of research on prediction approaches in synchromodal transport planning (Larsen, 2022). Exploring the potential of different prediction methods, such as neural networks and regression (Moscoso-López et al., 2019; Huang et al., 2021a), could be a valuable research direction to enhance the accuracy and efficiency of synchromodal transport planning. However, such prediction methods can be highly intractable and it needs to develop efficient and approximate methods that can incorporate both stochastic



Stochastic planning

Characteristics

- Uncertainties are considered in static planning, including travel/service time, demand, and capacity uncertainties.

Approaches

- Stochastic programming (Xu et al, 2015)
- Sample average approximation method (Demir et al, 2016)
- Decision tree (Van Riessen et al, 2016)
- Chance-constrained programming (Uddin and Huynh, 2019)
- Fuzzy set theory (Sun, 2020a; Xu et al, 2023)
- Robust optimization (Sun, 2022)

Dynamic stochastic planning

Characteristics

- Identify optimal decisions given the stochastic nature and the evolution of the environment over time. The initial plan is adjusted periodically or in real-time.

Approaches

- Receding horizon control (Li et al, 2015)
- Rolling horizon (Guo et al, 2020; Guo et al, 2021; Guo et al, 2022)
- Markov decision process (Yee et al, 2021)
- Approximate dynamic programming (Rivera and Mes, 2022)
- Event-triggered approach (Qu et al, 2019; Hrusovsky et al, 2021; Akyuz et al, 2023)
- Agent-based Simulation (Alaei et al, 2024)

Adaptive and resilient planning

Characteristics

- Incorporate adaptive approaches to handle the rapid changes in the environment over time and to accommodate new information that may arrive frequently by updating the decision policy.
- Withstand and recover from disruptions by resilient planning, ensuring continued operations.
- Integrate both adaptive and resilient approaches.

Approaches

- Reinforcement learning (Guo et al, 2022; Zhang et al, 2023)

Fig. 9. The trend in dynamic planning.

information and prediction strategies. It is important to compare reactive and predictive re-optimization approaches, as carried out in the study by Ulmer et al. (2018), to obtain insights into which solution methods are more appropriate based on different situations.

The trend in dynamic planning is depicted in Fig. 9. It has evolved from static stochastic planning to dynamic stochastic planning, and is moving towards adaptive and resilient planning in the future. This evolution reflects a shift towards more complex and sophisticated planning strategies that can better handle uncertain and changing environments.

Adaptive dynamic stochastic planning relies on data-driven optimization and learning techniques to continuously update plans based on real-time data (Zhang et al., 2023). Data-driven optimization in OSTP refers to the use of data analytics and machine learning techniques to optimize the routing and scheduling of vehicles and shipments. This can involve collecting and analyzing data on various aspects of the transport process, such as demand patterns, capacity utilization, and travel times, in order to identify opportunities for improvement and to make more informed decisions about how to allocate resources and schedule shipments (Yee et al., 2021; Zhang et al., 2023). There are the following sub-research directions: (a) Predictive modeling for demand forecasting: Using large datasets collected from various sources (e.g., GPS tracking, social media, and e-commerce platforms), machine learning algorithms can be utilized to build predictive models for demand forecasting and allocate resources accordingly. (b) Real-time monitoring and optimization: The integration of real-time data from devices and sensors can be used to monitor the performance of the transport network in real time. (c) Network analysis and visualization: Big data analytics tools can be utilized to visualize and analyze the transport network, providing insights into the flow of goods, bottlenecks, and potential inefficiencies.

Adaptive planning focuses on the system’s ability to change and evolve in response to dynamic conditions and new information, while the main focus of resilient planning is to ensure that a system can withstand and recover from disruptions, whether they are anticipated or unexpected (Wan et al., 2018). Fig. 10 shows the performance of a resilient synchromodal transport system against disruptions at different stages. Resilient planning emphasizes the system’s ability to maintain functionality and quickly bounce back to normal operations after a disruption. Most studies in dynamic synchromodal transport planning still perform re-planning just after the Time of Disruption (TD) (Qu et al., 2019; Zhang et al., 2023). Some approaches incorporate stochastic planning before TD (Demir et al., 2016; Guo et al., 2021), but rarely do studies focus on planning after the Time of Onset (TO)

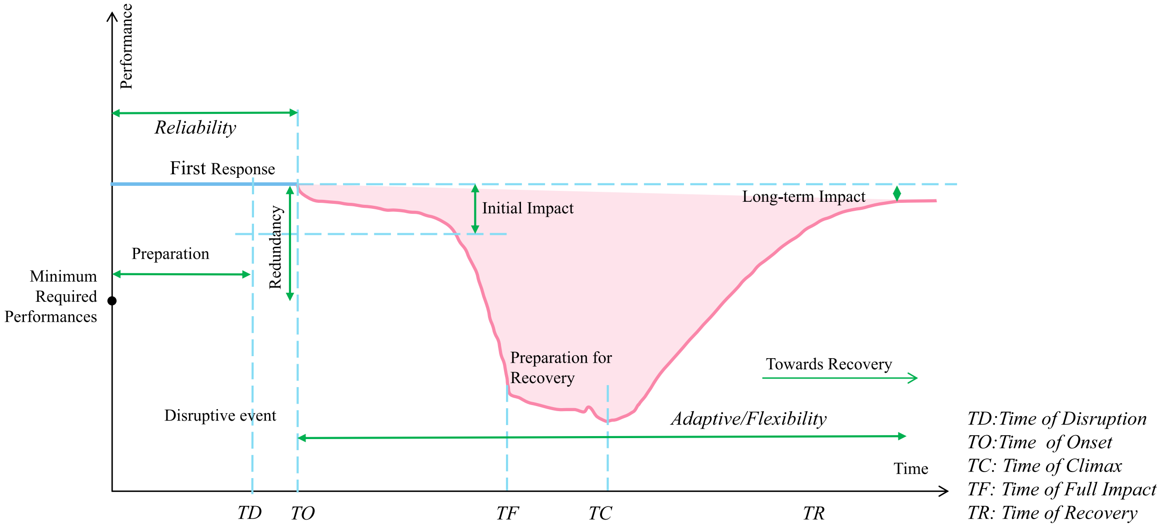


Fig. 10. Performance of a resilient synchromodal transport system against disruptions at different stages.
Source: Adapted from Wan et al. (2018)

of a disruption. Resilient planning goes beyond simply reacting to disruptions; it emphasizes the ability to withstand, adapt, and recover from unexpected disruptions while maintaining operations. Research in resilient synchromodal transport planning should explore strategies to maintain service continuity and quickly recover from disruptions. This involves not only optimizing response actions post-disruption but also developing robust plans that can endure disruptions with minimal performance degradation. This holistic approach to resilience, encompassing preemptive, real-time, and post-onset strategies, represents a significant advancement over traditional reactive and predictive planning methods. Another promising research direction is the integration of resilient and adaptive planning approaches. While resilient planning ensures system robustness and quick recovery from disruptions, adaptive planning enables continuous optimization and real-time adjustments to dynamic conditions. Exploring the synergies between these two approaches can significantly enhance the overall effectiveness and reliability of synchromodal transport planning.

5. Collaborative transport planning

Synchromodal transport that involves trains, barges, and trucks requires considerable coordination and cooperation (UNCTD, 2022). Collaborative planning in synchromodal transport involves carriers or/and shippers working together and sharing resources and information in order to optimize the delivery of goods. Collaborative planning can enable carriers to respond more effectively to changing demand and disruptions, as they can rely on each other for backup resources. It can also help to increase the range of services and improve service quality, as carriers can offer a wider variety of services by working together.

From a theoretical perspective, collaborative planning can be divided into three types: centralized planning, decentralized planning, and distributed planning (Negenborn and Maestre, 2014). If a controller has complete authority over all carriers, it is referred to as centralized planning. When carriers are in charge of the local transport planning and require no communication among them, it is decentralized planning. When the carriers communicate in order to find a cooperative solution for the overall planning, it is distributed planning. Distributed planning can be further classified based on the method of exchanging requests, such as non-auction or auction-based mechanisms (Gansterer and Hartl, 2018). There are various levels of cooperation between carriers, depending on the level of sharing information and resources and the establishment of joint partnerships.

Building on these foundational planning strategies, synchromodal transport also incorporates two distinct forms of collaboration in practice: horizontal and vertical collaboration. Horizontal collaboration involves carriers with overlapping networks who work together to enhance resource allocation efficiency and improve service frequency. This collaboration typically occurs at the same level within the transport chain, where stakeholders engage in activities like request exchange and capacity sharing to optimize transport resource use (Los et al., 2022; Dai et al., 2014). For instance, carriers might share vehicles and transportation requests to reduce empty runs and boost capacity utilization, leading to decreased transportation costs and potentially increased profits shared among the carriers. Vertical collaboration, in contrast, occurs between carriers operating at different tiers of the transport system and is often organized to synchronize the flow of shipments at interconnecting areas (Cleophas et al., 2019). An example of this could be coordinating the pickup and delivery of shipments between carriers on different continents within global synchromodal transport systems. This type of collaboration facilitates efficient and seamless transfers between various modes of transportation.

Current research on collaborative planning mainly focuses on vertical collaboration for carriers with interconnecting transport networks. Puettmann and Stadtler (2010) study decentralized planning of carriers through iterative proposal exchange, analyzing stochastic demand on coordinated plans. Li et al. (2017) investigate a coordinated container flow problem among hinterland carriers

Table 5
Summary of the literature review on collaborative planning in synchromodal transport.

Article	Participants	Category	Approach	Preferences	Information sharing
Puettmann and Stadtler (2010)	Drayage and intermodal carriers	VC	DP, IE		Proposal
Di Febbraro et al. (2016)	Customer and supplier	VC	DIP, LA		Due dates/delivery dates
Li et al. (2017)	Intermodal carriers	VC	DIP, MPC, ALR, ADMM		Container transport plan, volumes of container flows
Munim and Haralambides (2018)	Port operators	VC	CP, MILP		Transhipment capacity total transhipment demand
Huang et al. (2021b)	Intermodal carriers	VC	DIP, MPC		Real-time container number
Zhang et al. (2022c)	Intermodal/unimodal carriers	HC	ADP, ALNS	✓	requests
Zhou et al. (2023)	Intermodal carriers	VC	DIP, MPC, ADMM		Monitoring data of channels and terminals, transport time/cost, forecasted demand
Larsen et al. (2023a)	Logistics service providers and flexible service operators	VC	RHF, MPC, DP		Request, real-time information
Larsen et al. (2023b)	Truck operators and barge operators	VC	MPC, CP		Departure schedules, operational costs
Yuan et al. (2023)	Multimodal carriers and operators	HC	ADP, ESS, ABSH		Transport orders
Guo et al. (2024)	Local/global operators	HC, VC	ALR, HA, RHF, BS		Request, transport orders

VC: Vertical collaborative planning; HC: Horizontal collaborative planning; CP: Centralized planning; DP: Decentralized planning; DIP: Distributed planning; ADP: Auction-based distributed planning; IE: Information exchange mechanism; LA: Lagrangian-based approach; MPC: Model Predictive Control; MILP: Mixed Integer Linear Programming; ALR: Augmented Lagrangian Relaxation; ALNS: Adaptive Large Neighborhood Search; ADMM: Alternating Direction Method of Multipliers; HA: Heuristic Algorithm; RHF: Rolling Horizon Framework; BS: Buffer Strategy; ESS: Evolutionary Stability Strategy; ABSH: A*-Based Search Heuristic.

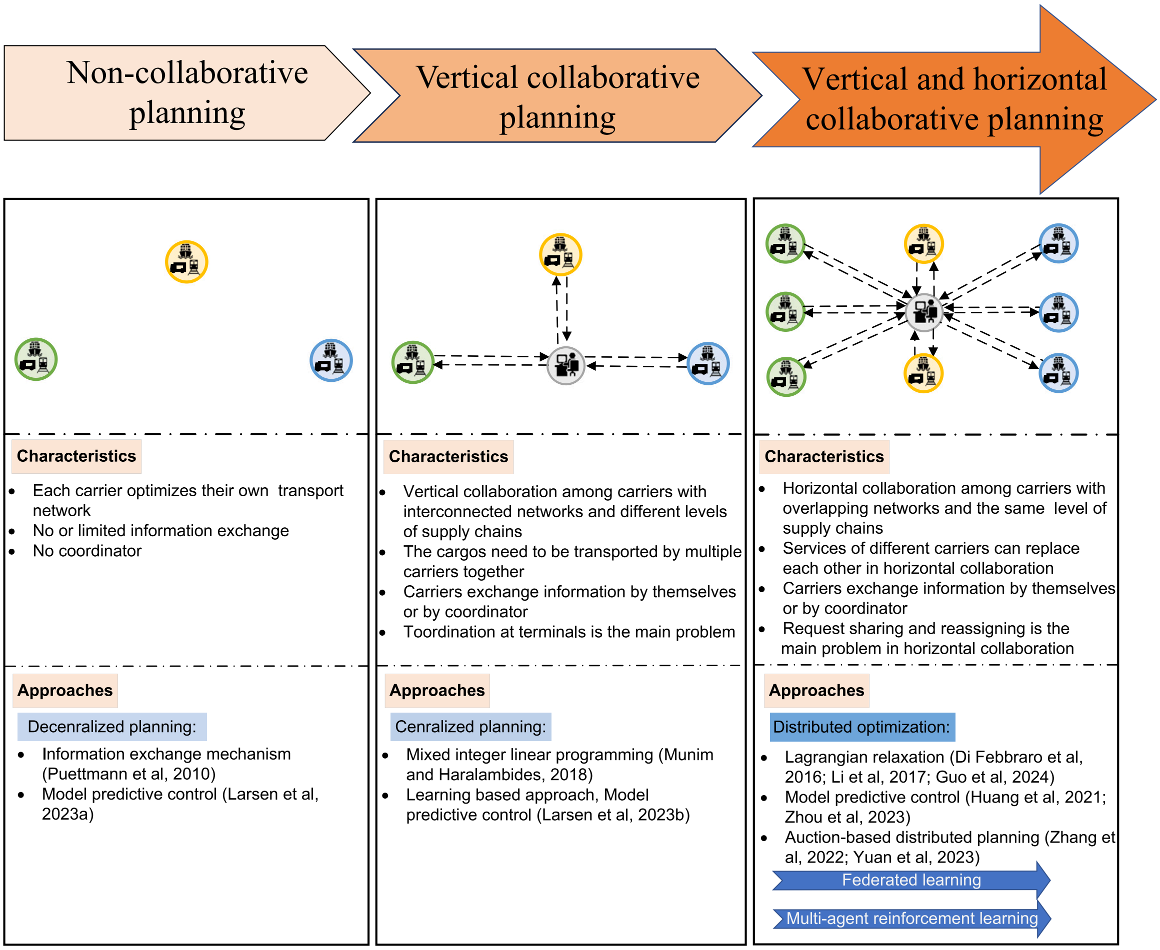
in interconnected service areas. The Lagrangian relaxation method is used for the coordination among carriers. Guo (2020), Huang et al. (2021b) and Zhou et al. (2023) use a similar coordination method as Li et al. (2017). Guo (2020) considers requests with temporal constraints instead of container flows in Li et al. (2017). Larsen et al. (2020) propose a departure learning method for co-planning between barge and truck carriers. Studies have shown that collaboration can lead to significant performance improvements in synchromodal transport, such as cost savings (Guo, 2020). Guo et al. (2024) propose an augmented Lagrangian relaxation-based coordinated approach for global synchromodal transport planning involving multiple operators. In this approach, a global operator offers incentives to local operators to choose the most efficient modes and routes for transporting containers across continents. The distributed method outlined by Guo et al. (2024) allows local operators to share only limited information, enabling them to achieve a common goal without compromising their individual benefits. Collaborative planning can enable carriers to share resources and information, such as equipment, routes, and demand forecasts, and to reduce empty runs and duplication of services. Collaborative planning can also facilitate the integration of multiple transport modes and the coordination of transshipment operations, which can optimize the resource allocation and the flexibility of the transport system.

Although horizontal collaboration is essential in synchromodal transport, it has not yet received an adequate level of attention in the existing literature for synchromodal transportation compared to vertical collaboration. Zhang et al. (2022e) explore a multi-depot collaborative VRP, incorporating transshipment at both customer locations and depots. Zhang et al. (2022c) investigate a collaborative approach that enables carriers to exchange shipment orders through an auction-based system. They also compare this proposed method with centralized and non-collaborative approaches using real data from multiple transport networks in Europe.

5.1. Summary and future trends

Table 5 summarizes the literature review on collaborative planning in synchromodal transport. Only 11 papers among 57 papers-which is about 19%-consider collaborative planning, which shows the potential of this research direction. Horizontal collaborative planning and auction-based distributed planning need to be investigated more in synchromodal transport. The studies on collaborative planning rarely consider preferences, although collaborative planning can also better satisfy the preferences of stakeholders. It can help carriers offer a wider range of services to shippers and meet their diverse preferences. This can increase the attractiveness of synchromodal transport to shippers, as it provides them with more options and the possibility of finding a service that better fits their needs.

The trend in collaborative planning is illustrated in Fig. 11. It has evolved from non-collaborative planning to distributed collaborative planning, and is expected to further develop into a combination of vertical and horizontal collaborative planning in the future. There is more research on collaborative planning in road transport, compared to synchromodal transport (Gumuskaya et al., 2020). In the field of road transportation, researchers frequently investigate the concept of horizontal collaboration. Within this area of study, the auction-based approach is a commonly utilized methodology (Los et al., 2022). Auction-based collaborative planning refers to the use of auctions as a means to exchange requests among carriers. Auctions can provide a transparent and fair



Characteristics

- Each carrier optimizes their own transport network
- No or limited information exchange
- No coordinator

Approaches

Decenralized planning:

- Information exchange mechanism (Puettmann et al, 2010)
- Model predictive control (Larsen et al, 2023a)

Characteristics

- Vertical collaboration among carriers with interconnected networks and different levels of supply chains
- The cargos need to be transported by multiple carriers together
- Carriers exchange information by themselves or by coordinator
- Toordination at terminals is the main problem

Approaches

Cenralized planning:

- Mixed integer linear programming (Munim and Haralambides, 2018)
- Learning based approach, Model predictive control (Larsen et al, 2023b)

Characteristics

- Horizontal collaboration among carriers with overlapping networks and the same level of supply chains
- Services of different carriers can replace each other in horizontal collaboration
- Carriers exchange information by themselves or by coordinator
- Request sharing and reassigning is the main problem in horizontal collaboration

Approaches

Distributed optimization:

- Lagrangian relaxation (Di Febbraro et al, 2016; Li et al, 2017; Guo et al, 2024)
- Model predictive control (Huang et al, 2021; Zhou et al, 2023)
- Auction-based distributed planning (Zhang et al, 2022; Yuan et al, 2023)

Fig. 11. The trend in collaborative planning.

platform for carriers to negotiate and agree on terms for the provision of transport services. By allowing carriers to bid for requests from shippers and to offer their available capacity, auctions can facilitate the matching of demand and supply, leading to increased efficiency and improved utilization of resources. Furthermore, auctions can enable carriers to diversify their portfolio of services by making use of shared services from other carriers.

Most research papers in synchromodal transport have a strong focus on collaborations between carriers (Zhang et al., 2022c). However, it is important to note that shippers can also conduct horizontal collaborations to improve efficiency in the transportation process. In this case, shippers work together to identify sets of lanes that can be bundled together and offered to carriers as an attractive package, reducing the need for asset repositioning and leading to more favorable rates for the shippers. However, information asymmetries between shippers and carriers in decentralized settings must be taken into account, emphasizing the need to differentiate between carrier and shipper collaborations and choose the appropriate type of collaboration based on the specific circumstances.

In collaborative planning for synchromodal transport, information sharing plays a crucial role in achieving efficient and effective coordination among collaborators. The value of information can vary depending on the nature of the information and the type of collaboration. For example, carriers may have customers whose information they cannot share due to confidentiality agreements. However, they may have other information that can be exchanged with their collaborators to facilitate better planning and coordination. In such cases, the value of information lies in its ability to enable better decision-making and planning, resulting in improved operational efficiency and reduced costs. Besides customer information, other critical information that can add value to collaborative planning includes data on transportation routes, capacity, delivery times, and prices. Collaborators who have access to such information can make more informed decisions and better align their transportation strategies to maximize efficiency and reduce costs. The value of information is not just restricted to the type of information exchanged but also extends to the timing and accuracy of the information. Timely and accurate information can help collaborators respond quickly to changing market conditions, reduce lead times, and improve service quality. It is worth investigating how the central authority can incentivize participants to share their data. This can be achieved by employing profit-sharing approaches or side payments. To address these

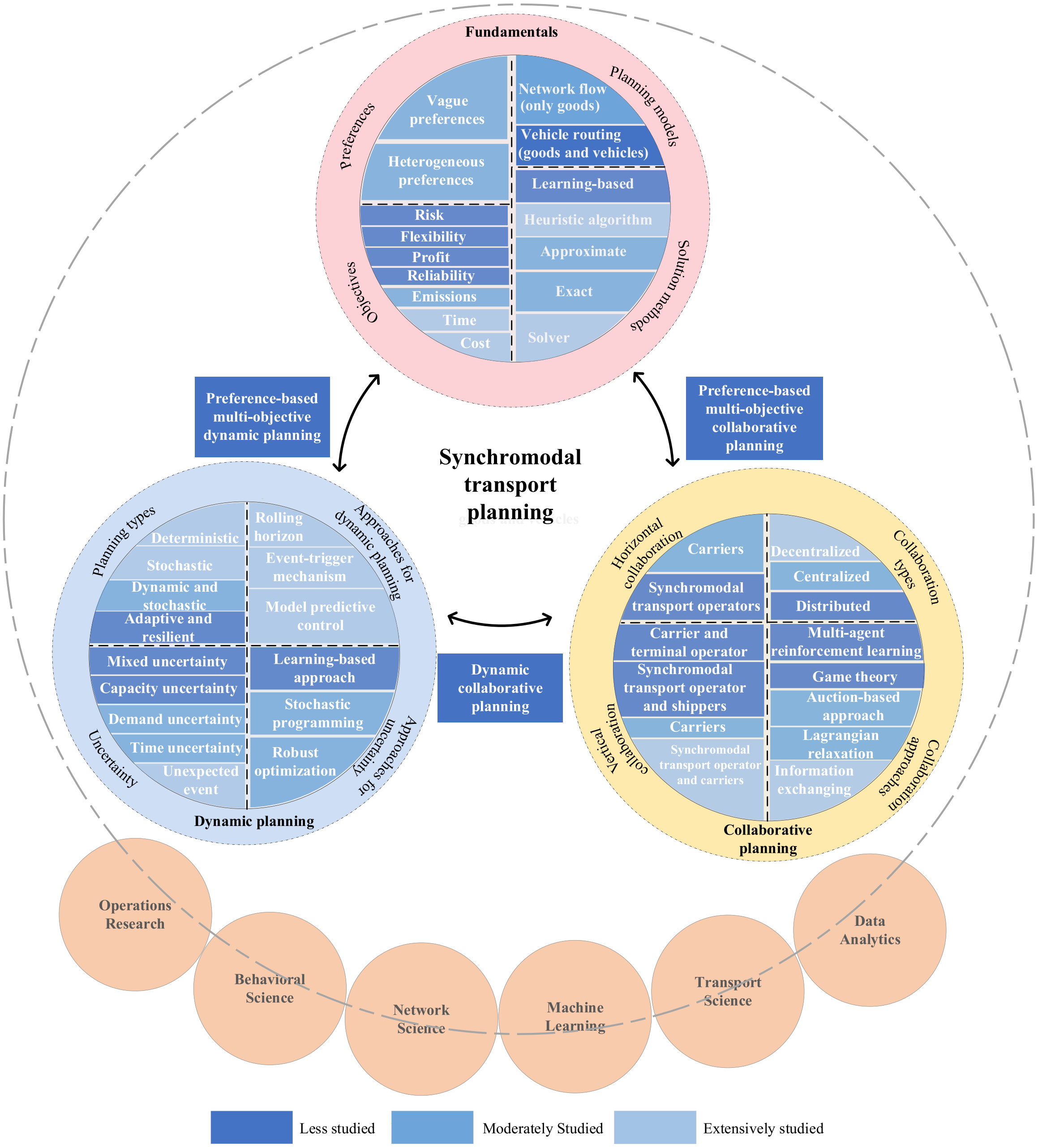


Fig. 12. The roadmap of operational synchromodal transport planning.

issues, investigations analyzing the degree of information revelation required to achieve reasonable collaboration profits would be beneficial.

In collaborative synchromodal transport, it is important to determine how to distribute the benefits gained from collaboration among the participants. Identifying a fair distribution mechanism can incentivize carriers to participate in the collaboration. Cooperative game theory-based sharing methods are commonly used in collaborative transportation problems, as identified by Guajardo and Rönnqvist (2016), who categorize over 40 different methods. However, they show that the Shapley value, proportional methods, and the nucleolus method are the most commonly employed methods.

6. Roadmap for operational synchromodal transport planning methodologies

After reviewing the literature, we identify key themes and methodologies that have been explored in previous studies, as well as potential future research directions. These are illustrated in the roadmap shown in Fig. 12. The classification of research in this field

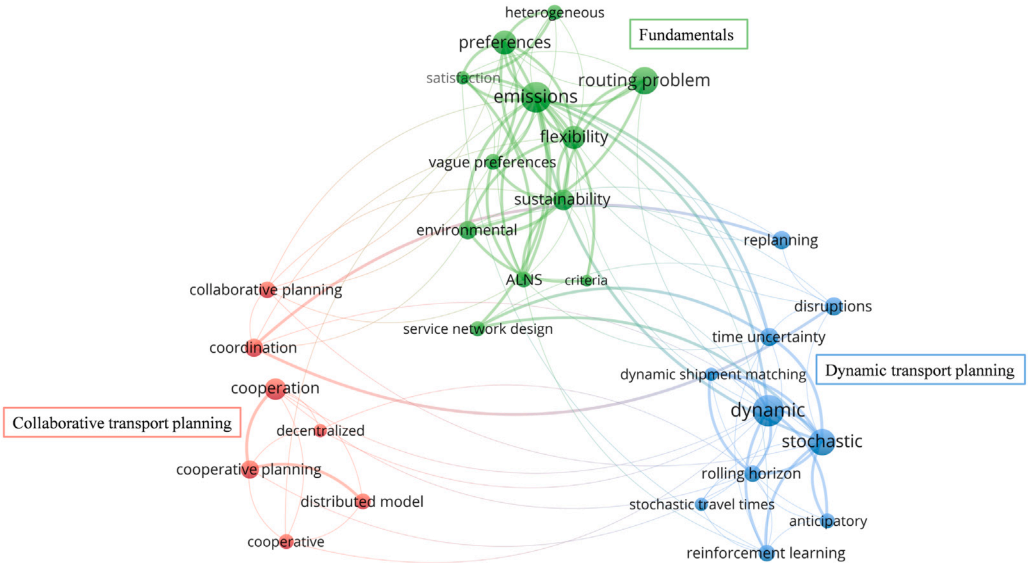


Fig. 13. The frequency of keywords in each category and their co-occurrences.

spans three main areas: fundamentals of planning, dynamic transport planning, and collaborative planning. Fundamentals form the base that supports the other two planning categories, which are interrelated and can be integrated. Each category is analyzed based on the extent of study: less studied, moderately studied, and extensively studied.

Starting with the fundamentals, research has evolved from focusing solely on goods to including both goods and vehicles. This shift is reflected in the transition from network flow models to vehicle routing models. In multi-objective and preference-based planning, while cost, time, and emissions have been primary focuses, future studies could consider additional attributes such as reliability, profit, flexibility, and risk. The varying preferences of different stakeholders have not been deeply explored, nor has the use of interactive methods within this domain. Methodologically, there is a noticeable trend moving from traditional solvers and heuristic algorithms to learning-based approaches, with both exact and approximate methods remaining critical areas for future exploration.

Dynamic planning studies that account for capacity and mixed uncertainties are sparse. The application of learning-based methods to address these uncertainties is an emerging area that promises further exploration. The field is progressively shifting towards more adaptive and resilient frameworks, moving beyond traditional dynamic and stochastic models.

Collaborative planning has seen extensive research in the cooperation among carriers and between synchromodal transport operators and carriers. However, collaboration involving multiple synchromodal transport operators, between synchromodal transport operator and shippers, as well as between carriers and terminal operators, remains less explored. The use of distributed collaborative planning, especially leveraging Game Theory and Multi-agent Reinforcement Learning, presents significant opportunities for advancement.

The above delves into the research directions in the domains of planning fundamentals, dynamic planning, and collaborative planning. These studies, while categorized distinctly, exhibit considerable interconnections, as illustrated in Fig. 13. The word frequencies of the titles, abstracts and keywords of the reviewed literature are counted and representative terms with a word frequency of no less than 4 in each category are selected. Larger nodes represent higher word frequencies. The strength of the connection between nodes is determined by the number of co-occurrences between terms. The greater the total number of documents in which two terms co-occur, the stronger their connection strength becomes. This figure visualizes the relationships and overlaps among the categories, with lines linking terms across these different sections. It is particularly noteworthy that several studies integrate multiple planning approaches, highlighting a crucial direction for future research. We summarize these research directions below:

1. Preference-based multi-objective dynamic planning: In dynamic planning, considering objectives and preferences is crucial for stakeholders who have strong priorities. For instance, reliability is crucial for carriers aiming to avoid delays caused by disturbances and disruptions. However, this task is complex due to the constantly changing operating environment. The selection of the optimal service that adheres to the reliability requires the ability to accurately recognize and respond to the changing conditions caused by uncertainty. Applying dynamic programming algorithm to address the optimal freight routing problem with two objective functions, Cho et al. (2012) quantitatively measure the savings in transport cost and time by comparing single transport mode with intermodal transport paths. Demir et al. (2016) introduce a stochastic approach considering travel time uncertainty for combined offline intermodal routing decision with the objective function minimizing

the total weighted cost, which reflects individual preferences regarding direct transportation, time-related and emission-related costs. Li et al. (2023) propose a combination of the weighted sum method and the collaborative game theory, namely the weights of each objective can be dynamically adjusted in the process of algorithm optimization based on the cooperative game theory.

2. Collaborative planning considering objectives and preferences: Developing a multi-agent system that considers the preferences and objectives of multiple stakeholders is a promising research direction. The stakeholders may have both cooperative and competitive relationships, and game theory could be used to model and analyze these interactions. Such a system could provide a more comprehensive view of the synchromodal transport ecosystem, and could help to identify more efficient and sustainable solutions that take into account the needs and preferences of all involved parties. In the context of collaboration among carriers for serving shippers' requests with preferences, it is necessary to design suitable collaborative planning mechanisms to ensure that unsatisfied requests are forwarded to the appropriate carriers efficiently according to their available resources. For shippers' preferences related to carbon emissions, Zhang et al. (2022c) use fuzzy set to describe vague preferences and consider constraints that assure the preferences are met under auction-based collaborative planning.
3. Collaborative and dynamic planning under uncertainty: Collaborative planning studies often assume deterministic scenarios, with little literature on collaboration potential under uncertainties. Collaboration with partners can be helpful in handling uncertainty. For example, carriers can collaborate to handle uncertainty and learn from each other by sharing their experience. Even a carrier that starts later than others could apply the matured model directly without training by leveraging the shared experiences of other carriers. Some studies formulate the cooperative intermodal/synchromodal transport planning as a cooperative model predictive container flow control problem, and solve it with Model Predictive Control (MPC) or Distributed MPC approaches (Li et al., 2017; Huang et al., 2021b; Zhou et al., 2023). This type of approach requires real-time information as input and generates flow control decision for containers. Based on MPC, Larsen et al. (2023b) develop a departure learning method between a truck operator and a barge operator exchanging expected cost and a number of potential schedules. Moreover, a co-planning method using a rolling horizon between a logistics service provider and a flexible service operator in real-time is proposed by Larsen et al. (2023a) with dynamic information exchange. Alaei et al. (2024) consider centralized and decentralized collaboration between different logistics service providers. They employ an agent-based simulation approach to address travel time uncertainty. Guo et al. (2024) address travel time uncertainties and dynamic requests for multiple operators in global synchromodal transport using an augmented Lagrangian relaxation approach.

In addition to integrating various planning approaches at the operational level, some researchers have also combined strategic, tactical and operational planning of synchromodal logistics including both transshipment, location and routing decisions. Giusti et al. (2021a) study the multi-period transshipment location–allocation problem and explore the impact of uncertainty about the facility capacity and handling operations utility. Crainic et al. (2021) display a Mixed-Integer Linear programming method for the synchronized location-transshipment problem and emphasize the precise demand fulfillment for the cross-docking operations. Giusti et al. (2023) propose a time-space network representation of the synchronized multi-commodity multi-service transshipment-hub location problem. Especially, a new paradigm called smart steaming for ship movement is proposed, which provides a real-time solution for overcoming the existing limitations of synchromodal logistics (Giusti et al., 2021b). With regard to collaborative platforms, the synchronization and smart steaming become two critical problems in SYNCHRO-NET approach (Giusti et al., 2018). This approach aims to offer stakeholders an integrated and cloud-based platform to implement real-time decisions from strategic to operational level (Giusti et al., 2019a). Integration of different planning levels is also a promising direction for future research.

The roadmap enables scholars and synchromodal transport operators to navigate the extensive literature on OSTP, highlighting current best practices and future trends. Given the rapid pace of change and innovation in the transport industry, keeping up-to-date with the latest developments is crucial. The roadmap offers a comprehensive and organized overview of the field, providing a useful resource for those seeking to deepen their understanding of OSTP and its implementation. By synthesizing current knowledge and identifying areas for future research, the roadmap promotes innovation in synchromodal transport planning and advances the field. Its emphasis on recognizing interconnectivity between existing research promotes cross-disciplinary collaboration and knowledge exchange, enabling integration and leveraging of previous research towards more effective and efficient approaches. Furthermore, the roadmap offers a flexible and adaptable framework for OSTP that can be customized to different transport contexts.

7. Conclusions

Synchromodal transport planning has been studied by researchers in recent years as a way to improve the efficiency and sustainability of transport systems. At the operational level, there are several aspects of synchromodal transport planning that have been addressed in the literature, including synchromodal transport planning fundamentals, dynamic transport planning under uncertainty, and collaborative transport planning. This review provides a summary and evaluation of the current state of research on synchromodal transport planning at the operational level. By examining existing literature, we identify key insights and best practices in the field, as well as areas for further exploration and development. We also propose roadmaps for future research in each area, outlining potential avenues for advancing knowledge and practice in synchromodal transportation planning. The roadmap for operational synchromodal transport planning methodologies offers a structured overview of the field, summarizing key themes and research directions. It emphasizes the integration and interconnectivity of planning fundamentals, dynamic planning, and collaborative planning, promoting cross-disciplinary collaboration to foster innovation and advance operational synchromodal transport planning practices.

In terms of synchromodal transport planning fundamentals, we have discussed different types of planning models and emphasized the importance of flexibility in enabling synchromodal transport to adapt to changing demands and disruptions. We have also reviewed how preferences are modeled and considered in synchromodal transport, and the benefits of taking preferences into account in transport planning. In terms of dynamic planning, we have discussed the importance of handling uncertainty in order to achieve reliable synchromodal transport. We have also reviewed the methods that can be used to handle travel time, service time, and demand uncertainties. Finally, in terms of collaborative planning, we have discussed the importance of collaboration in enabling synchromodal transport to provide a wider range of services and satisfy the preferences of stakeholders. We have also reviewed the different approaches to collaborative planning, including centralized, decentralized, and distributed approaches, and the benefits that can be obtained through collaboration.

The review of the literature has shown that synchromodal transport planning can benefit from various methodologies developed in the field of vehicle routing, machine learning, and multi-agent systems. In research on synchromodal transport planning fundamentals, synchromodal transport can utilize vehicle routing techniques to optimize the routes and schedules of both goods and vehicles. In dynamic optimization under uncertainty, synchromodal transport can utilize approaches such as robust optimization and stochastic programming, as well as leverage machine learning techniques to manage uncertainty in real time. In collaborative transport planning, synchromodal transport can benefit from techniques in multi-agent systems to facilitate cooperation and coordination among different transport actors. Overall, synchromodal transport planning can significantly benefit from the advances and developments in other fields in order to optimize the routing and scheduling of synchromodal transport services.

CRediT authorship contribution statement

Yimeng Zhang: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Xiangrong Tan:** Writing – review & editing, Writing – original draft, Visualization. **Mi Gan:** Supervision, Funding acquisition. **Xiaobo Liu:** Supervision, Funding acquisition. **Bilge Atasoy:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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