Connecting Europe through Intermodal Transportation – Building Efficient Networks and Embracing Digitalization

Department of Law and Economics
Chair of Management and Logistics

TECHNISCHE UNIVERSITÄT DARMSTADT

submitted in fulfillment of the requirements for the degree of
Doctor rerum politicarum (Dr. rer. pol.)

Dissertation
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Darmstadt 2024

Rentschler, Johannes: Connecting Europe through Intermodal Transportation –
Building Efficient Networks and Embracing Digitalization
Darmstadt, Technische Universität Darmstadt,
Year thesis published in TUprints 2025
Date of the viva voce 13.12.2024

Danksagung

Meine Dissertation ist das Ergebnis einer langen und anspruchsvollen Reise, die ohne die Unterstützung zahlreicher Personen nicht möglich gewesen wäre. An dieser Stelle möchte ich meinen Dank aussprechen.

Zuallererst gebührt mein aufrichtiger Dank meinem Doktorvater, Herrn Prof. Dr. Ralf Elbert, für seine unermüdliche Betreuung, sein fachliches Engagement und sein Vertrauen in meine Arbeit. Seine Anleitung und Ermutigung haben mir nicht nur geholfen, fachlich zu wachsen, sondern auch persönlich. Ebenfalls möchte ich mich bei meinem Zweitgutachter, Prof. Dr. Gunnar Stefánsson, für die Übernahme des Zweitgutachtens bedanken.

Ein besonderer Dank gilt meinen geschätzten Kollegen und Kolleginnen, deren Unterstützung und Zusammenarbeit mein wissenschaftliches Arbeiten und auch mein persönliches Leben bereichert haben. Insbesondere möchte ich Roland Lehner, Julia Wenzel und Jan Philipp Müller für ihre wertvolle Hilfe und ihre inspirierenden Gespräche danken, die meinen Forschungsprozess positiv beeinflusst haben. Weiterer Dank gilt Aylin Altun, Paul Bossong, Anne Friedrich, Christian Friedrich, Michael Gleser, Raphael Hackober, Ren Kajiyama, Jan-Karl Knigge, Tessa Sarnow, Jessica Schwarz, Yuerui Tang, Hongjun Wu, Eva Hartmann, Sabrina Merzenich, Alexandra Vianden und allen weiteren Kolleg:innen.

Des Weiteren möchte ich meine Wertschätzung gegenüber meiner Familie, insbesondere meiner Mutter Karin und meinen Geschwistern Anne und Frieder, zum Ausdruck bringen. Ihre fortwährende Unterstützung, Ermutigung und Liebe haben mir stets Kraft gegeben, auch in den herausforderndsten Momenten meiner akademischen Reise.

Abschließend möchte ich mich bei allen weiteren Personen bedanken, die mich auf meinem Weg begleitet und unterstützt haben. Ihre Hilfe hat dazu beigetragen, dass diese Dissertation erfolgreich abgeschlossen werden konnte.

Abstract

Intermodal transportation refers to the movement of goods in one and the same loading unit, which uses successively two or more modes—such as rail, road, and maritime—without handling the goods themselves in changing modes. This approach capitalizes on the strengths of each transportation mode, optimizing efficiency, cost-effectiveness, and environmental sustainability. This dissertation investigates continental intermodal transportation in Europe. It thereby focuses on the configuration of intermodal transportation networks and the transformative impact of digitalization. The European intermodal transportation market, characterized by diverse actors, varying laws, and non-standardized processes, presents distinctive challenges. These differences necessitate tailored approaches to address unique circumstances effectively. Given this complexity, multiple research methodologies on different planning levels are employed to systematically explore the structural configuration of transportation networks and the impact of digitalization. Qualitative methods, such as case studies and expert interviews, complement quantitative models by providing contextual and experiential insights and practical knowledge from industry professionals and stakeholders. Case studies are particularly suitable for analyzing the European intermodal transportation market. They allow for in-depth exploration of specific contexts, capturing nuances that broader methods might miss, providing a nuanced understanding of intermodal transportation systems, and helping to develop actionable solutions.

The main body of this dissertation is based on five research papers. The first two papers investigate the structural configuration of intermodal transportation networks and its impact on overall system performance. By integrating strategic hub location and tactical service network design models, the research provides deeper insights into network structure, leading to optimized configurations that enhance efficiency and reduce costs. A case study involving a German intermodal operator demonstrates that this integration leads to more realistic and efficient network designs, considering economies of scale and density. In the third paper, the feasibility and benefits of continental intermodal transportation as a possible solution for connecting Asia and Europe are studied. The qualitative analysis of the Trans-Caspian Corridor through interviews with logistics companies and political authorities revealed the intricate geopolitical and strategic challenges influencing the corridor's development.The fourth paper focuses on ETA forecasts in the pre-and post-haulage of intermodal transportation. Digitalization and real-time data significantly improve operational processes in intermodal transportation by enhancing visibility and enabling dynamic adjustments to routing and scheduling. A simulation study shows that ETA forecasts lead to an average cost reduction of 7%. The fifth paper investigates how digitalization drives the evolution of intermodal transportation towards synchromodal transportation, where different transportation modes are seamlessly integrated, providing flexible and adaptive real-time solutions. The integration of digital technologies such as IoT, blockchain, and AI further supports this transition, offering advanced tools for real-time monitoring, data analytics, and decision-making.

The findings of this dissertation contribute to both academic knowledge and practical applications, providing valuable insights for policymakers, industry stakeholders, and researchers in the field of intermodal transportation.

Zusammenfassung

Intermodaler Transport bezeichnet den Transport von Gütern in ein und derselben Ladeeinheit Dabei werden nacheinander zwei oder mehr Verkehrsträger– wie Schiene, Straße und Seeverkehr – genutzt ohne dass die Güter selbst beim Wechsel der Verkehrsträger umgeladen werden. Dieser Ansatz nutzt die Stärken jedes Verkehrsträgers und optimiert so die Effizienz, Wirtschaftlichkeit und Umweltverträglichkeit. Diese Dissertation untersucht den intermodalen Transport in Europa. Dabei konzentriert sie sich auf die Konfiguration intermodaler Transportnetze und die transformative Wirkung der Digitalisierung. Der europäische intermodale Transportmarkt, der durch unterschiedliche Akteure, verschiedene Gesetze und nicht standardisierte Prozesse gekennzeichnet ist, stellt besondere Herausforderungen dar. Diese Unterschiede erfordern maßgeschneiderte Ansätze, um den besonderen Umständen effektiv gerecht zu werden.

Angesichts dieser Komplexität werden mehrere Forschungsmethoden auf verschiedenen Planungsebenen eingesetzt, um die strukturelle Konfiguration von Verkehrsnetzen und die Auswirkungen der Digitalisierung systematisch zu untersuchen. Qualitative Methoden wie Fallstudien und Experteninterviews ergänzen quantitative Modelle, indem sie kontextbezogene und empirische Einblicke und praktisches Wissen von Branchenexperten und Interessengruppen liefern. Fallstudien eignen sich besonders gut für die Analyse des europäischen intermodalen Verkehrsmarktes. Sie ermöglichen eine eingehende Untersuchung spezifischer Zusammenhänge, erfassen Nuancen, die breitere Methoden möglicherweise übersehen, und vermitteln ein differenziertes Verständnis intermodaler Transportsysteme und helfen bei der Entwicklung umsetzbarer Lösungen.

Der Hauptteil dieser Dissertation basiert auf fünf Forschungsarbeiten. Die ersten beiden Arbeiten untersuchen die strukturelle Konfiguration intermodaler Verkehrsnetze und ihre Auswirkungen auf die Gesamtleistung des Systems. Durch die Integration strategischer Modelle für die Standortwahl von Knotenpunkten und taktischer Modelle für die Gestaltung von Servicenetzwerken bietet die Forschung tiefere Einblicke in die Netzwerkstruktur, was zu optimierten Konfigurationen führt, die die Effizienz steigern und die Kosten senken. Eine Fallstudie mit einem deutschen intermodalen Operateuren zeigt, dass diese Integration zu realistischeren und effizienteren Netzwerkdesigns führt, die Skaleneffekte und Dichte berücksichtigen.

In der dritten Arbeit werden die Durchführbarkeit und die Vorteile des intermodalen Transports als mögliche Lösung für die Verbindung zwischen Asien und Europa untersucht. Die qualitative Analyse des transkaspischen Korridors durch Interviews mit Logistikunternehmen und politischen Behörden ergab, dass die Entwicklung des Korridors durch komplexe geopolitische und strategische Herausforderungen beeinflusst wird.

Der vierte Beitrag konzentriert sich auf ETA-Prognosen im Vor- und Nachlauf des intermodalen Transports. Durch die Digitalisierung und Echtzeitdaten werden die Betriebsabläufe im intermodalen Transport erheblich verbessert, da die Transparenz erhöht und dynamische Anpassungen der Streckenführung und der Zeitplanung ermöglicht werden. Eine Simulationsstudie zeigt, dass ETA-Prognosen zu einer durchschnittlichen Kostensenkung von 7% führen.

Der fünfte Artikel untersucht, wie die Digitalisierung die Entwicklung des intermodalen Verkehrs hin zum synchromodalen Verkehr vorantreibt, bei dem verschiedene Verkehrsträger

nahtlos integriert werden und flexible und anpassungsfähige Echtzeitlösungen bereitgestellt werden. Die Integration digitaler Technologien wie IoT, Blockchain und KI unterstützt diesen Übergang weiter und bietet fortschrittliche Tools für die Echtzeitüberwachung, Datenanalyse und Entscheidungsfindung.

Die Ergebnisse dieser Dissertation tragen sowohl zum akademischen Wissen als auch zu praktischen Anwendungen bei und bieten wertvolle Erkenntnisse für politische Entscheidungsträger, Branchenbeteiligte und Forscher im Bereich des intermodalen Verkehrs.

Content Overview

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List of Abbreviations

BRA	Biased Randomized Algorithm
BRI	Belt and Road Initiative
C-HL-SNDP	Combined Hub Location and Service Network Design
EU	European Union
ETA	Estimated Time of Arrival
GHG	Greenhouse Gas
HLP	Hub location problem
ICT	Information and Communications Technology
IoT	Internet of Things
IP	Integer Program
ISO	International Organization for Standardization
ITU	Intermodal Transport Unit
LSP	Logistics Service Provider
MCS	Monte Carlo Simulation
MIP	Mixed-Integer Program
NFP	Network Flow Planning
OR	Operations Research
PDP	Pick-up and Delivery Problem
PDPTW	Pick-up and Delivery Problem with Time Windows
PDPTW-crd	Pick-up and Delivery Problem with Time Windows and clustered release dates
PPH	Pre-and Post-Haulage
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
RP	Research Propositions
RQ	Research Questions
SLR	Systematic Literature Review
SMT	Synchromodal Transportation
SNDP	Service Network Design Problem
TCC	Trans-Caspian Corridor
TEN-T	Trans-European Transportation Network
TEU	Twenty-foot Equivalent Unit
VRP	Vehicle Routing Problem
3PL	Third-Party Logistics Providers
4PL	Fourth-Party Logistics Providers
5PL	Fifth-Party Logistics Providers

1 Introduction

“The Box that Changed the World”

Arthur Donovan, 2006

The invention of the standardized shipping container has fundamentally altered global trade. As discussed by Professor Donovan in his interview on "How Cargo Containers Shrank the World and Transformed Trade," the container, or "The Box," enabled the seamless movement of goods across different transportation modes—truck, ship, and rail—without the need for repacking (Mirsky, 2007). This innovation drastically reduced loading times, minimized handling costs, and enhanced the reliability and efficiency of supply chains (Rodrigue and Notteboom, 2010). The introduction of containerization in the 1950s marked a pivotal shift from the labor-intensive break-bulk shipping method to a more streamlined process. Containers could be swiftly transferred from one mode of transportation to another, ensuring that goods spent more time in transit and less time being handled at ports (Broeze, 2002). This efficiency gain translated into significant cost savings and faster delivery times, which in turn facilitated the growth of global trade (Mirsky, 2007). This transportation process is also known as intermodal transportation: “the movement of goods in one and the same loading unit, which uses successively two or more modes without handling the goods themselves in changing modes” (United Nations, 2001).

This dissertation will investigate through a multi-method approach how continental intermodal transportation leads to a connected Europe by exploring the impact of physical network configuration and digitalization. The focus will be on determining and analyzing the structural configuration of intermodal transportation networks and how they contribute to improving overall system performance. Moreover, it will examine the profound impact of digitalization and real-time data availability on intermodal transportation systems, assessing how these technological advancements continue to evolve and improve the efficiency and reliability of global logistics networks.

The core of this dissertation comprises five studies, each published or under review in scientific journals. The following sections introduce the dissertation's objectives and provide a roadmap. Section 1.1 discusses the research motivation and provides an introduction to intermodal transportation and associated challenges. In Section 1.2, the overarching research questions (RQ) addressed in this dissertation are introduced, and the dissertation structure is outlined. Finally, Section 1.3 gives a brief scientific theoretical classification of the conducted research.

1.1 Research motivation

The advancement of containerization and intermodal transportation has fundamentally transformed global trade, enabling unprecedented levels of efficiency and connectivity in the movement of goods. Since its initiation in the 1950s, the use of standardized shipping containers has facilitated the seamless transfer of cargo between trucks, ships, and trains, dramatically reducing handling costs and times (Broeze, 2002). Today, over 90% of global trade is containerized, with container ships transporting approximately 1.9 billion metric tons of cargo annually (UNCTAD, 2023). The evolution in the size of container ships, from the modest vessels of the 1950s to today's mega-ships capable of carrying over 20,000 Twenty-foot Equivalent Units (TEU), has driven economies of scale but also introduced significant logistical and infrastructural challenges for ports and the associated logistic networks (Eskafi et al., 2021; Rodrigue, 2024b).

Intermodal transportation can be broadly categorized into maritime and continental systems. Maritime intermodal transportation involves the movement of goods by sea, often over long distances, and typically includes subsequent transportation by rail, barge, or truck to deliver goods from ports to their final destinations. This system handles large cargo volumes at relatively low costs, benefiting from economies of scale associated with large container ships (Rodrigue, 2024b).
Continental intermodal transportation focuses on land-based logistics, utilizing a combination of rail and road transportation to move goods efficiently within and across countries and regions (UIRR, 2024). This system is effective for medium to long distances within continents and involves the transfer of containers between trucks and trains at strategically located intermodal terminals (SteadieSeifi et al., 2014). Rail transportation offers energy efficiency and lower emissions. However, rail transportation requires substantial infrastructure investment and is often constrained by fixed routes and schedules (Monios and Bergqvist, 2017). In contrast, road transportation provides greater flexibility and accessibility, allowing for door-to-door delivery and easier access to remote or urban areas (Crainic and Kim, 2007). The combination leverages the strengths of both modes to optimize transportation routes and reduce transit times (Archetti et al., 2022). This dissertation will focus on continental intermodal transportation in Europe.

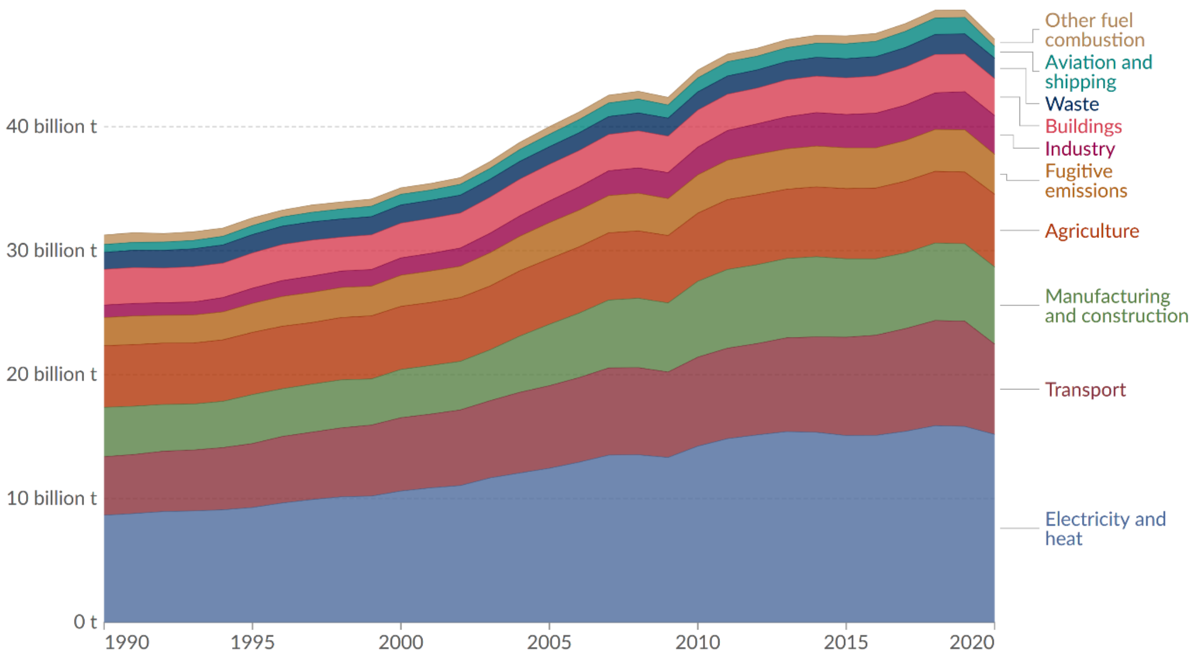


Figure 1: Greenhouse gas emissions by sector (Climate Watch, 2023)

When considering the environmental impact, the transportation sector plays a major role regarding greenhouse gas emissions (GHG) (Figure 1). In 2021, the transportation sector was responsible for around 15% of global emissions (Climate Watch, 2023). Therefore, promoting intermodal transportation, which shifts freight from road to more sustainable modes like rail and inland waterways, can substantially reduce these emissions and mitigate the environmental footprint of the transportation sector (SteadieSeifi et al., 2014).

The modal split, as shown in Figure 2, reflects the distribution of transport volumes among different modes and has remained relatively stagnant in Europe over the past few years despite significant investments and political support aimed at promoting intermodal transportation (Macário and Reis, 2019). This stagnation highlights the challenges in shifting freight volumes from road to more sustainable modes. High emissions from road transportation continue to be a concern, as it remains the dominant mode for freight transportation due to its flexibility and extensive network (Crainic and Kim, 2007). Conversely, rail and inland waterways, although more environmentally friendly, face limitations in reach and infrastructure capacity (European Court of Auditors, 2023).

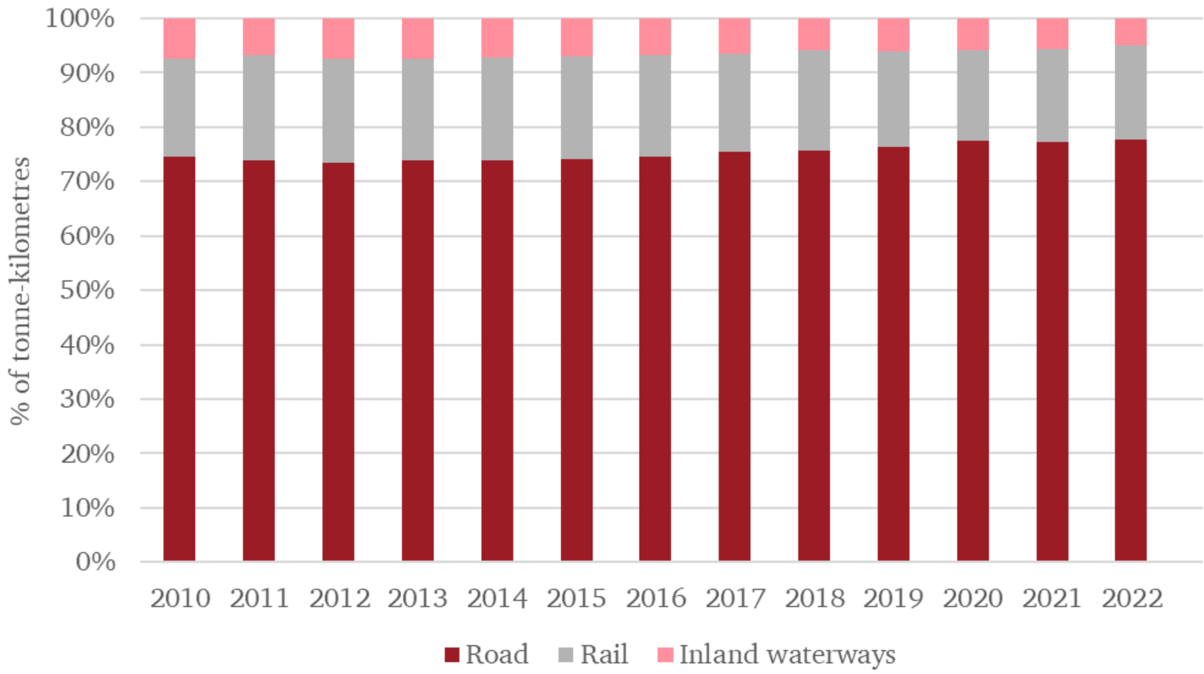


Figure 2: Inland freight transportation modal split in the EU (Eurostat - Statistics Explained, 2022)

Climate metrics and goals set by the European Union (EU) underscore the urgent need to reduce emissions across all sectors, including transportation. The EU's ambitious targets call for a significant reduction in GHG emissions by 2030, with intermodal transportation playing a crucial role in achieving these objectives. Specifically, the European Green Deal aims to cut emissions by at least 55% by 2030 compared to 1990 levels (European Commission, 2019). By shifting freight from road to rail and inland waterways and leveraging technological advancements in digitalization, the EU aims to create a more sustainable and efficient transportation network, significantly contributing to its climate goals.

The EU has taken major steps to address the challenges hindering this shift in rail transportation, particularly regarding infrastructure network capacity and reach. Central to these efforts is the Trans-European Transportation Network (TEN-T), which aims to develop a robust and integrated network across Europe (Goldmann and Wessel, 2020). Complementing this, the Connecting Europe Facility provides crucial funding for cross-border projects and the removal of bottlenecks (European Commission, 2024a). These initiatives collectively aim to improve the efficiency, connectivity, and sustainability of rail transportation in Europe, aligning with broader environmental and economic goals.

Besides infrastructural networks, digitalization has emerged as a cornerstone for enhancing intermodal transportation. Digitalization has profoundly transformed intermodal transportation, significantly improving planning and operational efficiency (Harris et al., 2015; Stefansson, 2012). Technologies such as GPS, tracking systems, big data analytics, the Internet of Things (IoT), and cloud computing have revolutionized intermodal transportation by enabling real-time shipment tracking and improving coordination (Chung, 2021). These technological advancements are used to optimize routes, improve asset utilization, reduce delays, foster more informed decision-making, and streamline processes (Dong et al., 2021). For instance, big data analytics provides valuable insights into traffic patterns and port congestion, while IoT devices ensure a highly connected network (Ambra et al., 2019b). Cloud computing facilitates seamless data sharing among stakeholders, enhancing coordination across the transportation chain (Altuntaş Vural et al., 2020).

To meet climate goals and further improve the efficiency of continental intermodal transportation, a holistic approach to planning and execution is essential. This dissertation uses a multi-method approach to explore various strategic, tactical, and operational planning. Employing multiple methods has the advantage of examining the research subject from different perspectives and gaining comprehensive insights (Creswell and Plano Clark, 2011; Easterby-Smith et al., 2002).

It investigates how the structural configuration of intermodal transportation networks contributes to addressing fundamental logistic challenges and improves overall system performance. This dissertation also examines the impact of digitalization on intermodal transportation systems, highlighting the transformative potential of modern technologies in enhancing the sustainability and effectiveness of global logistics networks.

It thereby focuses on European continental intermodal transportation. While maritime and continental intermodal transportation share some common characteristics, they are fundamentally different systems, which justifies an individual study (Archetti et al., 2022). The geographical focus on Europe results from several considerations:

The EU has a unique regulatory and policy framework as well as a highly advanced and dense infrastructure system (Rodrigue and Notteboom, 2010). The geographical layout of Europe, with its dense network of cities and shorter distances between countries, makes continental intermodal transportation particularly relevant (European Court of Auditors, 2023). In contrast, the vast distances in America and Asia often necessitate different logistical approaches and infrastructure (Clausen and Voll, 2013). Lastly, there is a wealth of research and data available on European intermodal transportation, supported by numerous EU-funded projects (Harris et al., 2015). The European transportation market is characterized by diverse actors, varying laws, and non-standardized processes, creating complex and highly specific cases that complicate analysis (Saeedi et al., 2017). These differences necessitate tailored approaches to address unique circumstances effectively.

Given this complexity, case studies are particularly suitable for analyzing the European intermodal transportation market (Agamez-Arias and Moyano-Fuentes, 2017; Eisenhardt, 1989; Yin, 2018). They allow for in-depth exploration of specific contexts, capturing nuances that broader methods might miss. By focusing on individual cases of European continental intermodal transportation, this dissertation aims to provide targeted insights that ensure a detailed and contextually relevant analysis, contributing to the broader goal of enhancing sustainability and efficiency in transportation.

1.2 Research setup

This section illustrates the setup of the research conducted in this dissertation. It starts by delineating the broader picture of research conducted and methodologies employed in intermodal transportation research. Following this, the overall objective and the research questions are presented. Finally, the structure of the dissertation is outlined.

1.2.1 Research setting

Intermodal transportation has been a focal point of logistics research for several decades. A search for *("intermodal" OR "multimodal" OR "combined") AND transport** in the titles of published scientific articles in the database "Web of Science" reveals more than 2.800 publications (Web of Science, 2024). While research on intermodal transportation started in the middle of the 20th century, research started to pick up in 2008, reaching its peak around 2022, as depicted in Figure 3.

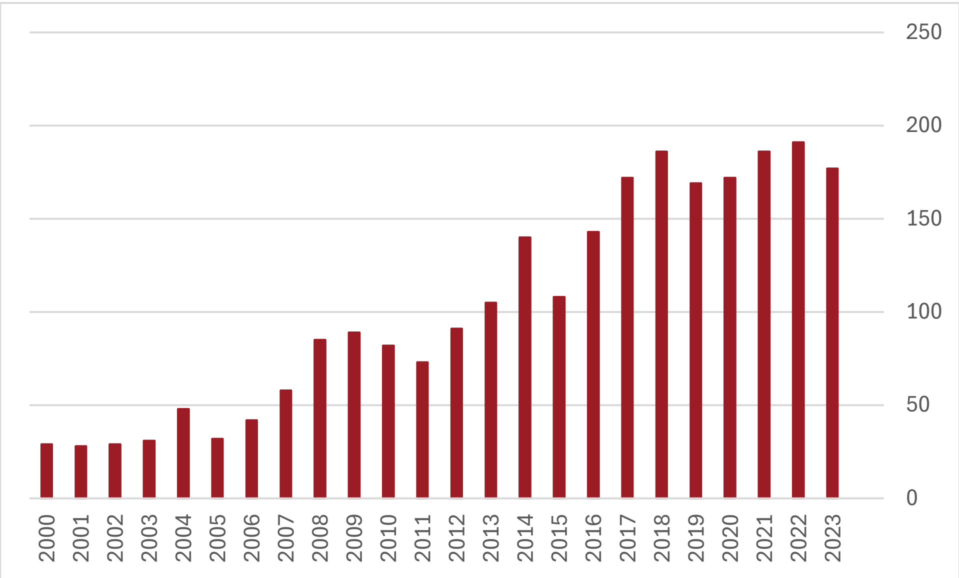


Figure 3: Web of Science search results for a title search of ("intermodal" OR "multimodal" OR "combined") AND transport* (Web of Science, 2024)

Scholars have extensively explored various facets of intermodal transportation, including its economic benefits, environmental impacts, and operational challenges (Agamez-Arias and Moyano-Fuentes, 2017; Mostert et al., 2017; Zhang et al., 2018). The growing importance of sustainability and the need for more efficient and eco-friendly transportation solutions has been highlighted by several studies (Bask and Rajahonka, 2017; Kelle et al., 2019). Trends in the literature indicate a shift towards examining the role of digitalization and network configuration in enhancing intermodal transportation efficiency (Altuntaş Vural et al., 2020; Callefi et al., 2024; Mejri et al., 2023; Stefansson, 2012).
A detailed analysis of the Web of Science search results indicates that research on intermodal transportation employs various methodologies and disciplines (Figure 4). Research on intermodal transportation can greatly benefit from employing and combining a variety of research methodologies, each contributing unique insights and perspectives (Agamez-Arias and Moyano-Fuentes, 2017; Goetz et al., 2009).

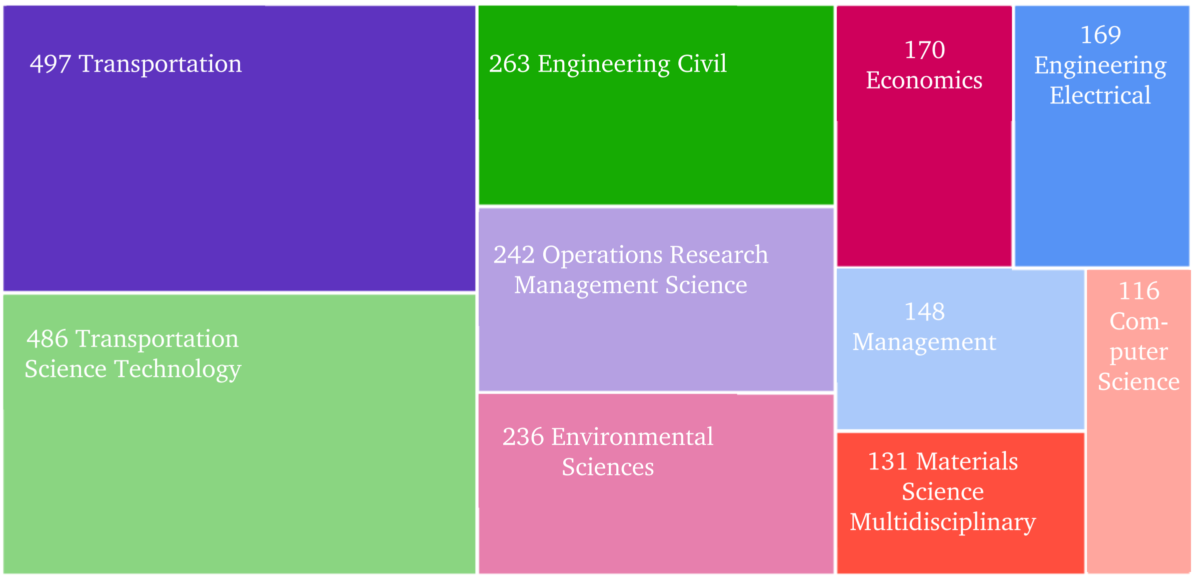


Figure 4: Treemap of research disciplines investigating intermodal transportation (Web of Science, 2024)

Qualitative methods, such as systematic literature reviews and expert interviews, provide an in-depth understanding of stakeholder experiences and contextual factors influencing transportation systems (Altuntaş Vural et al., 2020). Quantitative methods, including simulation and mathematical modeling, offer precise measurements and predictive capabilities (Archetti et al., 2022; SteadieSeifi et al., 2014). However, the different methodologies are rarely combined (Agamez-Arias and Moyano-Fuentes, 2017). Mixed-methods research aims to bridge this gap to enable comprehensive analyses that leverage both detailed qualitative insights and robust quantitative models (Fang et al., 2020; Tremerie, 2018). This methodological richness allows for a more nuanced understanding of intermodal transportation challenges and opportunities. For instance, qualitative research can uncover practical issues faced by logistics providers, while quantitative models can simulate the impact of potential solutions (Gleser et al., 2023; Gleser and Elbert, 2024). Integrating different planning levels — strategic, tactical, and operative — can significantly enhance research on intermodal transportation by providing a comprehensive and in-depth understanding of the system (Archetti et al., 2022; SteadieSeifi et al., 2014). Connecting these levels allows researchers to create models that reflect the complexity and interconnectedness of intermodal transportation systems (Hrabec et al., 2022; Müller et al., 2021a). By using a multi-method approach, researchers can develop balanced and actionable recommendations to improve the efficiency, sustainability, and resilience of intermodal transportation.

In light of the above discussion, this dissertation aims to connect multiple planning horizons and methodologies to overcome the limitations of isolated research approaches. This connected multi-method approach will align long-term strategic goals with short-term operational needs. Section 1.2.3 provides a detailed overview of the methodologies used and planning problems considered in this dissertation. This includes case studies, simulation models, optimization algorithms, systematic literature reviews (SLR), and stakeholder interviews, each selected to address specific RQs and provide a thorough understanding of continental intermodal transportation in Europe. By employing this multi-method approach, this dissertation aims to overcome the fragmentation in intermodal transportation research, offering nuanced insights and contributing to more connected and efficient transportation systems.

1.2.2 Research gaps and overall research questions

Intermodal transportation networks face several fundamental challenges that hinder their efficiency and effectiveness, including insufficient accessibility and capacity (Arunotayanun and Polak, 2011), long transportation times (Eng-Larsson and Kohn, 2012), inflexible and fixed schedules (Müller et al., 2021b), lack of standardization (Gharehgozli et al., 2019), and uncertainty (Delbart et al., 2021). The structural configuration of intermodal transportation networks plays a central role in mitigating these issues and enhancing overall system performance (Alumur et al., 2021). Therefore, the first RQ addressed in this dissertation is:

RQ 1 Connecting Networks – How does the structural configuration of intermodal transportation networks contribute to addressing fundamental challenges and improving overall system performance?

Effective network design, with strategically placed hubs and optimized services, can significantly reduce transportation times and improve accessibility (Campbell and O'Kelly, 2012). By strategically locating hubs and ensuring flexible services, transportation networks can better manage capacity and accommodate varying demand levels (Basallo-Triana et al., 2021; Müller et al., 2021b). Connecting strategic and tactical planning in the context of intermodal transportation networks has the potential to provide in-depth insights into their structure and performance. This research gap gives rise to the first subquestion:

RQ 1.1 Can strategic (HLP) and tactical (SNDP) planning of a transportation network be combined to provide in-depth insights into network structure?

The Hub Location Problem (HLP) involves identifying optimal locations for hubs, which serve as key transfer points within the network (Alumur and Kara, 2008). This strategic decision significantly impacts the overall efficiency and cost-effectiveness of the transportation system. On the other hand, the Service Network Design Problem (SNDP) focuses on determining the optimal routing and scheduling of services between these hubs, addressing medium-term operational decisions (Wieberneit, 2008). By connecting HLP and SNDP, researchers can investigate how strategic decisions regarding hub placement influence tactical service design and vice versa. This integrated approach allows for the development of more coherent and efficient network structures, ensuring that hubs are optimally located and well-connected through effective service networks. Such integration can help identify potential bottlenecks, optimize resource allocation, and improve the reliability of the intermodal transportation system. RQ 1.1 is further operationalized by four minor RQs:

RQ 1.1.1 How can research conducted on hub location planning and service network planning and design in intermodal transportation be systematically classified regarding problem characteristics, model formulations, and solution approaches?

RQ 1.1.2 In which way is uncertainty incorporated into the SNDP models, and how do problem characteristics, model formulations, and solution approaches differ from their deterministic counterparts?

RQ 1.1.3 Can integrated modeling of HLP and SNDP provide added value for a real-world use case?

RQ 1.1.4 Are there structural differences between the classical sequential modeling and the integrated problem?

Continental intermodal transportation offers the possibility of enhancing connectivity between Asia and Europe (Blanchard and Flint, 2017). This concept leverages the extensive rail and road networks across both continents to facilitate the transportation of goods over long distances. By utilizing intermodal transportation, it is possible to bypass some of the limitations associated with maritime transportation, such as long transit times, port congestion, and volatile freight rates (Almendral, 2021). This leads to the second subquestion:

RQ 1.2 Is continental intermodal transportation a suitable concept for connecting Asia and Europe?

The development of major infrastructure projects, such as the Belt and Road Initiative (BRI), has further highlighted the potential of continental intermodal transportation to create efficient and reliable trade corridors between Asia and Europe (Lin, 2019; Sheng, 2023). One of those projects that has come into focus recently is the Trans-Caspian Corridor (TCC), a transit pathway connecting Europe and Asia through Kazakhstan, the Caspian Sea, and the South Caucasus (Palu and Hilmola, 2023). The Russia-Ukraine war has significantly heightened demand for the TCC, as geopolitical tensions make Northern Corridors (e.g., the Trans-Siberian Corridor) less viable (Blackwood et al., 2023). However, implementing continental intermodal transportation on such a large scale also presents challenges, including the need for standardized regulations, coordination between multiple countries, stakeholder management, and significant infrastructure investments.
Overall, the structural configuration of intermodal transportation networks is fundamental in overcoming the inherent challenges and improving the performance and reliability of intermodal transportation systems. Therefore, RQ 1.2 is operationalized by two minor RQs:

RQ 1.2.1 What are the ambitions and motives of the different stakeholders involved in the TCC?

RQ 1.2.2 What are the areas of strategic interest fostering the development of the TCC into a mature corridor?

RQ 1 – Connecting Networks is answered by conducting an SLR on the (tactical) service network planning and design in intermodal transportation. Based on the results of the review, a case study for an intermodal rail operator is conducted. In this case study, a mathematical model for the integrated HLP and SNDP is developed and compared to the classical sequential approach. The second part of the RQ regarding the feasibility of connecting Asia and Europe via intermodal transportation is answered by means of a qualitative interview study.

Digitalization and the availability of real-time data have fundamentally transformed the landscape of intermodal transportation, offering numerous improvements in efficiency, reliability, and operational management (Callefi et al., 2024; Harris et al., 2015). The integration of advanced digital technologies, such as GPS, IoT, big data analytics, and cloud computing, has revolutionized how intermodal transportation systems are monitored and managed (Ambra et al., 2019b; Asborno et al., 2020). This gives rise to the second RQ:

RQ 2 Connecting Digitalization – How do digitalization and the availability of real-time data impact intermodal transportation?

At an operative level in the pre-and post-haulage (PPH) of intermodal transportation, real-time data enables LSPs to monitor the status and location of shipments continuously, enhancing visibility and transparency throughout the transportation chain (Carboni et al., 2020; Wide, 2020). In the PPH, real-time data can be used to optimize the scheduling and routing of vehicles, reducing waiting times and improving asset utilization (Bock, 2010; Jacobsson et al., 2020). This gives rise to the first subquestion:

RQ 2.1 What are the specific effects of real-time data availability in the form of dynamic and stochastic ETA on operational processes in the PPH of intermodal transportation?

Jacobsson et al. (2017) find that the data exchange between intermodal terminals and freight forwarders is currently poor or non-existent, leading to suboptimal processes in the terminal, vehicle waiting times, and possibly additional tours. However, current research suggests that reliable ETA forecasts will soon be available for rail freight (Barbour et al., 2018; Poschmann et al., 2019). Overall, the integration of real-time data into PPH operations can possibly enhance the efficiency, reliability, and responsiveness of intermodal transportation systems significantly. RQ 2.1 is operationalized through three minor RQs:

RQ 2.1.1 How do clustered dynamic and stochastic ETA forecasts impact the PPH of the intermodal transportation chain?

RQ 2.1.2 Which managerial insights can be derived for the decision-makers in intermodal transportation?

RQ 2.1.3 Which policy measures can be taken to foster the implementation of ETA forecasts in intermodal transportation?

Advancements in digitalization and the integration of real-time data are revolutionizing the overall concept of intermodal transportation, driving significant improvements in the synchronization of physical resources and business processes (Agbo et al., 2017; Tavasszy et al., 2010). Digitalization enables automation of processes such as booking, scheduling, tracking, and reporting, reducing manual intervention and minimizing errors (Bol Raap et al., 2016; Khakdaman et al., 2020; Yee et al., 2021). Real-time data integration allows continuous monitoring and dynamic adjustment of transportation operations, enhancing flexibility and responsiveness (Tsertou et al., 2016). Digital platforms provide end-to-end supply chain visibility, enabling stakeholders to track shipments in real-time and proactively manage disruptions (Acero et al., 2022). All these technological developments give rise to the next subquestion:

RQ 2.2 How does the overall concept of intermodal transportation evolve with advancements in digitalization and real-time data integration?

The next step to a more integrated transportation concept is the idea of synchromodal transportation (SMT), which leverages digitalization and real-time data to offer even greater flexibility and efficiency (Giusti et al., 2019b). SMT allows for dynamic switching between different transportation modes based on real-time conditions and demand. This approach aims to enhance the resilience and responsiveness of transportation systems, ensuring that the most efficient and sustainable mode of transportation is used at all times. As SMT entails profound operational, technical, and business changes, subquestion RQ 2.2 is operationalized by two minor RQs:

RQ 2.2.1 What is the current state-of-the-art of synchromodal transportation?

RQ 2.2.2 How can research on SMT be systematically classified, what trends can be observed, what primary research methods are used, and how do they relate and compare to each other?

The first part of RQ 2 – Connecting Digitalization, which focuses on the effects of real-time data availability on operational processes in the PPH of intermodal transportation, is answered by a simulation-optimization study. In contrast, RQ 2.2 investigates the futuristic concept of SMT, which is answered by means of an SLR.

In summary, this dissertation explores how continental intermodal transportation can contribute to connecting Europe. It focuses on the impact of network structure and the transformative role of digitalization. By addressing these research gaps, the dissertation seeks to provide a comprehensive understanding of connected intermodal transportation systems, ultimately leading to highly integrated concepts such as SMT. The findings of the dissertation are further supported by including rich real-world data and case studies in order to estimate the potential of the models for practical applications. The outline of the dissertation is presented in the next section.

1.2.3 Outline of the dissertation

The remainder of this dissertation is systematically divided into three main areas and comprises a total of nine chapters. Figure 5 provides a visual representation of the overall structure, detailing the corresponding RQs and contributions.

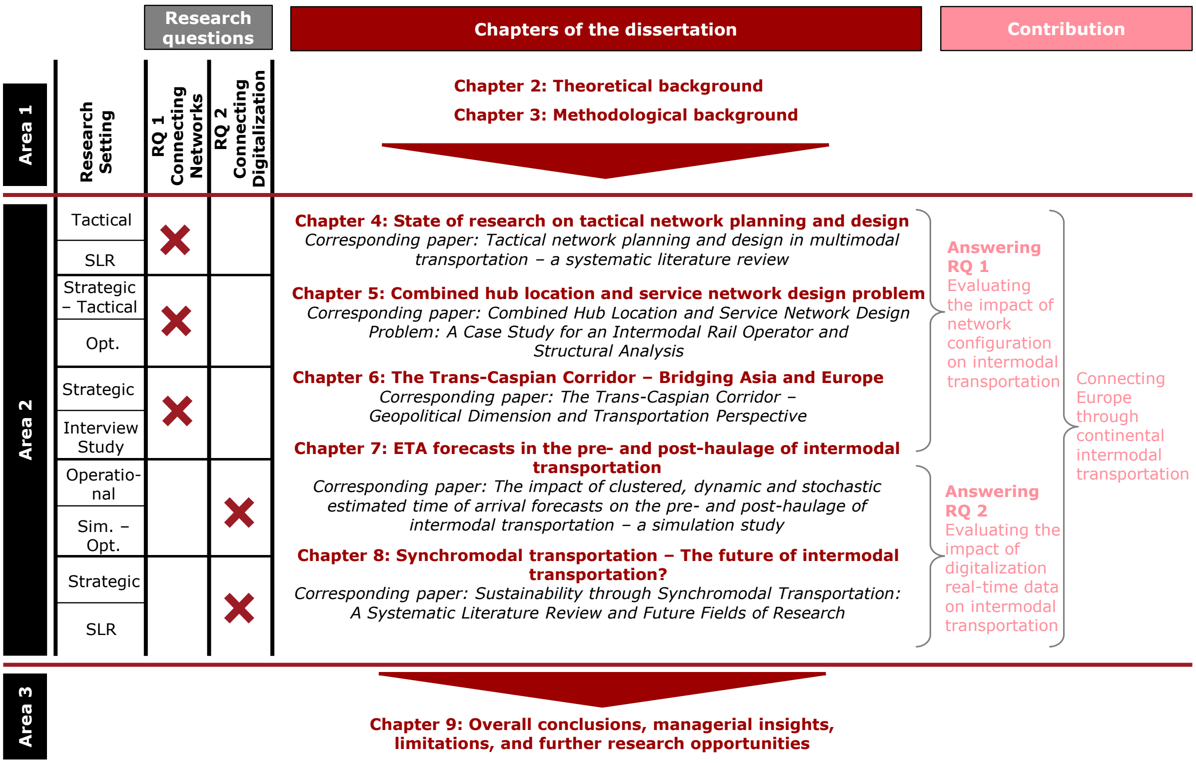


Figure 5: Outline of the dissertation

SLR: Systematic Literatur Review; Opt.: Optimization; Sim.: Simulation

Area 1 offers a comprehensive introduction to the theoretical background relevant to this dissertation. Chapter 2 delves into the concept of intermodal transportation, examining various aspects in detail. After introducing the research propositions (RPs), Chapter 3 focuses on the methodologies used and introduces the multi-method approach.

Area 2 constitutes the core of this dissertation, featuring five independent research papers, each presented in its own chapter. Chapter 4 results from the paper *"Tactical network planning and design in multimodal transportation – a systematic literature review"*, published in *Research in Transportation Business & Management (Elbert et al., 2020)*. Chapter 5 corresponds to the paper *"Combined Hub Location and Service Network Design Problem: A Case Study for an Intermodal Rail Operator and Structural Analysis,"* published in *Transportation Research Record* (Elbert et al., 2022). Chapter 6 is based on the paper *"The Trans-Caspian Corridor – Geopolitical Dimension and Transportation Perspective"* and is currently under review in a scientific journal. Chapter 7 represents the fourth research paper, *"The impact of clustered, dynamic and stochastic estimated time of arrival forecasts on the pre-and post-haulage of intermodal transport – a simulation study,"* currently under review in a scientific journal. The last Chapter 8 in Area 2 is based on the paper *"Sustainability through Synchromodal Transportation: A Systematic Literature Review and Future Fields of Research,"* published in *Sustainability* (Rentschler et al., 2022). Each chapter is designed to be read independently, yet they all contribute to the overarching framework. The content in this area specifically addresses the RQs: Chapters 4, 5, and 6 respond to RQ 1 by evaluating the impact of network configuration on intermodal transportation, while Chapters 7 and 8 address RQ 2 by examining the effect of real-time data and digitalization on intermodal transportation.

Area 3 encompasses Chapter 9, where overarching conclusions regarding the RPs are drawn, managerial insights are presented, and the limitations of the study, along with future research needs, are discussed. Prior to presenting the research results as outlined above, this chapter concludes with a brief scientific theoretical classification of the work conducted in this dissertation.

1.3 Scientific theoretical classification

In this section, the research conducted in this dissertation is discussed from a philosophy of science perspective. The philosophy of science can be described as a meta-discipline that studies the nature, objectives, and methods of science, as well as the classification and principles of knowledge (Fülbier, 2004; Helfrich, 2016). This dissertation's research intersects multiple scientific disciplines, such as business administration and operations research (OR), as well as transportation science and (applied) mathematics. It primarily focuses on intermodal transportation, which can be understood as a sociotechnical system involving the interaction of technical infrastructures and human actors.

Scientific disciplines can be broadly categorized into real sciences and formal sciences (Helfrich, 2016). Real sciences investigate phenomena in the real world and encompass natural sciences and social sciences (Jung, 2016; Kornmeier, 2007). In contrast, formal sciences, such as mathematics and computer science, deal with abstract structures independent of the real world (Domschke and Scholl, 2008; Kornmeier, 2007). The research in this dissertation is positioned within the real sciences, specifically social sciences, as it examines the human, technical, and organizational aspects of intermodal transportation systems (Baxter and Sommerville, 2011; Emery and Trist, 1960). Social sciences focus on human behavior and societal interactions (Heinen, 1985; Helfrich, 2016). Within this domain, business economics is concerned with the economic activities of companies and their role within the larger economy (Domschke and Scholl, 2008; Helfrich, 2016; Whitley, 1984). This dissertation contributes to business economics by analyzing intermodal transportation systems, which involve the coordinated movement of goods using multiple transportation modes such as rail, road, and waterways. Intermodal transportation is a critical area within logistics and supply chain management, representing a sociotechnical system where human actors interact with technological infrastructures (Emery and Trist, 1960).

The interdisciplinary nature of this field bridges social sciences and applied sciences, particularly OR and transportation science. While OR and transportation science utilize mathematical models—placing them within the formal sciences—they are applied to real-world problems, enhancing the efficiency and sustainability of intermodal transportation networks (Baxter and Sommerville, 2011; Bertrand and Fransoo, 2002).

Further distinctions between basic and applied sciences can be made (Helfrich, 2016). Basic sciences focus on theoretical understanding and knowledge, while applied sciences aim to solve practical problems and improve real-world applications (Fülbier, 2004; Heinen, 1985; Helfrich, 2016). This dissertation aligns with applied science, specifically practical science, as it seeks to provide actionable insights and decision support for optimizing intermodal transportation systems. Practical science, or "action science," emphasizes recommendations for action and decision-making in specific contexts (Steinmann, 1978). The research in this dissertation addresses the planning and operational challenges in intermodal transportation, offering solutions that enhance logistical efficiency and environmental sustainability. For instance, the research presented in this dissertation involves the development of decision-support models and optimization techniques aimed at improving the coordination and performance of intermodal transportation networks.

Business economics can be further classified into three distinct branches: descriptive, ethical-normative, and practical-normative (Domschke and Scholl, 2008). This dissertation primarily aligns with the practical-normative approach, which focuses on supporting rational economic choices through the development of planning models and decision-support systems.

Descriptive business economics aims to describe and explain entrepreneurial actions without providing explicit recommendations or instructions for action. This branch is concerned with observing and detailing business practices and outcomes, offering insights into how businesses operate under various conditions (Domschke and Scholl, 2008). In contrast, ethical-normative business economics addresses broader societal goals and values in addition to profit maximization. This branch incorporates considerations of social objectives, such as employee welfare, environmental sustainability, and corporate social responsibility (Domschke and Scholl, 2008).

Practical-normative business economics, which is the focus of this dissertation, includes not only the description and explanation of business activities but also the design and optimization of business operations to achieve specific objectives. This branch aims to provide actionable recommendations and decision support to enhance business performance. It emphasizes the development of practical tools and models that aid in decision-making processes, ensuring that business operations align with predefined objectives (Domschke and Scholl, 2008; Grünig and Kühn, 2012).

In the context of this dissertation, practical-normative business economics is operationalized through the application of planning models and decision-support systems to optimize intermodal transportation networks. These models are designed to support rational economic choices by providing insights into efficient logistics planning, resource allocation, and network configuration. The research employs advanced analytical methods from OR, a sub-discipline of applied mathematics and computer science, to develop these models (Bertrand and Fransoo, 2002). OR, which is closely related to decision-oriented business economics, involves the application of quantitative methods to solve complex decision-making problems. This field utilizes mathematical modeling, simulation, and optimization techniques to analyze and improve business operations (Domschke and Scholl, 2008; Kalua and Jones, 2020). By integrating these techniques, the dissertation aims to enhance the efficiency and sustainability of intermodal transportation systems, aligning with the practical-normative approach's goal of providing actionable business insights.

Furthermore, the practical-normative framework emphasizes the need for decision support that is based on rational economic choices rather than behavioral aspects (Grünig and Kühn, 2012). Bertrand and Fransoo (2002) further distinguish between empirical and axiomatic research. Empirical research is grounded in real-world data and observations, ensuring that models accurately represent practical scenarios (Bertrand and Fransoo, 2002; Roy, 1993). Axiomatic research, on the other hand, involves theoretical models that provide insights into complex decision-making processes (Bertrand and Fransoo, 2002). The research in this dissertation includes both empirical research and axiomatic quantitative research using simulation and optimization. Simulation modeling allows for the examination of intermodal transportation systems in a controlled, virtual environment. This approach is particularly valuable for analyzing scenarios that are too complex for formal mathematical analysis alone (Kalua and Jones, 2020).

The research presented in this dissertation is in line with the exploration strategy as described by Kubicek (1976). The exploration strategy critiques the excessive formalism that can hinder the acquisition of business knowledge, advocating for more flexibility in research approaches. According to this strategy, scientific research is viewed as a learning process where insights are progressively incorporated into a theoretical framework, becoming increasingly significant. This learning process involves three stages:

1. The first stage aims to gain a preliminary understanding or prior knowledge, clarifying research perspectives based on the current state of research and theoretical foundations.
2. The second stage involves collecting experiential knowledge, necessitating interaction between science and practice.
3. In the third stage, these findings are analyzed, and new assumptions or research directions are derived.

For this dissertation, employing the exploration strategy is deemed particularly effective in contributing to the advancement of scientific knowledge. The multi-method approach and the integration of real-world data underscores the applied nature of this research, contributing to the broader goal of advancing intermodal transportation and supporting sustainable transportation initiatives leading to a connected Europe.

2 Theoretical background

This chapter introduces the basic principles of intermodal transportation, briefly summarizing the theoretical background to provide a framework for the five papers presented in the following chapters. The first section introduces and compares the different multimodal transportation concepts. This section is followed by a presentation of the actors involved in the transportation process. In Section 2.3, the infrastructure of the intermodal network is described. Freight transportation policies on the European level are presented in Section 2.4. In the following section, the impact of digital transformation on intermodal transportation is briefly sketched. Finally, in Section 2.6, the overall research design is derived by operationalizing the RQs via the corresponding RPs.

2.1 Intermodal freight transportation concepts

Multimodal transportation port, intermodal transportation, combined transportation, co-modal transportation, and synchromodal transportation all describe different aspects of transportation systems that utilize multiple modes of transportation. While these terms are often used interchangeably, they each carry distinct nuances in their definitions and operational frameworks (Macário and Reis, 2019; Reis et al., 2013).

Multimodal transportation refers to the movement of goods or passengers using a combination of different modes of transportation within a single journey. These modes can include road, rail, sea, and, theoretically, air transportation. In multimodal transportation, a single carrier is responsible for the entire journey, providing seamless coordination between different modes to ensure efficient and effective transportation. This approach offers flexibility and can optimize routes based on factors such as cost, speed, and environmental impact (Reis, 2015).
Intermodal transportation is a specific subset of multimodal transportation defined as “the movement of goods in one and the same loading unit or road vehicle, which uses successively two or more modes without handling the goods themselves in changing modes” (United Nations, 2001). In intermodal transportation, the cargo remains in the same Intermodal Transportation Units (ITU), such as swap bodies, containers, or even semi-trailers, throughout its journey, transitioning smoothly between modes at designated intermodal terminals. This approach minimizes the need for manual handling, reducing the risk of damage or loss while streamlining the logistics process (Crainic and Kim, 2007).
Combined transportation, sometimes used interchangeably with intermodal transportation, specifically refers to journeys “where the major part of the journey is by rail, inland waterways or sea and any initial and/or final legs carried out by road are as short as possible” (United Nations, 2001). In combined transportation, the emphasis is on leveraging the efficiency of rail

or water transportation for long-distance haulage while utilizing road transportation for shorter feeder routes, enabling door-to-door transportation. This approach capitalizes on the strengths of each mode to create a cohesive and cost-effective transportation solution (Říha and Dočkalíková, 2021).

Co-modal transportation is a concept that emphasizes the seamless integration of different modes of transportation within a single logistics network. Unlike multimodal or intermodal transportation, which focuses on the physical movement of goods, co-modal transportation encompasses broader aspects such as route planning, scheduling, and information management. The goal of co-modal transportation is "the efficient use of different modes on their own or in combination to result in an optimal and sustainable utilization of resources" (European Commission, 2006).

Synchromodal transportation represents a modern approach to transportation logistics that leverages real-time information and digital technologies to dynamically optimize transportation routes and modes based on changing conditions (Tavasszy et al., 2017). In SMT, decisions regarding mode selection, routing, and scheduling are made in real time, considering factors such as traffic conditions, weather forecasts, and infrastructure capacity. This approach enhances flexibility, resilience, and efficiency within the transportation network, enabling seamless transitions between different modes to ensure timely delivery while minimizing costs and environmental impact (Acero et al., 2022).

In summary, while multimodal, intermodal, combined, co-modal, and SMT all involve the use of multiple modes of transportation, each term carries specific connotations and operational principles. Understanding the distinctions between these terms is crucial for developing effective transportation strategies that meet the evolving needs of modern supply chains (Macário and Reis, 2019).

Intermodal transportation can be differentiated between maritime and continental, as described in Section 1.1. Continental intermodal transportation further delineates two primary market segments, each presenting distinct organizational challenges. These segments are port hinterland transportation chains and continental transportation chains (Monios and Bergqvist, 2017). The planning approaches for these chains vary significantly due to differences in standards, infrastructure and equipment homogeneity, and transportation logistics (Gharehgozli et al., 2019).

Port-centric intermodal transportation chains are primarily designed to ferry sea freight containers to and from the hinterlands of ports. Consequently, the organization of these chains is intricately linked to the schedules of maritime vessels, the limited storage capacity within sea terminals, and the logistical complexities associated with train operations within port premises

(Ambrosino et al., 2021). Given their significance as critical infrastructure nodes, ports typically receive substantial support from national governments and have evolving hinterland concepts influenced by transportation network organization and technological advancements (Sdoukopoulos and Boile, 2020). The heightened efficiency, available transportation capacities, and improved connectivity of ports have spurred competition among them, increasingly focusing on hinterland connectivity and multimodal connections (Zondag et al., 2010).
In contrast, pure continental intermodal transportation chains entail main haulage transportation between two terminals, with PPH facilitated by trucks to reach final destinations. Such chains, or networks, encounter various challenges, including non-harmonized policies across Europe for cross-border transports, involvement of two or more transshipments, and the diversity of ITU types (Rodrigue, 2024b). The continental intermodal transportation chains can have different geographical distributions and range from simple networks in one country to transportation corridors connecting different continents through complex transportation routes (Wilmsmeier et al., 2011).

The cost and sustainability benefits from intermodal transportation become particularly evident over long distances. As intermodal journeys require at least two transshipments, the cost advantage of rail-based main haulage compensates for higher transshipment costs only beyond a certain distance threshold, as can be seen in Figure 6 (Monios and Bergqvist, 2017). While the conventional assumption pins this threshold at around 300 km, exceptions exist, particularly in port-related and barge transportation contexts (Meers et al., 2015).

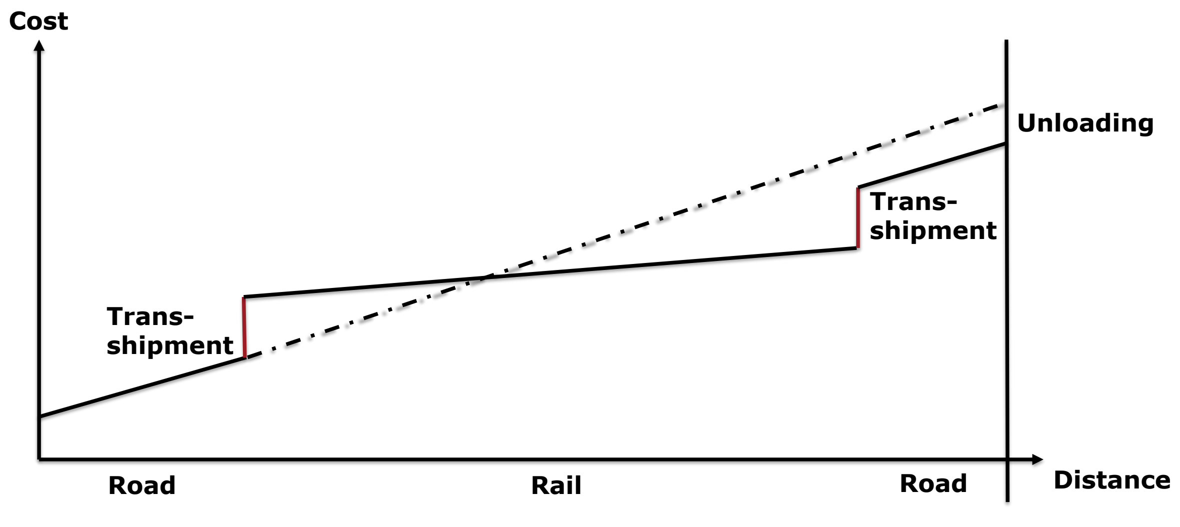


Figure 6: Comparison of unimodal road and intermodal cost by distance|own representation based on Monios and Bergqvist (2017)

2.2 Actors

Over time, the landscape of intermodal transportation has seen a significant increase in the number of involved entities, spanning from specialized firms focusing on specific transportation chain segments or product types to more generalized companies (Macário and Reis, 2019). In general, stakeholders within the transportation chain, as illustrated in Figure 7, can be broadly classified into seven groups: (1) shippers/consignors, (2) forwarders/logistics service providers (LSP), (3) transportation operators/actual carriers, (4) terminal operators, (5) infrastructure providers, (6) institutional authorities/governmental agencies, and (7) receivers/consignees (Macário and Reis, 2019; United Nations, 2001).

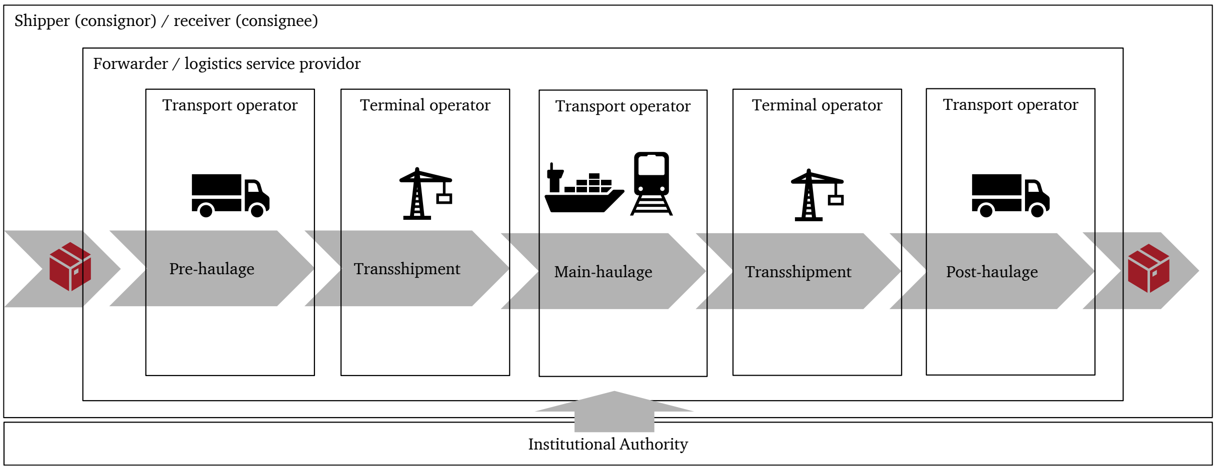


Figure 7: Actors in intermodal transportation | own representation

Shippers and receivers serve as the primary instigators of transportation demand, encompassing traders, consumers, importers, and exporters. While some may orchestrate their own end-to-end transportation chains, the majority opt to outsource freight transportation execution, thus laying the groundwork for various business models within the transportation sector (Agbo et al., 2017). Typically, the shipper delegates transportation organization to a freight forwarder, although the ultimate decision-making power regarding transportation strategy, including mode selection, often remains with the sender (Crainic et al., 2018; Tavasszy et al., 2017).

Freight forwarders are central in consolidating transportation orders from multiple shippers, acting as intermediaries between shippers and various transportation and terminal operators. Over time, the scope of services provided by freight forwarders has expanded significantly, leading to their evolution into third-party logistics providers (3PLs) (partly) devoid of transportation assets (Skender et al., 2016). 3PL tasks encompass a broad spectrum, ranging from document processing and transportation insurance to managing transportation services

and offering additional warehousing or labeling services (Macário and Reis, 2019).
A relatively novel concept, Fourth-party logistics providers (4PLs) integrate all entities upstream and downstream of a client's supply chain, representing a form of SCM outsourcing that aims for comprehensive supply chain management (Skender et al., 2017). 4PLs oversee multiple 3PLs, maintain long-term contractual agreements with clients, and are responsible for achieving clients' strategic objectives, operating without physical assets (Skender et al., 2017). They offer services such as control tower management, business planning, project management, and network design (Giusti et al., 2019b).
Less common yet emerging in the context of synchromodality is the concept of Fifth-party logistics providers (5PLs). Similar to 4PLs, 5PLs lack physical assets and focus on strategically aligning supply chains, albeit with a heightened emphasis on technology-driven solutions for automating complex interrelationships and interactions within supply chains, particularly those of large companies (Skender et al., 2016). Giusti et al. (2019b) advocate for a platform as the central core of 5PL operations, facilitating the provision of appropriate and customizable technology to involved stakeholders.

Beyond the freight forwarder's role, transportation companies physically move cargo between locations, assuming liability for damages during transportation execution. These companies may specialize in a single mode of transportation or offer services across multiple modalities (Macário and Reis, 2019). Terminal operators, in both deep sea and inland settings, play crucial roles in transshipment activities and value-added services such as container storage, labeling, and repackaging (Franc and van der Horst, 2010).
Infrastructure providers, whether public entities or private firms with public stakeholders are responsible for managing infrastructure such as construction, maintenance, and energy services (Crainic et al., 2018). This responsibility varies across transportation modes, with e.g., port operators providing the necessary infrastructure at port land areas (Agbo et al., 2017; van den Berg et al., 2012).

Lastly, regulatory agencies at local, national, or international levels form a fundamental actor group, imposing taxes, setting policies, and defining legal frameworks to guide transportation systems toward societal goals (Crainic et al., 2018). These agencies, such as the International Civil Aviation Authority and International Maritime Organization, enforce competition, security, operational, and labor standards, with customs authorities overseeing physical inspections to ensure freight document validity and accuracy (Macário and Reis, 2019).
The increasing complexity of stakeholder networks necessitates the application of advanced planning methods, particularly mathematical optimization techniques. As seen in the evolution from traditional freight forwarding to the emergence of 4PLs and 5PLs, logistics management

requires sophisticated coordination. Mathematical optimization offers a systematic approach to allocating resources, optimizing routes, and synchronizing operations across diverse actors. By leveraging mathematical models, such as linear programming or network optimization, stakeholders can enhance efficiency, minimize costs, and improve service quality. These quantitative models are described in detail in Chapter 3.

2.3 Network

In this section, the intermodal network with a focus on Europe is introduced. It is structured along "Nodes" – the ports and inland terminals, the "Arcs" – road, rail, and inland waterways, and the Equipment used.

2.3.1 Nodes

Rodrigue (2024b) defines terminals as a "facility where passengers and freight are assembled or dispersed." He further specifies them as a location where freight either originates, terminates, or is handled in the transportation process. Terminals serve as central points in the movement of both passengers and freight, acting as main and intermediate hubs along transportation routes. These locations often necessitate specialized facilities and equipment tailored to the specific traffic they manage. In intermodal networks, terminals play a critical role as transfer points between different modes of transportation (Monios and Bergqvist, 2017). Containerization has led to the development of a hierarchical structure of terminals serving various functions and providing added value. These terminals range from mega-gateways, which coordinate flows across expansive market areas, to small-scale rail yards or truck depots catering to local markets (Rodrigue, 2024b). Closely linked with the importance and performance of transportation terminals are three attributes (Rodrigue, 2024b):

- Location: Transportation terminals are strategically situated to serve dense economic regions, forming their market area.
- Accessibility: The effectiveness of a terminal depends on its connectivity to other terminals locally, regionally, and globally, as well as its integration with the regional transportation system.
- Infrastructure: Terminals are designed to handle and transship freight or passengers efficiently, necessitating significant investments in infrastructure.

Freight transportation terminals exhibit distinct characteristics encompassing core operations and added value activities (see Figure 8), leading to functional differentiation based on the mode of transportation and the types of commodities handled.

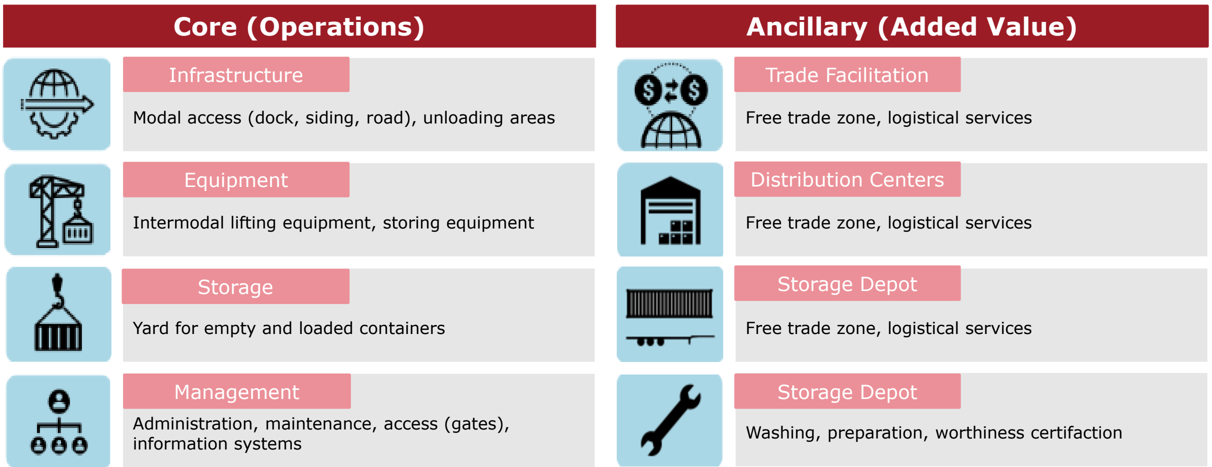


Figure 8: Characteristics of intermodal freight terminals | own representation based on Rodrigue (2024b)

Ports

Ports, as terminals, manage the highest volumes of freight, surpassing all other terminal types combined (Rodrigue, 2024b). Port infrastructures are tailored to handle freight, necessitating the seamless integration of transshipment activities to facilitate the convergence of land and maritime transportation systems. Across many regions globally, ports serve as pivotal points of convergence, acting as the origin points from which inland transportation systems, notably rail, were expanded (Rodrigue, 2024b). Among the ten largest ports worldwide (based on throughput volume), seven are located in China (Table 1). Ports exert their primary influence through their hinterlands, which represent the land areas they serve.

Table 1: Top-10 ports by container throughput 2021 (World Shipping Council, 2024)

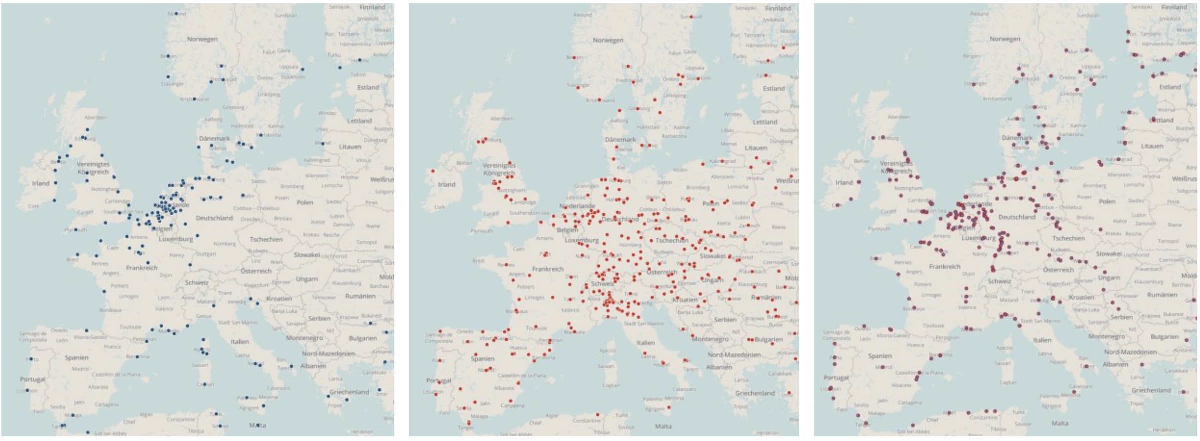
#	Name	Country	Volume (Million TEU)
1	Shanghai	China	47.03
2	Singapore	Singapore	37.49
3	Ningbo-Zhoushan	China	31.07
4	Shenzhen	China	28.77
5	Guangzhou	China	24.18
6	Busan	South Korea	22.71
7	Qingdao	China	23.71
8	Tianjin	China	20.27
9	Hong Kong	China	17.8
10	Rotterdam	The Netherlands	15.3
14	Antwerp	Belgium	12.02
18	Hamburg	Germany	8.72

The hinterland of a port delineates the geographical region where the terminal offers its services and interacts with its clientele (Notteboom, 2009). This hinterland encompasses the regional market share that a port commands relative to other ports servicing the same region, encompassing all customers directly linked to the port and the territories from which it attracts and distributes traffic. Two main categories define the hinterland: the fundamental hinterland, also known as captive, and the competitive hinterland. The fundamental hinterland denotes the primary market area where the port enjoys proximity and ease of access, resulting in most traffic naturally gravitating towards it due to the absence of competitive alternatives. Conversely, the competitive hinterland represents market areas where the port faces more intense competition for business, often situated at the periphery of the fundamental hinterland (Notteboom et al., 2022). One way this competition for the hinterland is fought is through the quality of rail access (Gleser et al., 2023).

Inland terminals

Wilmsmeier et al. (2011) investigate the development of intermodal freight corridors in relation to inland terminals. Initially exploring the seaport–hinterland connection, they differentiate between two spatial development concepts. In the Outside-In concept, inland nodes are used by the seaport to expand their hinterland. On the other hand, in the Inside-Out concept, corridor development and greater integration with the seaport are actively driven by inland intermodal terminals and often public body intervention. Witte et al. (2014) further suggest that paying more attention to inland terminals as standalone entities in the context of the Inside-Out concept is essential. They highlight the significance of the spatial, economic, and institutional aspects of inland terminals, alongside their role in transportation. The relationship between port activity and local development is further investigated by Hidalgo-Gallego and Núñez-Sánchez (2023). In a case study on the impact of port activity on local employment in Spain, they found a strong positive correlation. Lastly, Qi et al. (2020) examine the spatial spillover effects of logistics infrastructure in China. They find that investments in logistical infrastructure can promote regional economic development.

Europe enjoys a widespread network of terminals, as depicted in Figure 9, showcasing the distribution of water/road terminals and rail/road terminals alongside tri-modal terminals accommodating barge, rail, and truck transportation. Water/road and trimodal terminals tend to cluster along major rivers and port hubs, whereas rail/road terminals are primarily situated in densely populated regions. These terminals vary in characteristics, including the quantity and variety of transshipment facilities such as gantry cranes and reach stackers, storage capacity, versatility in handling intermodal cargo, and ancillary services related to transshipment and rail transportation (Monios and Bergqvist, 2017).



Water/Road Rail/Road Trimodal

Figure 9: Terminals in Europe (Intermodal Map, 2024)

2.3.2 Arcs

Europe's rail freight system encompasses an extensive network of tracks, terminals, and logistical facilities connecting major industrial centers, ports, and distribution hubs. The system operates on a mix of electrified and non-electrified lines, with varying levels of capacity and technological advancement across different regions (Monios and Bergqvist, 2017). Despite its importance, Europe's rail freight system faces several connectivity challenges that impact its efficiency, reliability, and competitiveness. These challenges include interoperability issues such as variations in track gauge, electrification standards, signaling systems, and administrative procedures among different countries (Figure 10) (Gharehgozli et al., 2019).

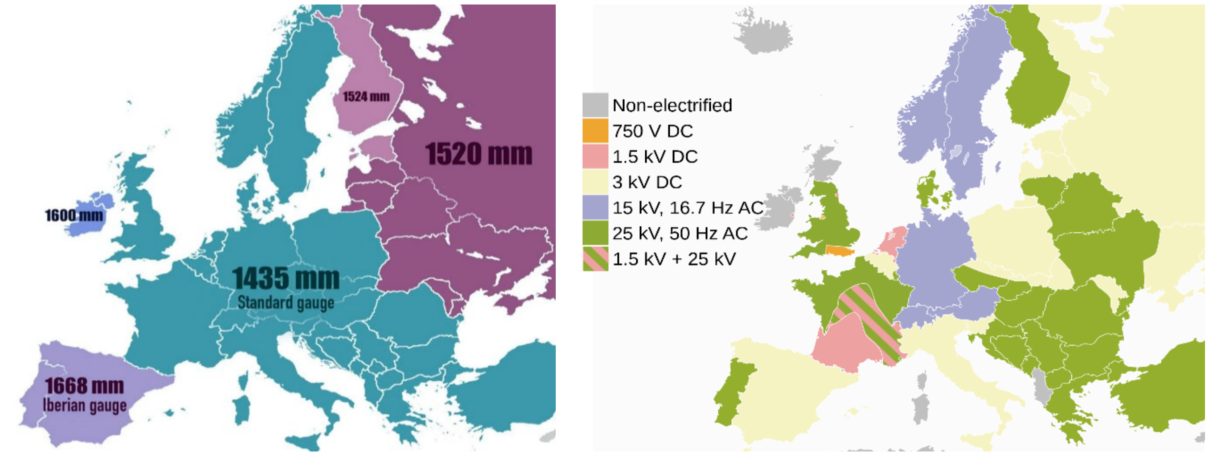


Figure 10: Railway gauge and electrification systems in Europe (European Commission. Directorate General for Mobility and Transport., 2023)

In response to these challenges, the EU has initiated projects to modernize and improve the efficiency of Europe's rail system, with a particular focus on the TEN-T Corridors (Goldmann and Wessel, 2020). The development of the TEN-T Corridors seeks to improve the connectivity of Europe's rail network by upgrading key transportation corridors and removing bottlenecks, facilitating seamless cross-border transportation, and promoting multimodal integration. The TEN-T corridors are not only limited to the rail network but attempt to create multimodal transportation corridors (Figure 11).

Figure 11: European TEN-T Network (TENtec Interactive Map Viewer, 2024)

Besides interconnectivity issues, rail freight faces competition from road and inland waterway transportation. Road transportation offers greater flexibility, speed, and door-to-door connectivity, especially for short-distance and time-sensitive shipments (Rodrigue, 2024b). Transportation along inland waterways can offer benefits such as lower cost, high capacity, energy efficiency, and environmental sustainability. However, due to limited accessibility, seasonal variability, and low speed, their utility is limited. Despite these challenges, inland waterway transportation remains a valuable component of the multimodal transportation network, offering cost-effective, environmentally sustainable solutions for the movement of bulk cargo over long distances (Giusti et al., 2021b), as can be seen in Figure 12.

Figure 12: Transportation performance by main European river basins (CCNR - Observation Du Marché, 2023)

2.3.3 Equipment

Loading units

Intermodal transportation involves the transportation of goods in a standardized loading unit. This unit can either be a single consignment of goods or a groupage load of smaller consignments organized by a freight forwarder. Referred to as an intermodal transportation unit or intermodal loading unit, it typically takes the form of an International Organization for Standardization (ISO) maritime container, a swap body, or a semi-trailer (Monios and Bergqvist, 2017). Figure 13 displays the shares of each loading unit among intermodal rail transportation in Europe.

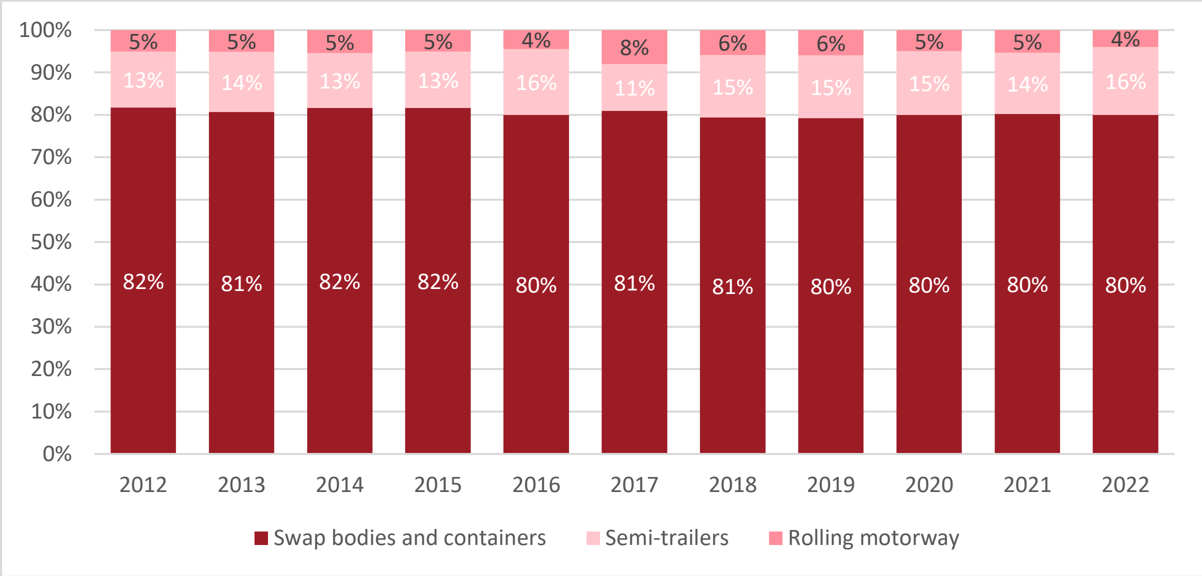


Figure 13: Share of loading units in the EU | own representation based on (European Commission. Directorate General for Mobility and Transport., 2023)

Intermodal transportation relies on a variety of equipment, with ISO containers serving as the cornerstone due to their strength, stackability, and versatility. Their increasing standardization has been pivotal in facilitating successful intermodal logistics (Mirsky, 2007). Today, a wide range of container types are utilized in international trade. While 20 ft and 40 ft containers dominate deep-sea vessels, intra-European shipments often utilize 45 ft containers, including 'pallet-wide' variants on short sea routes (See Figure 14). Containers are versatile and can accommodate a wide range of goods, including dry cargo, refrigerated products, and hazardous materials (Rodrigue and Notteboom, 2009).

Figure 14: Tank container, 20 TEU container with canvas cover, and swap body

Ideally, a loaded container would travel from its origin to its destination, where it would be unloaded and then reloaded for export to a new destination. However, in reality, there may not always be an export load waiting. In such cases, once a container is emptied, it is taken back to the nearest port or depot. There, it may wait until needed, or it may be repositioned. Approximately 30% of all recorded container handlings in world ports involve empty containers (Monios and Bergqvist, 2017). Western countries, being net importers, often lack enough export loads to fill all the incoming containers. Even if an export load is anticipated, revenue loss becomes a concern if a container sits idle for too long (Monios and Bergqvist, 2017).

Swap bodies, similar to containers but with a stronger frame, are commonly used in road and rail transportation within Europe and other regions, offering flexibility in cargo handling. Unlike containers, swap bodies do not have standardized dimensions and can vary in size and configuration depending on regional standards and regulations (SGKV e.V., 2024f).
Semi-trailers are connected to road tractor units and feature legs for support when uncoupled. They come in various configurations suitable for different cargo types, similar to swap bodies. In the United States, they are often referred to as chassis.
In Europe, intermodal terminals typically use grounded methods, where containers are transferred between trains and road trailers or stacked on the ground. In contrast, wheeled terminals are common in the United States, where containers are unloaded from trains onto waiting chassis (Monios and Bergqvist, 2017). However, a challenge arises with non-cranable semi-trailers, which make up a significant percentage (Die Güterbahnen, 2021). Horizontal transshipment, as can be seen in Figure 15, by extending a platform to accommodate semi-trailers, offers one solution (Cargobeamer, 2024). Rolling highways, also known as piggybacking or accompanied transportation, involve the transportation of road trailers or swap bodies on specially designed railcars (SGKV e.V., 2024e).

Figure 15: CargoBeamer, rolling highway

Handling equipment

Handling equipment is instrumental in facilitating the efficient movement of cargo containers and swap bodies within intermodal transportation systems. These equipment types serve various purposes, from loading and unloading vessels to stacking and transporting containers within terminal yards (Monios and Bergqvist, 2017). An overview is given in Figure 16.

Ship-to-shore Cranes are located at container terminals and are primarily used for loading and unloading cargo containers onto and off container ships. These cranes feature long, horizontal booms with spreader bars that can reach out over the water to access containers on ships' decks (Monios and Bergqvist, 2017).

Straddle carriers are specialized vehicles with tall, gantry-like structures mounted on top of mobile platforms. They are commonly used in container terminals to lift and transport containers horizontally within the terminal yard (Monios and Bergqvist, 2017).

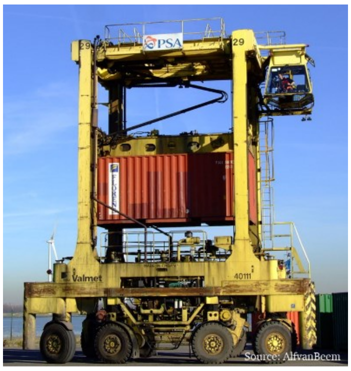
Rubber-tired gantry Cranes are mobile gantry cranes mounted on rubber tires, enabling them to move independently within terminals. They are used for stacking and retrieving containers within the terminal yard. Rail-mounted gantry Cranes are gantry cranes mounted on tracks, allowing them to move along rail lines within container terminals (SGKV e.V., 2024c).

Reach stackers are versatile vehicles equipped with telescopic arms and hydraulic lifting mechanisms designed to lift and stack cargo containers vertically (SGKV e.V., 2024d).

Forklifts are industrial vehicles equipped with forks or other attachments for lifting and moving cargo. They are used for various tasks within intermodal terminals, including loading and unloading trucks and railcars, stacking and de-stacking containers, and transporting cargo within the terminal yard. Forklifts provide flexibility and efficiency in handling a wide range of cargo types and sizes (SGKV e.V., 2024b).

Automated Guided Vehicles are driverless, automated vehicles equipped with sensors and navigation systems for transporting cargo containers within terminal facilities. They are programmed to follow predefined routes and can efficiently transport containers between storage locations, loading bays, and transportation vessels (SGKV e.V., 2024a).

(a)



(b)

(c)

(d)

(e)

(f)

Figure 16: (a) Ship-to-shore Crane, (b) Straddle carrier, (c) Rail-mounted gantry crane, (d) Reach stacker, (e) Forklift, (f) Automated Guided Vehicle

2.4 Policy

In Europe, freight transportation is regulated by multiple bodies operating at both the EU and national levels. At the EU level, the European Commission oversees transportation policies and proposes legislation through its Directorate-General for Mobility and Transport, with the European Parliament and Council of the European Union participating in the legislative process. Several EU agencies, including the European Railway Agency, European Maritime Safety Agency, and European Aviation Safety Agency, specialize in regulating specific modes of transportation. Additionally, each EU member state has its own national transportation authority responsible for implementing and enforcing regulations within its jurisdiction (European Commission, 2022). Industry associations and standardization organizations also play roles in shaping freight transportation regulations. Overall, these regulatory bodies collaborate to ensure the safety, efficiency, and sustainability of freight transportation operations across Europe (European Commission, 2024b).

The United Nations Framework Convention on Climate Change and its Kyoto Protocol, signed in 1997, marked a significant step in global efforts to limit greenhouse gas (GHG) emissions. The protocol, the first legally binding document addressing global warming, established emission reduction targets for industrialized nations referenced to 1990 values. Among the signatories was the EU, which ratified the Kyoto Protocol in 2002, committing to reduce GHG emissions by 8% during the "First Commitment Period" from 2008 to 2012 (European Commission, 2004). This commitment was reinforced by the publication of the EU's medium- to long-term emission reduction strategies in March 2005, proposing a reduction target of 60-80% by 2050 compared to the 1990 baseline (Council of the European Union, 2005).

An analysis by the European Commission highlighted the transportation sector's significant contribution to the EU's total CO2 emissions, with projections indicating that almost 50% of emissions would originate from transportation, primarily reliant on oil products like diesel. Additionally, congestion posed a significant challenge for European citizens (European Commission, 2011a).

In response, the European Commission published the White Paper "Roadmap to a Single European Transport Area" in 2011 as part of its broader initiative "Roadmap to a Resource Efficient Europe." This paper aimed to facilitate the transition to a low-carbon European economy by promoting easier movements of passengers and cargo, reducing costs, and enhancing environmental and social sustainability in transportation (European Commission, 2011b; Golinska and Hajdul, 2012).

Recognizing the limitations of unimodal long-distance road freight transportation, the White Paper advocated for optimizing multimodal logistics chain performance. It emphasized the importance of integrating Member States' national infrastructure to establish a core network of strategic European infrastructure, focusing on projects with high European added value (European Commission, 2011c). Assessment of GHG reduction targets utilized ten benchmarks, including shifting 30% of road freight over 300 km to rail or waterborne transportation by 2030 and establishing a fully functional EU-wide multimodal TEN-T core network by 2030 (European Commission, 2011c).

The unveiling of the European Green Deal in December 2019, also known as “fit for 55”, underscored the EU's commitment to ambitious climate action and sustainability. The Green Deal outlines a comprehensive framework for achieving climate neutrality by 2050. In the context of freight transportation, the Green Deal introduces measures such as Green Freight Corridors, Infrastructure Investment, and Carbon Pricing to reduce emissions and promote sustainable logistics (European Commission, 2019).

Besides shaping the (supra-)national transportation landscape, transportation policy plays a fundamental role in the realm of geopolitics, serving as a cornerstone for economic development, strategic influence, and international relations. Access to efficient transportation networks facilitates trade, connectivity, and mobility, thereby shaping the economic fortunes of nations and regions (Lin, 2019). Control over key transportation routes, such as maritime chokepoints and strategic highways, can confer significant geopolitical leverage, enabling states to exert influence and project power (Schindler et al., 2022). Moreover, transportation infrastructure projects, such as railways, pipelines, and ports, often serve as symbols of geopolitical ambitions, reflecting broader strategic objectives and regional alliances. In an era of globalization, where supply chains span continents, and energy resources traverse vast distances, transportation policy has become inseparable from broader geopolitical dynamics, influencing alliances, rivalries, and the distribution of power on the global stage (Lin, 2019). As such, understanding and navigating the complexities of transportation policy is essential for states seeking to navigate the geopolitics of the 21st century (Rodrigue, 2020).

2.5 Digital transformation

Digitization is one of the main trending topics within the freight transportation sector (Callefi et al., 2024). In the course of the 4th Industrial Revolution, entire logistics operations are being changed and restructured through the use of smart technology that drives the interconnectivity of digital and physical assets (Macário and Reis, 2019). However, it is important not to assume that digital transformation in the logistics sector refers exclusively to a newly used technology but to fundamental changes in the way of communicating, combining information, and the usage and fusion of a variety of new technologies (Bharadwaj et al., 2013). Despite these advancements, the level of digitalization in daily logistics practices falls short of expectations for such a globally interconnected sector (Bundesministerium für Wirtschaft und Klimaschutz, 2024; Karl et al., 2019). Interviews conducted with LSPs reveal significant disparities in digitalization across different transportation modes, with the rail freight sector lagging behind (Mikl et al., 2021).

Among the barriers and success factors of digital transformation identified by Cichosz et al. (2020), the complexity of logistics systems and the scarcity of skilled personnel emerge as major barriers, hindering swift progress (see Figure 17).

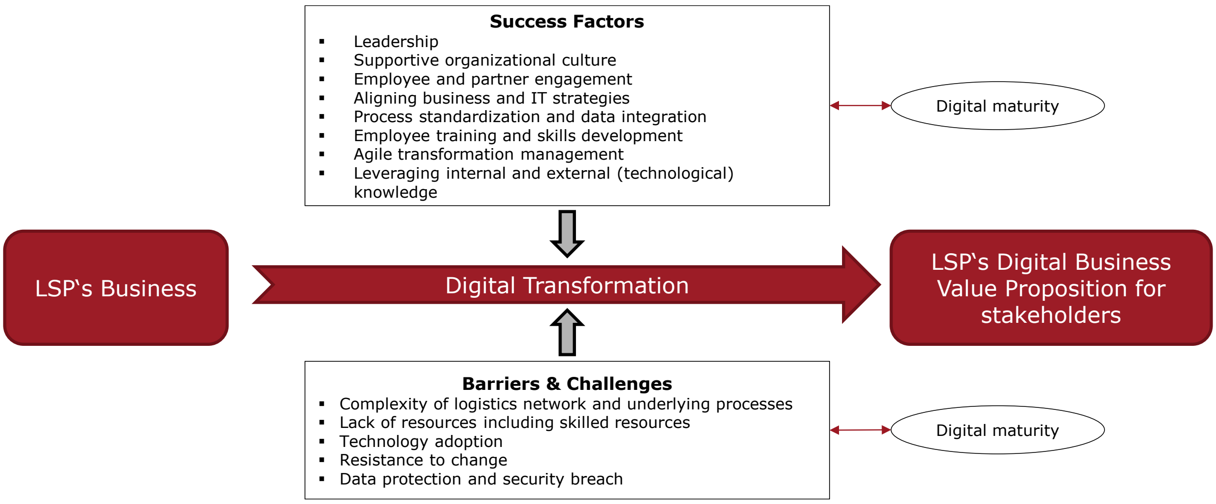


Figure 17: Barriers and success factors of digital transformation |own representation based on Cichosz et al. (2020)

Moreover, substantial investments in technology-specific solutions and concerns regarding data protection further impede the pace of digitalization (Cichosz et al., 2020; Heinbach et al., 2021). Nevertheless, mounting societal and customer pressure is prompting a reevaluation within the transportation sector, leading to the development and implementation of new business strategies and digitalization projects (Cichosz et al., 2020). Digital transformation promises numerous benefits, including real-time data processing for dynamic decision-making, enhanced transparency, and improved resilience against disruptions (Guo et al., 2021a; Harris et al., 2015; Macário and Reis, 2019). To facilitate this transformation, organizations must prioritize factors such as clear vision, active management engagement, and building a supportive organizational culture (Cichosz et al., 2020). Additionally, fostering trust among employees, promoting cross-departmental collaboration, and investing in skills development are essential for driving successful digital initiatives (Cichosz et al., 2020).

To sum up, Altuntaş Vural et al. (2020) conclude that the digitalization of the transportation market fosters the attractiveness of intermodal transportation. In the background of digitalization, the landscape of transportation companies will change drastically. The sector will continue to be infused with transparency, which is why small and medium sized enterprises, in particular, will need to further differentiate their product portfolio and engage in alliances (Mikl et al., 2021).

2.6 Overall research design

The overall research design of this dissertation is structured around the two primary RQs raised in Section 1.2.2 that investigate the structural configuration of intermodal transportation networks and the impact of digitalization on intermodal transportation. Each of these RQs is further operationalized into specific research propositions to address the objectives of this dissertation systematically.

Propositions are statements that are based on the previous insights of this dissertation and establish an expected outcome that needs to be investigated. The investigation aims to accept or reject these propositions, thereby contributing to the precise answering of the research questions. According to Yin (2014), propositions help direct data collection and analysis, concretizing the research objective in terms of gaining specific insights. Unlike hypotheses, which are primarily verified through statistical tests, propositions focus on qualitative elaboration to analyze relationships. Often, the elaboration of propositions is complemented by quantitative approaches, creating a holistic framework for analysis (Mayring, 2022).

The first RQ focuses on understanding how the configuration of intermodal transportation networks can address key challenges such as capacity, schedule, and operational efficiency. RQ 1.1 aims to determine if combining strategic and tactical planning models, such as the HLP and SNDP, can provide a comprehensive framework for analyzing network structures and optimizing transportation operations. RQ 1.2 investigates the feasibility and benefits of continental intermodal transportation to connect Asia and Europe. This gives rise to the following RPs:

RP 1.1: *Integrating strategic hub location and tactical service network design models provides deeper insights into the network structure, leading to optimized configurations that enhance efficiency and reduce costs.*

RP 1.2: *Continental intermodal transportation offers a viable solution for connecting Asia and Europe, leveraging the strengths of various transportation modes. It can be a feasible alternative to sea freight transportation, offering an opportunity to diversify networks and increase resilience*.

To answer RQ 1.1, an integrated hub location and service network design problem is developed and compared to the sequential modeling process to assess the impact on network efficiency and performance. For RQ 1.2, a qualitative interview study with political authorities and logistics companies is conducted to assess the geopolitical dimension and transportation perspective of the Trans-Caspian Corridor.

The second RQ examines the transformative effects of digitalization and real-time data on intermodal transportation systems. RQ 2.1 seeks to understand how the availability of real-time data enhances visibility, coordination, and decision-making in PPH of intermodal transportation. RQ 2.2 investigates how digital advancements facilitate the integration of various transportation modes, leading to the evolution of more dynamic and adaptive intermodal transportation systems. This leads to the following RPs:

RP 2.1: *Real-time data availability significantly improves operational processes in the pre-and post-haulage phases of intermodal transportation by enhancing visibility and enabling dynamic adjustments to the pickup and delivery process.*

RP 2.2: *Digitalization and real-time data integration evolve the intermodal transportation concept toward synchromodal transportation, enhancing overall system performance and enabling more responsive and adaptive transportation solutions.*

To answer RQ 2.1, the effects of real-time data on operational processes in the pre-and post-haulage phases of intermodal transportation will be examined through a simulation-optimization study based on a real-world case study. For RQ 2.2, the broader impacts of digitalization on intermodal transportation will be assessed through an SLR.

The overall research design of this dissertation is structured to provide a comprehensive analysis of intermodal transportation systems by leveraging multiple methodologies and planning levels. By connecting qualitative and quantitative methods, integrating real-world data, and employing advanced analytical techniques, this research aims to contribute to the development of more efficient, sustainable, and adaptive intermodal transportation solutions. An overview of the methodologies employed is given in the next chapter.

3 Methodological background

The selection of methods in this dissertation is primarily determined by the delineation of the research subject, the formulated research questions, the fundamental theoretical framework, and the current state of research. These elements guided the theory-driven development of propositions.

In order to answer these extensive questions in full, a multi-method approach is pursued. Employing multiple methods has the advantage of examining the research subject from different perspectives and gaining comprehensive insights (Creswell and Plano Clark, 2011; Easterby-Smith et al., 2002). Mingers and Brocklesby (1997) aptly describe this with the following words: "In order to make the most effective contribution in dealing with the richness of the real world, it is desirable to go beyond using a single […] methodology to generally combine several methodologies, in whole or in part, and possibly from different paradigms." However, even today, a single method is often chosen for a study. Therefore, Wall et al. (2015) call for more multi-method approaches. This dissertation adheres to this call by connecting several qualitative and quantitative methods.

The various approaches for collecting, analyzing, interpreting, and presenting data in multi-methods studies are reflected in diverse designs (Creswell and Plano Clark, 2011). These designs can be differentiated based on whether the methods are applied in parallel or sequentially and whether their significance in answering the research questions is equal or unequal. The approach pursued in this dissertation involves the combination of systematic literature reviews (qualitative), expert interviews (qualitative), grounded theory (qualitative), case study (qualitative) as well as simulation (quantitative), and mathematical optimization (quantitative), which corresponds to a complementarity design (Davis et al., 2011). In this design, different aspects of the same phenomenon are examined by equally weighted methods in a one-phase design. Data and insights from multiple studies are analyzed and interpreted concurrently, merging the findings in a single report of results. In contrast to development and initiation designs, the sequence of methods does not play a decisive role in addressing the research questions. The outcomes derived from one method do not influence the planning or execution of the subsequent methods (Davis et al., 2011).

The chosen methods are a mix of qualitative and quantitative approaches. Although there is often opposition between the two camps, with quantitative researchers criticizing qualitative methods for lacking theory and being arbitrary and qualitative researchers criticizing quantitative methods for being too rigid and unable to capture the meanings behind human behavior, this dichotomy does not reflect common practice (Gläser and Laudel, 2010; Maxwell, 2010). This dissertation connects quantitative and qualitative approaches to complement each other. For example, a systematic literature review is conducted, and a mathematical optimization model is developed to complement it.

The specific methods employed in this dissertation are detailed in the following sections. In Section 3.1, an overview of the quantitative research approaches is given. Followed by an introduction of the qualitative research approaches in Section 3.2.

3.1 Quantitative research approaches

An analysis of the body of literature on research on intermodal transportation presented in Section 1.2.1 reveals that most of the research conducted in the field is of quantitative nature. From the 2.886 research items identified, more than 1.950 (67,6%) employ a quantitative methodology like simulation, optimization, or statistical analysis[1].

Quantitative planning in logistics leverages mathematical optimization and simulation to enhance decision-making (Domschke et al., 2015). Mathematical optimization employs models to identify the best solutions for logistics challenges, such as minimizing costs and maximizing efficiency in various operational scenarios (Günther and Tempelmeier, 2016). Techniques like linear programming, (mixed) integer programming, and dynamic programming are used to solve complex logistics problems, providing precise and actionable strategies for resource allocation, scheduling, and routing (Kilger et al., 2015).

Simulation creates digital replicas of logistics processes to analyze and predict system behavior under different conditions (Gutenschwager et al., 2017). By modeling operations as sequences of events, simulations can identify potential bottlenecks and evaluate the impact of various strategies in a controlled environment (Borshchev, 2013). This allows logistics managers to test changes and make data-driven decisions without disrupting actual operations.

The integration of mathematical optimization and simulation provides a robust framework for logistics planning. While optimization offers precise solutions, simulation provides a dynamic and flexible approach to understanding and improving logistics systems (Domschke et al., 2015).

Quantitative decision-making in the management of intermodal freight transportation systems is typically split into three distinct planning levels: Strategic, tactical, and operational (Domschke and Scholl, 2008). Each level addresses different timeframes and aspects of intermodal transportation (SteadieSeifi et al., 2014).

Strategic planning is the highest level of planning, concerned with long-term decisions that

[1] A subset analysis with the querry ("OR" OR "operations research" OR optimiz* OR simula* OR model* OR mathematical OR quantitative OR stochastic OR fuzzy) identified 1.962 research items

shape the foundation of the transportation network for years to come (Alumur et al., 2021). Strategic planning focuses on selecting transportation modes, placing hubs and terminals, and major investments in infrastructure. The aim is to design a network that maximizes efficiency, minimizes costs, and has the flexibility to adapt to future changes in demand and market conditions (Archetti et al., 2022). Decisions made during strategic planning are generally broad and high-level, such as determining which new markets to enter, where to build new logistics centers, or how to respond to large-scale economic or environmental changes. The output of strategic planning typically includes policies and objectives that guide more detailed planning at the tactical and operational levels (Domschke and Scholl, 2008).

Tactical planning translates the broad directives set out in the strategic plan into specific, actionable initiatives that can be implemented over the medium term (Domschke and Scholl, 2008). It involves detailed analyses of the various components of the transportation network, such as route and service planning, fleet management, and the scheduling of operations. Tactical planning addresses questions like how to increase network capacity by adding vehicles or routes or how to improve service quality through better logistics management (SteadieSeifi et al., 2014). Tactical plans are more dynamic than strategic plans and require frequent adjustments to respond to changes in the business environment or operational performance (Archetti et al., 2022).

Operational planning is the most granular level of planning, focusing on the day-to-day management of operations within the framework set by strategic and tactical plans (SteadieSeifi et al., 2014). Operational planning ensures the effective execution of tactical plans and the ongoing management of all logistical activities (Domschke and Scholl, 2008). At this stage, the emphasis is on efficiency and the immediate responsiveness of the transportation network to daily fluctuations in demand or disruptions. Operational planning involves specific decisions like the dispatching of vehicles, routing, staff scheduling, loading and unloading operations, and the handling of unexpected events such as vehicle breakdowns or sudden changes in weather conditions (Archetti et al., 2022; SteadieSeifi et al., 2014).

Strategic, tactical, and operational planning cover the spectrum from long-term planning to daily operations in intermodal freight transportation. Each level of planning serves a distinct purpose but is interconnected with the others, ensuring that decisions are aligned and reinforcing across all levels of the organization.

The following sections provide an overview of the relevant planning problems at each decision horizon. Thereby, the conceptual and mathematical models, the solution methods, and the opportunities for future research are presented.

3.1.1 Strategic

Strategic planning in continental intermodal freight transportation involves addressing complex infrastructure investment and network optimization challenges (SteadieSeifi et al., 2014). Central to these challenges is the concept of consolidation, which optimizes cargo flow by concentrating low-volume shipments at consolidation centers for bundling into larger, more economical loads. This strategy leverages high-capacity intermodal services, offering significant cost reductions per load unit compared to less consolidated links (Alumur et al., 2021). Various network topologies (see Figure 18) are employed to manage these flows, including direct link, corridor, and hub-and-spoke. Among these, the hub-and-spoke design is predominant, serving as the focal architecture for most strategic planning literature, with hubs acting as crucial consolidation points for cargo distribution and consolidation (Woxenius, 2007).

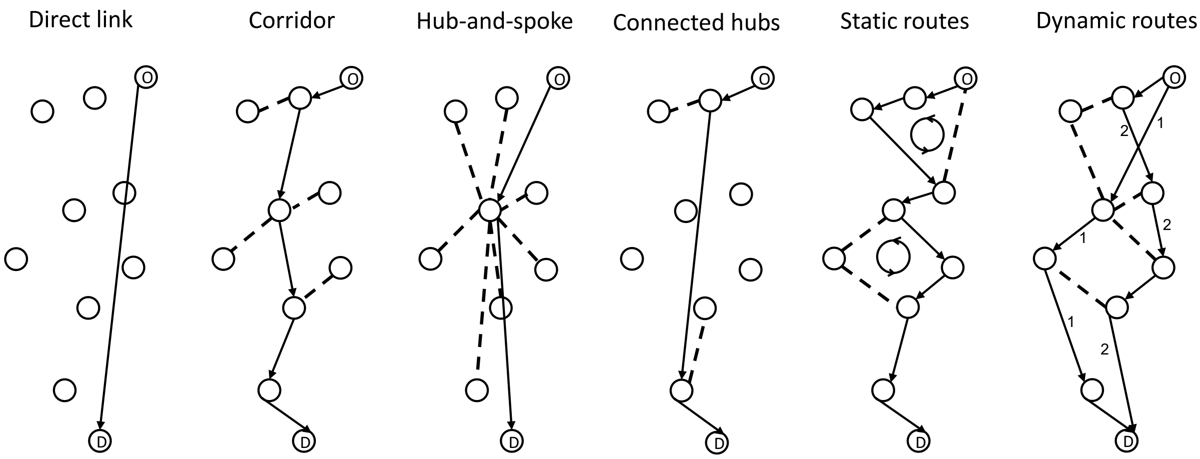


Figure 18: Network topologies for O/D transportation | own representation based on Woxenius (2007)

The hub-and-spoke model is extensively analyzed in the scholarly landscape, particularly through hub location problems (HLP) (SteadieSeifi et al., 2014). These problems typically manifest in three forms: hub median problems, aimed at minimizing total transportation costs; hub center problems, focused on minimizing the maximum distance between origin-destination pairs; and hub covering problems, which seek to maximize the number of served nodes (Alumur et al., 2021; Alumur and Kara, 2008; Meyer et al., 2009). Each model addresses different strategic objectives, from cost efficiency to service quality and market coverage.

However, real-world applications often reveal the limitations of these theoretical HLPs. For example, the typical assumption of a complete graph (every nod is connected with every nod) is impractical at a global scale, where direct shipments and incomplete networks are common. This discrepancy introduces significant challenges in modeling and requires further investigation to align theoretical models with practical logistics operations (Alumur et al., 2012a; Basallo-Triana et al., 2021; Rodríguez-Martín and Salazar-González, 2008). Moreover, the nature of the cargo significantly influences the choice of HLPs, especially in multi-commodity transportation of sensitive goods like perishables or hazardous materials. Here, the hub center problem often provides a more suitable framework for managing large, time-sensitive networks, considering the special handling and safety requirements these goods demand (Basallo-Triana et al., 2021). Allocation strategies (assigning a nod to a hub) also play a critical role in strategic planning. Policies range from single allocation, where nodes are linked to one hub, to more complex multi-, r-, and hierarchical allocations, which allow for more flexible and efficient network configurations (Alumur et al., 2021; Kara and Taner, 2011). Emerging research areas include the study of network capacities and congestion, transshipment costs, and the environmental impacts of hub-and-spoke networks (Basallo-Triana et al., 2021; SteadieSeifi et al., 2014).

An overview of HLP problem formulations and solution approaches is given in Table 2, and an in-depth review of HLPs is provided in Section 5.2. To test the various solution methodologies, data sets like the Australian Post and Civil Aeronautics Board are employed to benchmark algorithm performance (Alumur et al., 2021; Cánovas et al., 2007; Gelareh and Pisinger, 2011). Despite advancements, the complexity of real-world networks frequently outstrips the capability of existing algorithms.

Table 2: Overview of strategic planning challenges in intermodal transportation. Based and extended on SteadieSeifi et al. (2014)

Strategic Planning Problems	Models	Hub-and-Spoke	P-hub median (Elhedhli and Hu, 2005; Kartal et al., 2017)
			P-hub center (Kartal et al., 2019; Meyer et al., 2009)
			P-hub covering (Fotuhi and Huynh, 2017; Tan and Kara, 2007)
		Multi-allocation Hub-and-Spoke	P-hub median (Camargo et al., 2009)
			P-hub center (Ghaffarinasab, 2020)
			P-hub covering (Wagner, 2008)
		r-allocation Hub-and-Spoke	P-hub median (Yaman, 2011)
			P-hub center
			P-hub covering
		Hierarchical allocation Hub-and-Spoke	P-hub median (Yaman, 2009) (Shang et al., 2020)
			P-hub center
			P-hub covering (Dukkanci and Kara, 2017)
	Solution	Exact	Branch & Cut (Rodríguez-Martín and Salazar-González, 2008)
			Benders decomposition (Gelareh and Nickel, 2011; Martins de Sá et al., 2018)
		Approximation	Continuum approximation (Smilowitz and Daganzo, 2007)
		Heuristics	(Fotuhi and Huynh, 2017; Gelareh and Nickel, 2011)
		Metaheuristics	Tabu Search (Ishfaq and Sox, 2011)
			GRASP (Sörensen et al., 2012)
			Simulated Anneling (Mohammadi and Tavakkoli-Moghaddam, 2016; Rodríguez et al., 2007)
			VNS (Rodríguez-Martín and Salazar-González, 2008)
		Hybrid Heuristics	Lagrangian heuristics (Elhedhli and Wu, 2010)
			Lagrangian decomposition (Alumur et al., 2012c)
			Lagrangian relaxation (Alibeyg et al., 2018; Racunica and Wynter, 2005)

3.1.2 Tactical

Tactical planning in continental intermodal transportation focuses on the utilization of existing infrastructure by selecting appropriate services and transportation modes, allocating capacities, and scheduling vehicles and frequencies (Andersen et al., 2009a; Elbert et al., 2020; Wieberneit, 2008). This planning layer involves critical decisions about whether to send cargo directly or through a consolidation system, evaluating trade-offs influenced by system costs, operational times, network structures, and specific customer requirements (Meng and Wang, 2011). Predominantly, tactical planning considers the utilization of hub-and-spoke network structures where cargo is transported either by a single service or a sequence of services, with transfers occurring at intermediate hubs (SteadieSeifi et al., 2014). Each service within this network is distinctly characterized by parameters such as its origin, destination, intermediate stops, mode of transportation, route, and service capacity. Similarly, each transportation mode is defined by attributes including loading capacity, speed, and cost, which are typically associated with fixed expenses (Gelareh and Pisinger, 2011).

The methodology for addressing these tactical challenges is divided into two primary modeling approaches: Network Flow Planning (NFP) and Service Network Design (SNDP) (SteadieSeifi et al., 2014). NFP deals with the movement of orders or commodities throughout the transportation network. In contrast, SNDP is more comprehensive, encompassing all decisions related to the selection of transportation services and modes necessary for moving these commodities. SNDP challenges are subdivided into static and dynamic issues, where static scenarios assume that all network conditions remain constant over the planning horizon, whereas dynamic scenarios accommodate variables such as demand fluctuations over time (Andersen et al., 2011; Elbert et al., 2020). An in-depth review of SNDP problems is given in Chapter 4. SNDPs typically employ a mixture of continuous and binary variables. Continuous variables represent commodity flows throughout the network, while binary variables select services (Elbert et al., 2020). These variables can be structured as arc-based, representing flow on specific network arcs, or path-based, detailing flows along sequences of arcs. Dynamic SNDP problems incorporate a time dimension by introducing a space-time network that captures many real-life dynamics, such as waiting or transfer operations at terminals (Hoff et al., 2010; Pedersen et al., 2009).

In addition to planning flows of commodities and scheduling services, the management of limited available resources or assets (e.g., containers, vehicles, and crew) is part of the SNDP. This aspect of tactical planning involves positioning, balancing, repositioning, and rotating assets to ensure full utilization throughout the planning horizon. Cycle-based variables are particularly useful in integrating the rotation of modes or vehicles into the SNDP models (Zhu et al., 2011).

Given the complexity and scale of NFPs and SNDPs, solving them requires sophisticated heuristic and metaheuristic solution methods, with Tabu Search being a notably popular choice due to its robustness in handling complex and large variable sets (Bai et al., 2012; Elbert et al., 2020; Pedersen et al., 2009). These methods are particularly relevant in dynamic SNDPs, where the physical network expands multiplicatively with the number of time periods considered, making traditional solution approaches less feasible. Moreover, benchmarking these solutions is challenging due to the specific nature of real-world problems addressed in the literature (Elbert et al., 2020). An overview of the tactical planning challenges in intermodal transportation is provided in Table 3.

Table 3: Overview of tactical planning challenges in intermodal transportation. Based and extended on (SteadieSeifi et al., 2014)

Tactical Planning Problems	Models	Network Flow Planning	Arc-based (SteadieSeifi et al., 2017; Verma et al., 2012)
			Path-based (Cohn et al., 2008; Zhou et al., 2018)
			Stochastic programming (Miller-Hooks et al., 2012)
		Static Service Network Design	Arc-based (Chouman and Crainic, 2011; Katayama, 2020)
			Path-based (Caris et al., 2012; Zetina et al., 2019)
			Stochastic programming (Rahmaniani et al., 2018)
		Dynamic Service Network Design	Arc-based (Andersen and Christiansen, 2009; Bai et al., 2018)
			Path-based (Andersen and Christiansen, 2009; Müller et al., 2021b)
			Cycle-based (Pedersen et al., 2009; Wang et al., 2019b)
			Stochastic programming (Hewitt et al., 2019; Hoff et al., 2010)
	Solution	Exact	Branch & Bound (Pazour et al., 2010), B&P (Andersen et al., 2011)
			Decomposition (Bauer et al., 2010; Rahmaniani et al., 2018)
			Relaxation and Decomposition (Meng et al., 2012; Wang and Qi, 2019)
		Heuristics	Decision algorithm (Huang et al., 2011)
			Greedy heuristic (Agarwal and Ergun, 2008; Katayama, 2019)
			Local search (Bai et al., 2012; Heggen et al., 2019; SteadieSeifi et al., 2017)
			Scenario tree generation (Puettmann and Stadtler, 2010)
		Metaheuristics	Tabu search (Bai et al., 2012; Li et al., 2017b)
			Randomized neighborhood search (Anghinolfi et al., 2011)
			Genetic algorithm (Shintani et al., 2007; Yang et al., 2011)
		Hybrid Heuristics	Column generation based (Moccia et al., 2011)
			Dynamic programming based (Cho et al., 2012)
			Decomposition based (Teypaz et al., 2010)
		Others	Simulation (Caris, 2011; Hrušovský et al., 2018; Layeb et al., 2018)
			Matheuristic (Hewitt et al., 2019; Wang and Qi, 2020; Zetina et al., 2019)

3.1.3 Operational

Operational planning focuses on the day-to-day management of operations. It faces challenges due to the need for real-time decision-making in response to dynamic and stochastic factors (Archetti et al., 2022; SteadieSeifi et al., 2014). It can be categorized into two primary areas: resource management and itinerary replanning (SteadieSeifi et al., 2014).

Resource management focuses on the optimal utilization of available resources such as vehicles, containers, and crew, addressing tasks like positioning, repositioning, storing, and allocating these resources to fulfill customer orders. On the other hand, itinerary replanning deals with the real-time optimization of schedules and modal routes to effectively accommodate operational disturbances. However, there are certain overlaps between these two areas.

Resource management involves decisions about the allocation and repositioning of resources to maximize their utility and minimize idle times and unnecessary repositioning costs. Empty loading unit repositioning is a significant issue, where empty containers or other loading units must be moved back to their points of necessity. This process often involves balancing transportation and storage costs against service levels and availability (Di Francesco et al., 2013; Erera et al., 2005). The stochastic nature of future demands complicates these decisions, as the planners must forecast and plan without definite knowledge of future requirements. Itinerary replanning addresses the need for flexibility in the transportation network, allowing for adjustments to schedules and routes in response to unexpected changes in the operational environment. Di Francesco et al. (2013) explore the impact of disruptions such as port closures, employing time-space network models to simulate various disruption scenarios and assess the effectiveness of different planning strategies. They highlight the importance of robust planning models that can adapt to both minor and significant changes in the operational context.

Two planning problems that often combine resource management and itinerary replanning are Vehicle Routing Problems (VRP) and Pickup and Delivery Problems (PDP).

The VRP is a classic logistics challenge first introduced by Dantzig and Ramser (1959). It involves determining the most cost-effective routes for a fleet of vehicles to service customers with known demands, classically within a static and deterministic context. In real-world applications, however, the problem often exhibits dynamic and stochastic characteristics due to unpredictable factors such as traffic conditions, weather changes, and real-time customer requests (Psaraftis et al., 2016; Ritzinger et al., 2016).

The dynamic VRP emerged as a response to these real-world challenges, incorporating real-time data and adapting routes as new information becomes available. Advances in Information and Communications Technology (ICT) have significantly facilitated the processing and collection of real-time data, enabling more effective dynamic routing solutions (Ritzinger et al., 2016).

The PDP is a specialized variant of VRP where goods or passengers need to be transported from various pickup locations to corresponding delivery locations. PDPs are classified into three main categories: many-to-many, one-to-many-to-one, and one-to-one problems (Toth and Vigo, 2014). In the context of PPH in intermodal transportation, PDPs play a crucial role in ensuring that containers and cargo are efficiently moved between ports, terminals, and inland destinations. As in dynamic VRPs, dynamic PDPs add another layer of complexity by introducing uncertainties and real-time requests. These dynamic aspects require continuous route adjustments and decision-making based on new information, such as sudden customer requests or disruptions like vehicle breakdowns and traffic congestion (Berbeglia et al., 2010; Mitrović-Minić et al., 2004).

Stochastic variants of VRP and PDP further complicate the operational planning landscape by introducing probabilistic elements, such as uncertain demand, travel times, and service times, into the problem. Both the dynamic and stochastic nature of real-world operations can be considered simultaneously in the PDP. This means that customer requests, travel times, and service times are not fully known in advance and may change over time. The challenge in these PDPs is to develop routing strategies that can anticipate and adapt to these uncertainties in real-time. For example, in the dynamic VRP with stochastic service requests, some customer requests are known in advance, while others are only revealed as the vehicle is en route (Ulmer and Thomas, 2019). Similarly, uncertain service times, such as varying loading and unloading times at different locations, add complexity to the problem.

The dynamic and stochastic nature of VRPs and PDPs requires sophisticated real-time solutions to ensure efficient and reliable freight movement. Given the complex nature of these problems, operational planning often relies on heuristic and metaheuristic solution methods capable of providing good solutions within acceptable time frames for real-time decision-making. Techniques such as Branch-and-Bound heuristics and various forms of decomposition strategies are employed to manage the computational complexity associated with large-scale problems (Bandeira et al., 2009; Ojeda Rios et al., 2021; Psaraftis et al., 2016; Soeffker et al., 2022). An Overview of the operational planning challenges in intermodal transportation is given in Table 4.

Table 4: Overview of operational planning challenges in intermodal transportation. Based and extended on (SteadieSeifi et al., 2014)

Operational Planning Problems	**Models**	Fleet Management and Resource Allocation	Time-space representation and network flow problem (Bandeira et al., 2009; Di Francesco et al., 2013)
		Itinerary Re-planning	Time-space representation & routing, and scheduling (Bock, 2010; Goel, 2010)
		VRP	Overview (Adewumi and Adeleke, 2018; Braekers et al., 2016; Fleckenstein et al., 2023; Mor and Speranza, 2020; Ojeda Rios et al., 2021)
		PDP	Overview (Berbeglia et al., 2010; Ulmer et al., 2020)
	Solution	Exact	Commercial Solver (Baldacci et al., 2011; Paradiso et al., 2020)
		Heuristics	Decomposition (Bandeira et al., 2009; Cordeau et al., 2015; Côté et al., 2023; Zhang et al., 2017)(Côté et al., 2023)
			GRASP (Santos and Xavier, 2015)
			Two-stage shortest-path based (Györgyi and Kis, 2019; Song and Dong, 2012)
		Metaheuristics	Variable neighborhood search (Archetti et al., 2018; Ghilas et al., 2016; Sarasola et al., 2016)
			Tabu search (Shi et al., 2018)
			Genetic Algorithmns (van Lon et al., 2018)
		Matheuristics	Branch-and-Bound heuristic (Côté et al., 2023)
		Others	Simulation (Juan et al., 2014; Topaloglu, 2006)
			Simulation + Exact (Hrušovský et al., 2018)

Despite the advancements, there remains a significant need for research focused on integrating more realistic dynamics and stochastics into operational planning models, such as better handling of uncertainty and developing more effective real-time decision-making tools (Archetti et al., 2020; Balster et al., 2020; Poschmann et al., 2019).

In this dissertation, two quantitative evaluation approaches are employed. In Chapter 5, an integrated HLP and SNDP model is investigated. It connects strategic and tactical planning to develop more coherent and efficient network structures, ensuring that long-term goals are aligned with short-term actions. This novel modeling approach is compared to the classical sequential modeling approach. It is subsequently tested in a case study involving a German intermodal operator.

In Chapter 7, the impact of digitalization and real-time data on the PPH of intermodal transportation is analyzed. A simulation-optimization study was conducted to investigate this operational planning problem. With this, various scenarios of clustered, dynamic, and stochastic ETA forecasts and their impact on the PPH of intermodal transportation can be simulated. Unlike previous analysis approaches that rely on simple traveling salesman problems, an intricate stochastic and dynamic PDP with time windows is used. The simulation utilized a simheuristic solution procedure combining simulation and a biased randomized savings algorithm, including a rolling horizon framework to handle real-time data. The problem is evaluated in a real-world case study in Central Europe.

3.2 Qualitative research approaches

This section briefly introduces qualitative research in the context of intermodal transportation. After giving a characterization of qualitative research, the most important methodological approaches are introduced. It closes by summarising the benefits and challenges.

Qualitative research can help understand intermodal transportation's intricate and dynamic nature. It focuses on exploring processes, stakeholder interactions, and contextual factors, making it particularly valuable for addressing "how" and "why" questions (Eisenhardt, 1989). Unlike quantitative research, which aims to quantify variables and establish statistical relationships, qualitative research seeks to provide a rich, detailed understanding of phenomena by exploring them from multiple perspectives (Pratt, 2009). Qualitative research is defined by its emphasis on understanding the meanings and interpretations of concepts within specific contexts (Gephart, 2004). It employs various methods such as interviews, focus groups, participant observations, and content analysis (Davis et al., 2011). These methods allow researchers to capture the subtleties of human experience and the context within which intermodal transportation operates (Golicic and Davis, 2012). For instance, interviews and focus groups can reveal the underlying motivations, beliefs, and attitudes of stakeholders, providing insights into the decision-making processes that influence intermodal transportation (Roso, 2008). Qualitative research can further uncover insights into the challenges faced in coordinating different modes of transportation and the contextual factors influencing transportation efficiency and effectiveness (Pham and Yeo, 2018). For example, it can explore how logistics providers navigate regulatory environments, how technological innovations are adopted and integrated, and how different stakeholders collaborate to optimize transportation networks (Jesus et al., 2023; Sugawara, 2017).

Qualitative research is inherently interpretive, involving ongoing reflection and analysis to identify patterns and themes (Eisenhardt, 1989). By doing so, qualitative research provides nuanced insights that inform both theory and practice. It complements quantitative approaches by adding depth and context to numerical findings (McCutcheon and Meredith, 1993). Developing sound and rich theory based on real-world conditions is a prerequisite for analytical modeling and testing (Flynn et al., 1990). While quantitative research might reveal patterns and correlations, qualitative research explains the reasons behind these patterns, offering a comprehensive understanding (Eisenhardt, 1989). Overall, qualitative research in intermodal transportation helps develop a holistic view of the industry, which is essential for informed decision-making and effective policy development.

Methodological approaches

Case studies involve an in-depth examination of specific instances within their real-life context (Eisenhardt, 1989). Case studies can be single or multiple, holistic or embedded, depending on the RQ and scope (Yin, 2014). They are particularly useful in intermodal transportation research because they allow for a detailed exploration of complex systems and processes involving multiple stakeholders (Islam and Zunder, 2018). Case study research in intermodal transportation often focuses on specific corridors, transportation hubs, or logistical operations (Monios, 2016). By examining these cases, researchers can identify best practices, understand the challenges faced by different actors, and explore the impact of various policies and regulations on transportation efficiency (Bask et al., 2014).

Conducting interviews with experts in the field is another critical method in qualitative research. These interviews can be structured, semi-structured, or unstructured, depending on the research objectives (Hoffmeyer-Zlotnik, 1992). Expert interviews provide valuable insights into the practical realities of intermodal transportation, including the perspectives of policymakers, transportation operators, logistics managers, and other stakeholders (Glaser, 1992). In intermodal transportation research, expert interviews can shed light on issues such as the integration of different transportation modes, the effectiveness of regulatory frameworks, and the technological advancements shaping the industry (Friedrich et al., 2023). These interviews help to contextualize quantitative data and enrich the overall analysis (Gioia et al., 2013).

Grounded theory is an inductive research methodology that involves developing theories based on data collected during the research process (Gioia et al., 2013). This approach is particularly useful when existing theories do not adequately explain the phenomena under study (Glaser and Strauss, 1980). The grounded theory approach involves iterative cycles of data collection and analysis, with the goal of developing a theory that is grounded in empirical data (Gioia et al., 2013). This method is well-suited for exploring new or poorly understood aspects of intermodal transportation, such as the adoption of digital technologies or the impact of climate change on transportation networks (Fang et al., 2020).

The Delphi study is a structured communication technique used to gather expert opinions and achieve consensus on specific topics (Landeta, 2006). This method involves multiple rounds of surveys, where experts respond to questionnaires and provide feedback. The responses are aggregated and shared with the group after each round, allowing participants to refine their views based on the collective feedback (Sossa et al., 2019). In the context of intermodal transportation, Delphi studies can be particularly useful for predicting future trends, identifying emerging challenges, and practice-oriented theory building within communities (Brady, 2015). By leveraging the knowledge and experience of a diverse panel of experts, Delphi studies can generate comprehensive and forward-looking insights that inform policy-making and strategic planning (Gleser and Elbert, 2024).

Systematic literature reviews (SLRs) are another fundamental qualitative research method (Kitchenham and Charters, 2007). SLRs provide a comprehensive and methodical synthesis of existing studies, essential for identifying gaps in the current body of knowledge, summarizing evidence, and informing future research directions (Denyer and Tranfield, 2009). SLRs are characterized by their rigorous and transparent methodology. Unlike traditional narrative reviews, SLRs follow a structured process that includes the formulation of RQs, systematic search and selection of relevant literature, critical appraisal of the studies, and synthesis of the findings (Kitchenham and Charters, 2007). This methodological rigor ensures that the review process is replicable and minimizes bias. In intermodal transportation, SLRs consolidate knowledge from diverse sources, providing a holistic understanding of the field (Durach et al., 2017). They identify methodological trends, highlight areas where further research is needed, and uncover inconsistencies and contradictions in the literature, guiding researchers toward resolving these issues (Durach et al., 2021).

Application and benefits

Qualitative research allows a nuanced understanding of the contextual factors influencing intermodal transportation (Yin, 2016). Researchers can identify the factors that facilitate or hinder effective transportation by exploring the specific circumstances and conditions in which transportation operations occur. By engaging directly with stakeholders through interviews and case studies, qualitative research provides insights into the perspectives and experiences of those involved (Friedrich et al., 2023). The open-ended nature of qualitative research methods allows for flexibility in exploring complex issues (Merriam, 1989). Researchers can adapt their methods to suit the specific research context and delve deeply into the aspects that are most relevant to their RQs (Eisenhardt, 1989). It further contributes to the development of theories that explain the dynamics of intermodal transportation. By grounding theories in empirical data, researchers can develop robust explanations that are directly applicable to real-world contexts (Gioia et al., 2013). The insights gained from qualitative research can inform policy-making and practical decision-making (Gleser and Elbert, 2024). By understanding the challenges and opportunities faced by transportation operators and other stakeholders, policymakers can develop more effective regulatory frameworks and support measures.

Challenges and considerations

While qualitative research offers many advantages, it also presents certain challenges: The interpretive nature of qualitative research means that findings can be influenced by the researcher's perspectives and biases (Hirschhorn, 2019). It is important to adopt rigorous methods for data collection and analysis to ensure the reliability and validity of the findings. Due to the specific and contextual nature of qualitative research, the findings may not always be generalizable to other contexts (Gioia et al., 2013). Researchers must carefully consider the extent to which their findings can be applied to other settings (Eisenhardt, 1989). Finally, qualitative research methods, such as in-depth interviews and case studies, can be time-consuming and resource-intensive. Researchers need to plan and allocate sufficient resources to ensure the thoroughness and depth of their studies (Yin, 2014).

In this dissertation, three qualitative evaluation approaches are used. In Chapter 4, an SLR of SNDPs is conducted. Combined with the literature review in Section 5.2 on HLPs, the research conducted on hub location planning and service network planning and design in intermodal transportation is systematically classified. It was found that the combination of HLP and SNDP has the potential to lead to more detailed and realistic solutions but, at the same time, to a significant increase in complexity (Rothenbächer et al., 2016).

Chapter 5 uses expert interviews and grounded theory to explore the feasibility and benefits of continental intermodal transportation as a possible solution for connecting Asia and Europe. The qualitative analysis of the Trans-Caspian Corridor through interviews with logistics companies and political authorities revealed the intricate geopolitical and strategic challenges, which are often difficult to quantify. The grounded theory approach allowed for the identification of emergent themes and patterns that were not initially anticipated.
In Chapter 8, an SLR on the research of SMT is conducted. Digitalization drives the evolution of intermodal transportation towards SMT, where different transportation modes are seamlessly integrated to provide flexible and adaptive real-time solutions. The SLR highlights the importance of dynamically integrating different transportation modes to achieve a more flexible and adaptive transportation system.

With this overview of the background of intermodal transportation, the quantitative and qualitative research approaches, the conceptual backgrounds of this dissertation have been thoroughly described. Since the following five chapters are based on independent papers, an overall summary of the results according to the RQs and corresponding RPs is given in the overall conclusion in Chapter 9.

4 Study 1: State of research on tactical network planning and design[2]

Multimodal transportation, which refers to the combination of different modes in a transportation chain, can be a cost-efficient and green alternative to unimodal road transportation in the carriage of goods. However, complex transportation processes require network flow planning and design models on a tactical level that cover the multiple stages and paths of a multimodal network to determine cost-minimal and reliable operations. This paper summarizes the current state of research since 2008 on the specific categories of those models by means of a systematic literature review. The references within each category are evaluated in terms of problem characteristics, model formulations, and solution approaches. Moreover, the research streams on deterministic and stochastic models (including uncertain demand, transportation times, costs, and capacities) are compared. Finally, the main fields for future research, among others, the further inclusion of environmental aspects and the more frequent application of simulation as a solution approach, are identified.

4.1 Introduction

Due to the ongoing trend towards specialization and internationalization of members within supply chains, freight transportation plays a crucial role in efficiently meeting customer demand. Cost-efficient and reliable transportation plans are a key pillar of successful supply chains (Sanchez-Rodrigues et al., 2010). Multimodal transportation can be a beneficial approach for enhancing transportation operations by simultaneously exploiting the advantages of different modes (Crainic and Kim, 2007). The term refers to the transportation of goods by a sequence of at least two different modes of transportation. It includes intermodal transportation (where the load is transported from an origin to a destination in one and the same intermodal transportation unit without the goods themselves being handled when changing modes) and combined transportation (intermodal transportation of goods where the major part of the journey is by rail, inland waterway or sea and any pre and/or post haulage carried out by road is as short as possible) (EUROSTAT et al., 2019).

Besides advantages for the individual economic actors (multimodal operators, freight forwarders, and shippers), the society as a whole can profit from a modal shift towards more environmentally friendly transportation modes as a means for reducing the climate impacts of

[2] The content of this study is similar with only slight modifications to the paper Elbert, R., Müller, J.P., Rentschler, J., 2020. "Tactical network planning and design in multimodal transportation – A systematic literature review". Research in Transportation Business & Management 35, 100462. Thus, in section the pronoun "we" refers to the authors of the paper.

the globalized economy. For the EU, road transportation remains the dominant mode of inland transportation, with a modal split of approximately 76% of total ton-kilometers in 2016 (EUROSTAT, 2018). In this context, multimodal transportation can contribute significantly to reducing GHG emissions of the EU member states by 40% in 2030 compared to 1990 (Delbeke and Vis, 2015).

Despite these positive economic and environmental impacts, in many cases, unimodal transportation solutions remain the preferred option, even if a multimodal network infrastructure is available. One reason is the increased complexity of the transportation process, compared to unimodal transportation, due to the combination of different modes, including transshipment operations, and the necessity of the different actors along the transportation chain to coordinate their activities (Elbert and Seikowsky, 2017). A higher planning effort is needed to determine the capacities and schedules of the single transportation services and to identify cost-efficient and reliable transportation paths through the network.

In addition to the increased complexity of planning, reservations concerning flexibility and reliability can motivate decision-makers to rely on one transportation mode (Demir et al., 2016). Uncertainty includes unknown or stochastic transportation demand and stochastic transportation times (e.g., delays of transportation services). Stochastic demand is related to flexibility reservations, e.g., capacity shortages of transportation services in case of unforeseen demand peaks (Bai et al., 2014). Stochastic transportation times refer to reliability reservations. In consequence, on the one hand, the consideration of uncertainty in the planning of multimodal transportation is a crucial factor for realizing its full potential and providing decision makers with adequate support for shifting transportation modes. On the other hand, the complexity of planning is further increased by including stochastic parameters. An example is the prolongation of delays in one part of the transportation chain to the subsequent parts, which can require complex re-planning activities.

For those reasons, multimodal operators rely on planning models, which provide adequate decision support for handling the complexity of the networks. In general, multimodal transportation planning models can be categorized into strategic, tactical, and operational planning with regard to their decision horizon (SteadieSeifi et al., 2014). Strategic planning problems relate to investment decisions on the infrastructures (e.g., hub location problems). Tactical planning problems deal with network flow planning and design, which refers to optimally utilizing the given infrastructure by choosing services and associated transportation modes, allocating their capacities to orders, and planning their itineraries and frequency. A further field of tactical planning is asset management, in which schedules for single vehicles are derived (Andersen and Christiansen, 2009). As the third field, demand and capacity management aim to maximize revenue for the offered services or transportation capacities respectively (Luo et al., 2016). Operational planning covers the same planning problems as tactical planning but with consideration of real-time requirements. In contrast to tactical planning, operational planning arises immediately before or during the execution of the transportation services.

Of the three decision horizons, network flow planning and design, as a field of tactical planning, is of special interest to create incentives for a modal shift to more environmentally friendly transportation modes in the short and medium term. Sophisticated planning models can help multimodal operators determine schedules with minimized costs for their transportation services, which are tailored to the specific demand. Their customers (freight forwarders and shippers) can benefit from the evaluation of the different transportation paths of the network, identifying superior alternatives to unimodal transportation, and choosing transportation modes and suitable services accordingly. An additional field of application is the analysis of complete transportation networks on national or even supranational level conducted by governments, researchers, or planning agencies. Besides evaluating transportation times and costs, environmental indicators for greenhouse gases and pollutant emissions are of special interest from an overall economic perspective. Planning models for network flow and design can provide precise estimates for emission values because they cover the single transportation processes of the entire network on an aggregated level.

By further incorporating uncertainty into the models, flexibility and reliability reservations for modal shifts can be reduced. With regard to flexibility (stochastic demand), multimodal operators can ensure a trade-off between capacity utilization and providing sufficient capacity for covering peak demand. Analogously, freight forwarders and shippers can determine capacity bookings in advance in order to fulfill transportation orders and avoid unused capacity. In terms of reliability (stochastic transportation times), multimodal operators are enabled to analyze the punctuality of their services and plan measures for increasing reliability (e.g., buffer times between subsequent services). Freight forwarders and shippers can benefit from reliable estimates for transportation costs, transportation times, and shares of on-time delivered orders. To sum it up, planning models for network flow and design can strengthen the competitive position of multimodal operators vis-à-vis unimodal road service providers by simultaneously optimizing cost, capacity allocation, and reliability. Moreover, the mode choice behavior of freight forwarders and shippers can be transformed from a predefined selection of road transportation to a rational selection of the most suitable transportation mode.

Despite the importance of planning models for network flow and design for supporting modal shift, a comprehensive overview of the current state of research is missing. General reviews on planning in multimodal transportation (Steadieseifi et al., 2014) cover tactical planning only as one aspect besides strategic and operational planning and do not expound on planning models for network flow and design in detail. Specific reviews on Service Network Design (Crainic, 2000; Wieberneit, 2008) require an update to cover the large amount of research on this topic during the last decade. Especially the consideration of uncertainty has gained increasing attention in recent years, which justifies the necessity for a special focus on stochastic planning approaches. In order to address this research gap, the objective of the paper at hand is to provide a comprehensive survey of network planning and design under consideration of uncertainty. In detail, three RQs should be answered by means of a systematic literature review:

- RQ 1: How can research conducted on network planning and design in multimodal transportation be systematically classified with reference to problem characteristics, model formulations, and solution approaches?
- RQ 2: In which way is uncertainty incorporated into the models, and how do problem characteristics, model formulations, and solution approaches differ from their deterministic counterparts?
- RQ 3: Which aspects (in terms of problem characteristics, models, and solution approaches) are already considered, and which fields for future research can be derived?

The remaining parts of the paper are structured as follows: Section 4.2 introduces network planning and design problems as part of tactical planning in multimodal transportation. In Section 4.3, we describe the methodological approach of the literature review and give an overview of publication data for the references contained in the content-related evaluation. In Section 4.4, the literature is analyzed (RQ1, RQ 2), and further fields of research are identified (RQ3). Finally, Section 4.5 summarizes the limitations of the review and gives a conclusion.

4.2 Network planning and design as part of tactical planning

Network planning and design is an important part of tactical planning in multimodal transportation. It covers the planning problems of service network design and network flow planning. According to SteadieSeifi et al. (2014), service network design involves service planning decisions, including all decisions on choosing the transportation services and modes to move those commodities. Network flow planning relates to the flow planning decisions addressing the movement of orders (commodities) throughout the network. Figure 19 shows the input parameters and decisions for both problems.

The input parameters include a given hub-and-spoke transportation network with node set N and arc set A. Moreover, values for fixed and variable network costs are given. Fixed costs cover costs $c_{a,ij}$ for offering transportation services on a single arc of the network. Variable costs $c_{c,ij}$ represent the costs for each unit of commodity flow between the node pairs $i, j \in N$. As demand parameters, a transportation demand d_{ij} for each node pair $i, j \in N$ is given, which must be fulfilled by the network. Crainic (2000) differs between non-dynamic and dynamic service network design problems, whereby the latter incorporates the dimension of time into the model. In this case, transportation times t_{ij} between the node pairs $i, j \in N$ as well as transshipment times t_h for each hub node h are additionally given.

Based on the classification of Crainic (2000), a further dimension can be added, which distinguishes between a given or variable network structure. On this level, the decision variables can be introduced. The decisions in the dynamic service network design with variable network structure include the provided service capacity, in terms of frequency or number of offered services within a predefined time schedule, or can additionally define the time schedule within the model (number of services on network arcs for each period in planning horizon). For the dynamic service network design with a given network structure, the transportation schedule is given, and adequate transportation modes and services must be chosen for a predefined set of transportation orders. In the non-dynamic service network design with a variable network structure, a subset of open arcs $A_o \subseteq A$, on which transportation services are offered, is determined. Transportation schedules are neglected.
Both models with variable network structure (non-dynamic and dynamic) assume the perspective of a multimodal operator, who is in charge of a complete transportation network. On the opposite, the dynamic service network design with a given network structure also addresses freight forwarders or shippers, who select respective services for their transportation demand.

A non-dynamic service network design with a given network structure is usually not introduced within the literature because it would not significantly differ from a network flow problem. In general, a service network design problem always includes the corresponding network flow problem, in which the resulting commodity flow on the arcs of the network for a given network design is determined. The commodity flow defines the variable transportation costs within the network and can, therefore, imply changes in the service network design. A change in mode or service choice, as well as additional opened arcs or offered transportation services, can reduce commodity flow costs and contribute to an overall cost reduction (trade-off between fixed costs. $c_{a,ij}$ and variable costs $c_{c,\,ij}$) (Crainic, 2000). Apart from that, the network flow problem is also considered independently in the literature for an exogenously given service network design.

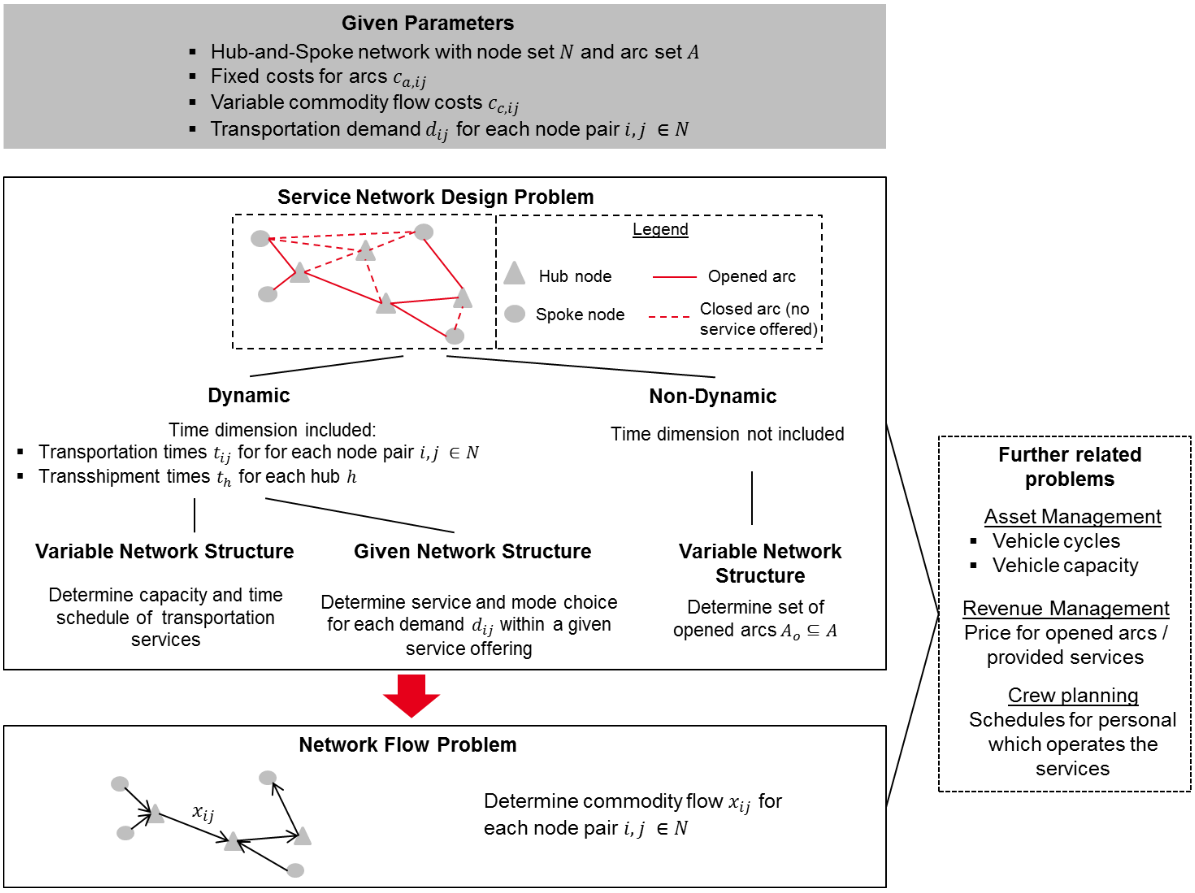


Figure 19: Overview of service network design and network flow problems

In terms of further related problems, the service network design is closely connected to asset management because for the provision of transportation services in a periodical schedule (e.g., weekly schedule), respective vehicle cycles must be determined (Andersen and Christiansen, 2009). In addition, if different vehicle types are used, the capacity decisions in the network depend on the assignment of those vehicles to the arcs in the network. Besides that, revenue management can also play a role for service network design as well as for network flow problems. Revenue management refers to price decisions for the services in the network (Gorman, 2015). Regarding service network design, revenue management can be integrated by replacing the objective of cost minimization with the goal of profit maximization. The cost-minimization approach of service network design assumes the fulfillment of the given transportation demand with minimal costs. The results can provide lower limits for pricing decisions. However, in a service network design problem with profit maximization, the decision to offer a service is interrelated to the price decision for the service. If it is possible to charge a high price for certain services due to customers' strong willingness to pay, those services would be offered even if they do not contribute to a minimum-cost network design. For the network flow problem, results for commodity flow can change if prices for the use of services are considered instead of flow costs (e.g., discount rates for fixed capacity bookings of certain services). As the last related problem, crew planning can also be included in order to determine corresponding schedules for the personnel, which operates the multimodal services.

Whereas (Crainic, 2000) introduces and systematizes the general service network design problems into dynamic and non-dynamic problems, (Wieberneit, 2008) conducts a review on service network design, which also includes road besides multimodal transportation. She notices that service network design always includes decisions on service selection and traffic distribution, whereas the latter part is covered by the corresponding commodity flow problem in the classification scheme of Figure 19. Moreover, service network design can include empty balancing of vehicles and loading units as well as vehicle and crew planning (which is covered by the further related problems in Figure 19).

The literature review introduced in the next section aims to update the last reviews with the large amount of research that has been conducted since 2008. Furthermore, the current state of research on stochastic service network design and network flow problems is also explicitly included. In this case, the demand and time parameters are random, and the solution approaches, and characteristics can differ significantly from those of the deterministic case. The review should point out which concrete uncertainty issues have already been incorporated and which stochastic model and solution approaches exist. Moreover, open problems in the field of network planning/design bearing potential for future research become apparent.

4.3 Methodology

To identify the relevant literature, a systematic review according to the recommendations of Denyer and Tranfield (2009) was conducted. Their recommendations for a systematic review process are based on the following four core principles: Transparency, inclusivity, explanatory, and heuristic.

The first principle of transparency states that reviewers must be open and explicit about the process and methods employed and also lay open their value stance towards the object of study. A way to do so is to produce a review protocol. Furthermore, the findings should be presented in such a way that there are clear links between the evidence found and the conclusions drawn. Inclusivity means that the reasons for or against the inclusion of a document in the literature review must be explicitly stated. The principle of explanation describes the synthesis of the identified relevant literature. This includes the systematic presentation of the articles and the analysis of their contribution to the overall theory. If recommendations for action are derived from the research results, then these will tend to be of a heuristic nature

These four principles translate to the following five concrete steps for carrying out a systematic literature review:

1. Formulation of the research questions
2. Locating studies. This includes the transformation of the research questions into query strings and the execution of the search
3. Study selection and evaluation entails defining explicit selection and exclusion criteria
4. Analysis and synthesis of the selected literature
5. Reporting and using the results

While the research questions were already formulated in Section 4.1, the query strings derived from the research questions and the study selection are now presented.

Four runs with different query strings for title, abstract, and keywords were carried out with the Scopus database. The reasons for choosing the Scopus database were twofold. First, Scopus is one of the largest peer-reviewed databases for science (Elsevier, 2019) that covers all relevant peer-reviewed journals for the research topic. Second, the SCImago Journal Rank, based on the Scopus database, can be used to filter the journals according to quartiles, which reflect their impact. According to the research questions, the query strings should ensure that the two important types of multimodal transportation are included: intermodal transportation and combined transportation. Moreover, the literature on service network design and network flow planning should explicitly be included in the survey. Furthermore, literature that tackles problems by considering uncertainty is of special interest. The following research queries result from those requirements, which were applied to the title, keyword, and abstract:

- *(„network design“ OR „network flow “) AND (transport* OR freight) AND (intermodal OR multimodal OR combined)*
- "*network design*" *AND transport* AND (stochastic OR uncertain*)*
- "*network flow*" *AND transport* AND (stochastic OR uncertain*)*
- *“service network design”*

In order to provide an overview of the current state of research on the design of service networks in general since the last study conducted by Wieberneit (2008), we have analyzed references published between 2008 and 2019. In total, 990 references were found, and the abstracts were screened to collect relevant literature in the next step. Criteria for including papers in the evaluation are as follows:

- The paper explicitly tackles service network design and/or network flow planning in multimodal transportation
- The main focus is on multimodal transportation and not on other research fields (e.g., supply chain management, reverse logistics, maritime liner shipping)
- Papers on disruption management and designing resilient transportation networks are excluded. Planning approaches can significantly differ compared to network planning/design and are therefore seen as an independent research topic

Additionally, only papers in peer-reviewed journals with SCImago Journal Rank (as index based on the Scopus database) in the first and second quartile were included in the evaluation to ensure a survey with relevant and high-quality research. Finally, further references fulfilling those criteria that were cited among the considered papers were integrated, too. Overall, 60 references remain for content-based evaluation. The high number of excluded papers results from a large amount of literature dealing with network design in the context of supply chain networks and maritime liner shipping, which was also covered by the research queries. Figure 20 gives an overview of the search procedure.

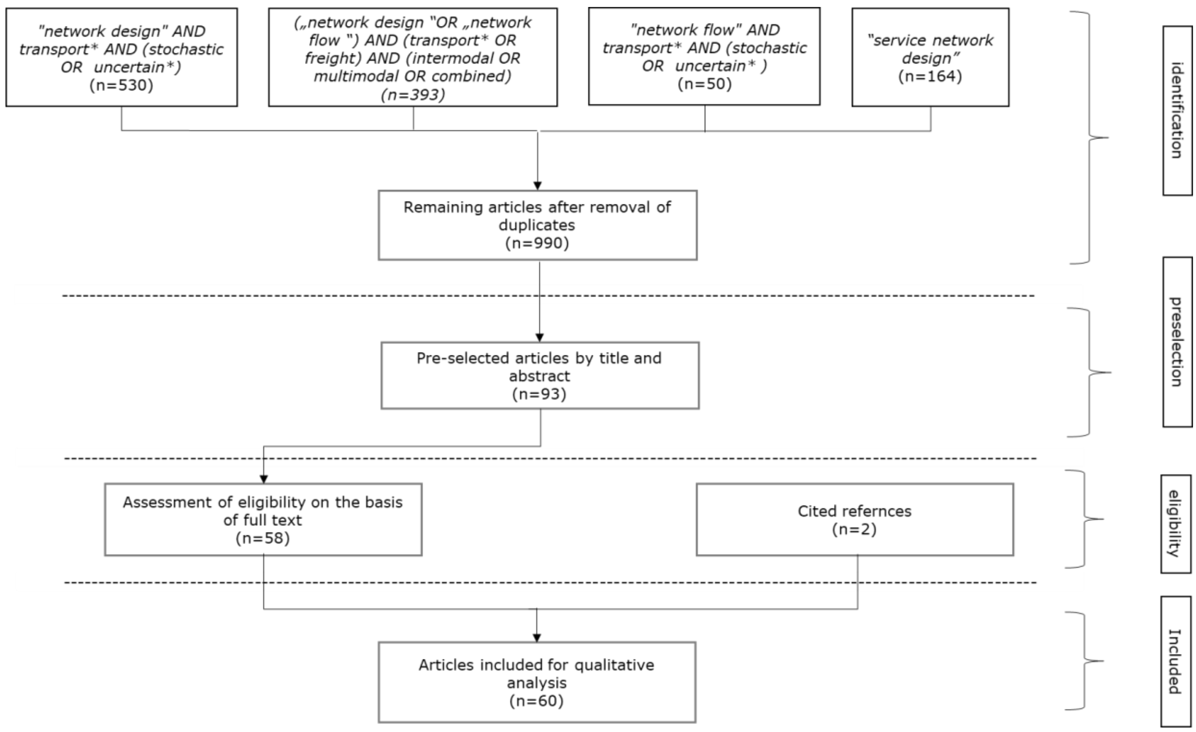


Figure 20: Search process of the identified articles

4.4 Results of the literature review

As shown in Figure 21, the identified references of the literature review are assigned to each category of the service network design problem and to the network flow problem, which were introduced in Section 4.2. Additionally, the references are further divided between deterministic and stochastic models within each category. Regarding the dynamic service network design with variable network structure, one part of the references considers asset management, which is introduced as supplementary dimension for the systematization in Figure 21.

For deterministic models, the vast majority of the references address the dynamic service network design with variable network structure (18 out of 35 references overall for deterministic problems). Most of them (15 out of 18) also consider asset management requirements. Only 4 references address the network flow problem, none of them with consideration of stochastic parameters. As service network design includes network flow decisions, this could be seen as an indicator for the progress research has achieved in this field, putting the focus on more complex planning decisions.

25 out of 60 references overall integrate uncertainty. Referring to those stochastic models, the references are distributed more evenly across the categories (dynamic service network design with variable network structure: 8 out of 25 references overall for stochastic problems, dynamic service network design with given network structure: 9 out of 25 and non-dynamic service network design with variable network structure: 8 out of 25). A reason might be the increased computational complexity of stochastic models per-se, compared to the deterministic counterparts. The application scope of dynamic service network design models, with time as an additional dimension in the models, is limited to rather smaller networks in this case. If only uncertain demand is to be considered, non-dynamic models provide the opportunity to analyze larger networks at the expense of neglecting time related decisions.

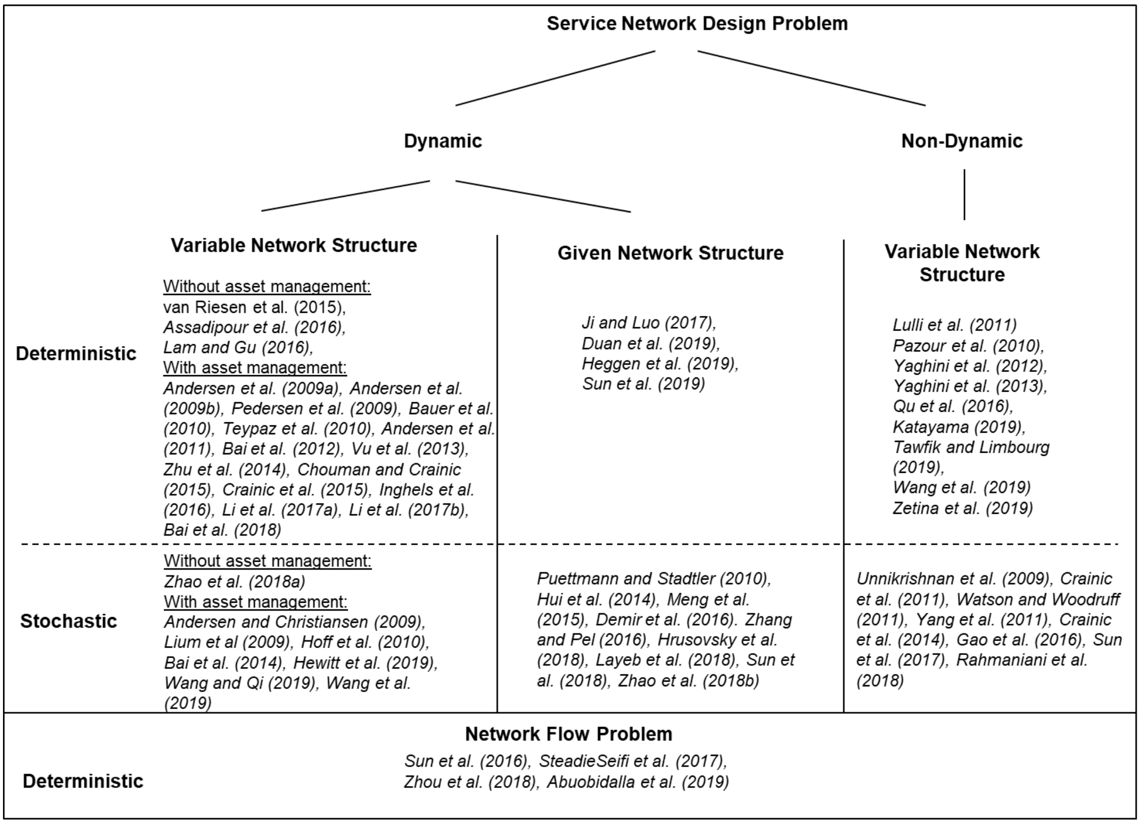


Figure 21: Identified references for each category of service network design problem and for the NFP

In the further part of this section, the references of each problem category are evaluated with regard to problem characteristics (including actors, covered components in the model and stochastic parameters, when uncertainty is included) and model formulations (basic approach and decision variables). The results are presented in Section 4.4.1. In Section 4.4.2, the solution approaches (exact methods and heuristics) are analyzed. Section 4.4.3 gives a summary on general characteristics of stochastic solutions and the value of stochastic planning approaches, when they are compared to deterministic counterparts. In Section 4.4.4 fields for future research are identified.

4.4.1 Problem characteristics and model formulations

4.4.1.1 Dynamic service network design with variable network structure

Table 5 gives an overview of problem characteristics and model formulations of the deterministic dynamic service network design problems with variable network structure. Problem characteristics include the analyzed transportation mode, the actors covered by the model, and the components (revenue, cost, transit time, emissions, risk exposure caused by hazardous materials for the population living close to the multimodal network, and tolls).

Table 5: Problem characteristics and model formulations for deterministic dynamic service network design problems with variable network structure

Reference	Problem characteristics			Model Formulation		
	Mode	Actors	Covered components	Basic Approach	Decision Variables	Asset management
Deterministic						
Without asset management						
van Riessen et al. (2015)	Maritime hinterland transportation	Multimodal operator	Cost-only	Mixed integer linear programming	- Service frequency (integer) - Commodity flow on self-operated and subcontracted services (continuous)	-
Assadipour et al. (2016)	Road, Rail	Government, Multimodal operator	Cost, tolls and risk exposure	Bi-level bi-objective mixed integer programming	- Number of services (integer) - Commodity-flow (continuous) - Tolls for terminal usage (continuous)	-
Lam and Gu (2016)	Maritime hinterland transportation	Multimodal operator	Cost, transit time and emissions	Bi-objective mixed integer linear programming	- Vehicle flow (integer) - Commodity flow laden and empty containers (continuous)	-
With asset management						
Andersen et al. (2009a)	Not specified	Multimodal operator	Cost-only	Mixed integer linear programming	- Arc-based, path-based and cycle-based vehicle flow (integer) - Arc-based and path-based commodity flow (continuous)	Homogeneous assets
Andersen et al. (2009b)	Rail, Short sea shipping	Railway operator	Cost and transit time	Mixed integer linear programming	- Service frequency (integer) - Vehicle flow (integer) - Commodity flow (continuous)	Heterogeneous assets
Pedersen et al. (2009)	Not specified	Multimodal operator	Cost-only	Mixed integer linear programming	- Arc-based vehicle flow (integer) - Arc-based commodity flow (continuous)	Homogeneous assets
Bauer et al. (2010)	Road, Rail, inland waterway	Multimodal operator	Emission-only	Mixed integer linear programming	- Arc-based vehicle flow (integer) - Arc-based commodity flow (continuous)	Heterogeneous assets

Reference	Problem characteristics			Model Formulation		
	Mode	Actors	Covered components	Basic Approach	Decision Variables	Asset management
Teypaz et al. (2010)	Not specified	Multimodal operator	Revenue and costs	Mixed integer linear programming	- Fraction of demand to transport (continuous) - Vehicle flow (integer) - Commodity flow (continuous)	Heterogeneous assets
Andersen et al. (2011)	Not specified	Multimodal operator	Cost-only	Mixed integer linear programming	- Cycle-based vehicle flow (integer) - Path-based commodity flow (continuous)	Homogeneous assets
Bai et al. (2012)	Not specified	Multimodal operator	Cost-only	Mixed integer linear programming	- Arc-based vehicle flow (integer) - Arc-based commodity flow (continuous)	Homogeneous assets
Vu et al. (2013)	Not specified	Multimodal operator	Cost-only	Mixed integer linear programming	- Arc-based vehicle flow (integer) - Arc-based commodity flow (continuous)	Homogeneous assets
Zhu et al. (2014)	Rail	Railway Operator	Cost-only	Mixed integer linear programming	- Service selection (binary) - Block selection (binary) - Arc-based vehicle flow (continuous)	Homogeneous assets
Chouman and Crainic (2015)	Not specified	Multimodal operator	Cost-only	Mixed integer linear programming	- Arc-based vehicle flow (integer) - Arc-based commodity flow (continuous)	Homogeneous assets
Crainic et al. (2015)	Rail	Multimodal operator	Cost-only	Mixed integer linear programming	- Arc-based vehicle flow (binary) - Assignment of commodity to service (binary) - Arc-based commodity flow (continuous)	Homogeneous assets
Inghels et al. (2016)	Maritime hinterland transportation	Multimodal operator	Cost for transportation and emission	Mixed integer linear programming	- Arc-based vehicle flow (binary) - Number of services (integer) - Arc-based commodity flow (continuous)	Heterogeneous assets
Li et al. (2017a)	Not specified	Multimodal operator	Cost-only	Mixed integer linear programming	- Assignment of different vehicles to arcs (binary) - Arc-based commodity flow for	Heterogeneous assets

Reference	Problem characteristics			Model Formulation		
	Mode	Actors	Covered components	Basic Approach	Decision Variables	Asset management
					different vehicles (continuous)	
Li et al. (2017b)	Not specified	Multimodal operator	Cost-only	Integer linear programming	- Opened arcs (binary) - Selected arcs for commodities (binary)	Homogeneous assets
Bai et al. (2018)	Not specified	Multimodal operator	Cost-only	Mixed integer linear programming	- Arc-based vehicle flow (integer) - Arc-based commodity flow (continuous)	Homogeneous assets

Most of the references (10 out of 18) do not limit their model to a specific mode and aim to provide a general approach suitable for a broad range of networks. Moreover, the main focus is on cost optimization for the multimodal operator. Only Teypaz et al. (2010) include revenue in the objective function for solving a profit maximization service network design problem. Furthermore, transit time (the overall time span for an order in the network, including all transportation, transshipment, and storage times) is only included by Lam and Gu (2016) as well as Andersen et al. (2009b). The other references assume strict release and due times for orders or commodities, whereas those two references treat the transit time as variable for the model, reflecting a constellation where the customer delegates the trade-off between cost and transit time minimization to the multimodal operator. Only four references (Assadipour et al., 2016; Bauer et al., 2010; Inghels et al., 2016; Lam and Gu, 2016) integrate risk exposure caused by hazardous materials or GHG emissions as further indicators for the environmental impact of transportation operations.

With regard to model formulations, the basic approach, including decision variables and the consideration of asset management, is presented in Table 5. All of the references apply an integer or mixed integer programming approach. Assadipour et al. (2016) and Lam and Gu (2016) extend this approach to a bi-objective optimization for representing the trade-off between cost and transit time (Lam and Gu, 2016) or economic (cost, tolls) and environmental (risk exposure) concerns (Assadipour et al., 2016). Assadipour et al. (2016) further conduct a bi-level optimization with separate objectives for the different actors (government and multimodal operator). In the three references, without consideration of the asset management model, the service network design decisions either by means of service frequency variables or the number of offered services on different paths. Lam and Gu (2016) apply integer variables for the vehicle flow and assume a limited number of available vehicles for the network. Concerning the references with asset management consideration, only five references include heterogeneous assets with different capacities. The other references consider homogeneous vehicles, hence reducing the computational complexity, because an additional assignment problem of vehicle types to services can be neglected.

Whereas the references without asset management include the time dimension by continuous variables, all of the references with asset management rely on a time-space graph for reducing model complexity by means of assuming a given number of time periods. The basic idea is shown in Figure 22. A time-space graph is a directed graph of the network in which each geographical node is replicated for each time period within the given time horizon. The arc set consists of all possible connections between the nodes with regard to geographical transportation links and minimum transportation time.

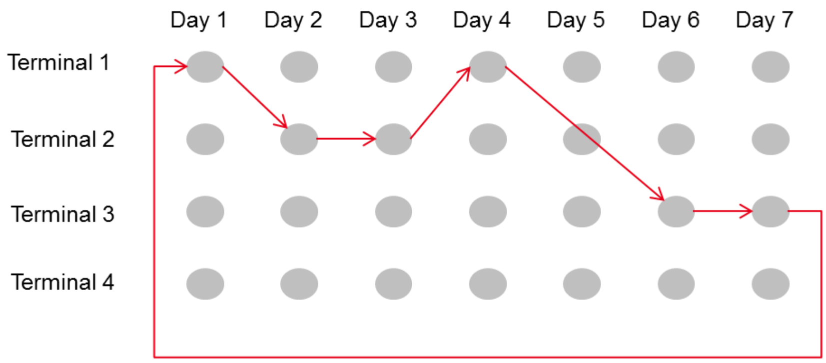


Figure 22: Vehicle cycle in time space graph | own representation based on Pedersen et al. (2009))

A periodic transportation schedule is defined by cycles for each vehicle so that the vehicles return to their geographical start node at the end of each period. Decision variables are the vehicle flow within the time-space graph, which can either be arc-based, path-based, or cover complete cycles derived by enumeration of feasible arc combinations.

In the following subsection, the different research streams are expounded in more detail. The largest research stream provides a general approach for solving the dynamic service network design problem with homogeneous assets (Andersen et al., 2009a; Andersen et al., 2011; Bai et al., 2012; Bai et al., 2018; Chouman and Crainic, 2015; Li et al., 2017b; Pedersen et al., 2009; Vu et al., 2013). Andersen et al. (2009a) analyze the different model formulations regarding thee vehicle flow (arc-based, path-based, cycle-based decision variables). Cycle-based formulations can be solved significantly faster by commercial solvers. However, for large networks, the time for enumerating all cycles beforehand can be high, which may compensate for time reductions for the actual model-solving process. The further references concentrate on developing meta-heuristic or branch-and-price solution approaches, as commercial solvers are limited to rather small network sizes (see Section 4.4.2).

Teypaz et al. (2010) include revenues from transported orders and heterogeneous assets in a three-phase decomposition approach for the service network design, starting from basic network construction (geographical routes to integrate) and determining schedules for the single vehicles in the last phase. As profit maximization is the objective of the model, decisions on the fractions of the single demands to be transported are integrated, hence, only profitable transportation orders are selected by the multimodal operator.

Li et al. (2017b) introduce the single-path design-balanced service network design as a special case of the service network design problem, in which the transportation of each commodity is restricted to one path, respectively. As a practical example for motivating this constraint, the authors mention the transportation of hazardous materials, which should not be split over several paths in order to minimize risk exposure.

More specific approaches for individual transportation modes are developed by Andersen et al. (2009b), Zhu et al. (2014), Van Riessen et al. (2015), Crainic et al. (2015), Inghels et al. (2016) and Lam and Gu (2016). Andersen et al. (2009b) solves a service network design problem with the coordination of internal (rail services of a railway operator) and external services (short sea shipping). Their results from a case study in Eastern Europe (Polcorridor) show that significant overall cost reductions can be achieved if time schedules of railway and short sea services are coordinated, stressing the importance of integrated planning along the complete transportation chain. Zhu et al. (2014) present a model for a railway operator, in which train and yard operations are considered in a more detailed degree. Train services are built from blocks, which in turn consist of single railway cars. The model decides how cars should be assigned to blocks, and blocks should be assigned to train services so that overall transportation costs and block building costs in the yards are minimized. Van Riessen et al. (2015) and Crainic et al. (2015) focus on maritime hinterland transportation, including case studies for the port of Rotterdam (Van Riessen et al., 2015) and a hinterland networks in Italy (Crainic et al., 2015). Van Riessen et al. (2015) incorporate the opportunity of sub-contracting certain transportation processes, which contributes to reducing overall costs in the case study. Crainic et al. (2015) investigate how dry ports, which are inland freight terminals directly connected to one or more seaports with high-capacity transportation means, can support multimodal freight transportation systems.

Four references include environmental and social impacts in their analysis (Bauer at al., 2010, Lam and Gu, 2016 and Inghels et al., 2016, Assadipour et al., 2016). Bauer et al. (2010) break away from the traditional approach of minimizing the travel or time-related cost of a network. Instead, they focus solely on environment-related costs and minimize GHG emissions. Tests on the dataset provided by Andersen et al. (2009b) show that by changing the objective function, significant GHG reductions can be achieved, but the time-related costs increase sharply. Lam and Gu (2016) analyze the impact of different limits for CO_2 emissions on the network design. Sharper environmental restrictions increase the share of barge transportation in their case study for a hinterland network in China. However, the authors also stress the importance of more investments in multimodal infrastructure, as within the current network structure emission reductions can only be achieved at the expense of increases in transit times. Inghels et al. (2016) studied how a shift from the road toward inland waterways could reduce GHG emissions and benefit the societal impact associated with municipal solid waste management. They verify their approach through a case study conducted in Flanders, Belgium. Assadipour et al. (2016) introduce a service network design for hazardous materials, where risk exposure indicators for the population close to the network arcs and nodes are considered in the optimization. The government is included as a further actor in the model, with the objective of determining toll levels for each terminal to minimize risk exposure and overall costs for the multimodal operator in a bi-objective optimization approach. Results from a case study in the USA show that both objectives (risk exposure and costs) are conflicting and cannot be minimized simultaneously, which substantiates the regulating task of the government to limit possible negative impacts on the population.

After summarizing the state of research for the deterministic models, the corresponding stochastic versions are presented in the following paragraphs. Table 6 shows the respective references. As in the deterministic case, generally applicable models for multimodal operators for cost minimization dominate. Seven references deal with stochastic demand, whereby only one additionally covers stochastic transportation times. Andersen and Christiansen (2009) solely incorporate stochastic transportation times.

The largest research stream focuses on general service network design models with homogeneous assets for uncertain demand based on a time-space graph model (Bai et al., 2014; Hewitt et al., 2019; Hoff et al., 2010; Lium et al., 2009; Wang et al., 2019a; Wang and Qi, 2020). The models aim to find an optimal trade-off between low-cost, preplanned services with respective capacity (that could not be exploited in low-demand cases), and high-cost outsourced commodity flow to external service providers for fulfilling high-demand scenarios.

Table 6: Problem characteristics and model formulations for stochastic dynamic service network design with variable network structure

Reference	Problem characteristics				Model Formulation		
	Mode	Actors	Covered components	Stochastic parameters	Basic Approach	Decision Variables	Asset management
Stochastic							
Without asset management							
Zhao et al. (2018a)	Rail, Deep sea shipping	Multimodal operator	Cost and delay penalties	Demand Volume and Transportation time	Two stage chance constraint programming	First stage - Operated services (binary) -Service frequency (integer) Second stage - Service choice (binary) - Commodity flow (continuous)	-
With asset management							
Andersen and Christiansen (2009)	Rail	Railway operator	Revenue, costs and transit times	Transportation time	Mixed integer programming	- Served transportation demand (binary) - Service frequency (integer) - Vehicle flow (integer)	Heterogeneous assets
Lium et al. (2009)	not specified	Multimodal operator	Cost-only	Demand Volume	Two stage stochastic programming	First stage - Arc-based Vehicle Flow (integer) Second stage - Regular Commodity Flow (continuous) - Ad-hoc Commodity Flow (continuous)	Homogeneous assets
Hoff et al. (2010)	not specified	Multimodal operator	Cost-only	Demand Volume	Two stage stochastic programming	First stage - Arc-based Vehicle flow (integer) Second stage - Regular Commodity Flow (continuous) - Ad-hoc Commodity Flow (continuous)	Homogeneous assets

Reference	Problem characteristics				Model Formulation		
	Mode	Actors	Covered components	Stochastic parameters	Basic Approach	Decision Variables	Asset management
Bai et al. (2014)	not specified	Multimodal operator	Cost-only	Demand Volume	Two stage stochastic programming	First stage - Arc-based Vehicle flow (integer) Second stage - Regular Commodity Flow (continuous) - Increase/decrease in vehicle flow (integer) - Ad-hoc Commodity Flow (continuous)	Homogeneous assets
Hewitt et al. (2019)	Road	Multimodal operator	Cost-only	Demand Volume	Two stage stochastic programming	First stage - Cycle-based Vehicle flow (binary) - Resource acquisition and allocation Second stage - Path-based Commodity Flow (continuous) - Ad-hoc Commodity Flow (continuous)	Homogeneous assets
Wang and Qi (2019)	not specified	Multimodal operator	Cost-only	Demand Volume	Two stage robust programming	First stage - Arc-based Vehicle flow (integer) Second stage - Regular Commodity Flow (continuous) - Ad-hoc Commodity Flow (continuous)	Heterogeneous assets
Wang et al. (2019)	not specified	Multimodal operator	Cost-only	Demand volume	Two stage stochastic programming	First stage - Arc-based Vehicle flow (integer) - Loading unit flow (integer) Second stage -- Regular Commodity Flow (continuous) - Ad-hoc Commodity Flow (continuous)	Homogeneous assets

The predominant model formulation for those models is two-stage stochastic programming in the extensive form (Lium et al., 2009, Hoff et al., 2010, Bai et al., 2014, Hewitt et al., 2019 and Wang et al., 2019). In this approach, random parameters are incorporated by a set of possible scenarios. Each scenario represents a possible realization of the stochastic parameters (in this case, transportation demand). The first-stage decision variables are taken before random scenario realization. Therefore, they represent fixed decisions throughout all scenarios, which are the fixed schedules for the services in the case of stochastic service network design. Hewitt et al. (2019) extend this first stage by additionally considering the decision on resource acquisition and allocation. The second stage refers to disclosed uncertainty (revealing a demand realization), whereby recourse actions can be taken (Birge and Louveaux, 2011). Recourse actions refer to possible operations for improving the transportation plan, which can only be taken within a concrete scenario when demand realization is known. For the presented references, the recourse actions are the outsourcing of commodity flow, which exceeds the capacity determined in the first stage. Only Bai et al. (2014) additionally includes a scenario-dependent adaption of the schedule by increasing or decreasing the number of vehicles in the different cycles. Wang and Qi (2019) apply a robust optimization formulation. The two-stage structure is identical to the other four references, but the aim of the optimization is the minimization of the expected costs over a set of high-demand scenarios.

Besides uncertain demand, stochastic transportation times impact service schedules and commodity flow decisions, but they are only considered in two references. The schedules may include time buffers in order to avoid delays. Regarding commodity flow, transportation paths with high delays or short transit times, which can lead to infeasible order deliveries when a connecting service is not reached, are avoided so that the minimum transportation cost path is not necessarily chosen for the orders. Andersen and Christiansen (2009) integrate uncertain transportation times in a simplified manner by a time variability parameter on each service leg. Their model solves a service network design problem for a railway operator, who can choose the most profitable orders out of the given transportation demand. The results of a case study on the Polcorridor in Eastern Europe demonstrate that fewer contracts are selected due to the time variability (compared to deterministic transportation times) to ensure fast and timely delivery by respective time buffers. Zhao et al. (2018a) rely on two-stage chance constraint programming. In their approach, capacity and on-time delivery chance constraints are introduced. They ensure that transportation capacity is not exceeded with a given probability in all considered demand scenarios, and on-time delivery is guaranteed with a given probability in all considered transportation time scenarios.

To summarize the state of the research regarding dynamic service network design with variable network structure, three main findings can be pointed out. First, the main research stream is the development of solution procedures for a generally applicable model with homogeneous assets (deterministic), which is extended to incorporate uncertain demand volumes in the stochastic case. Those models are formulated by means of mixed integer linear programming or two-stage stochastic programming based on a time-space graph. The number of references for deterministic and stochastic approaches also makes it clear that stochastic models are underrepresented in this field. Second, further models in the deterministic case develop more specific approaches for individual transportation modes (e.g., rail, maritime hinterland), but no clear ongoing research stream has evolved here. Therefore, those contributions can be rather seen as a starting point for further research. Finally, approaches that cover heterogeneous assets, environmental or social impacts, and uncertain transportation times (stochastic) are limited. Research in this field would contribute to enriching the scope of dynamic service network design with variable network structure.

The references for the counterpart with the given network structure are presented in the next subsection.

4.4.1.2 Dynamic service network design with a given network structure

In contrast to the models with variable network structures, the references for the service network design models with a given network structure assume a given set of transportation services from which services and commodity flow paths must be selected. Problem characteristics and model formulations are summarized in Table 7. The majority of the references include stochastic parameters, whereas only four references deal with a deterministic problem. Furthermore, the models focus on concrete transportation modes more frequently compared to service network design with variable network structure, leading to a broader scope of different research streams. Regarding model formulations, simulation or simulation optimization is applied by three references for the stochastic case, whereas the models for variable network structure solely concentrate on optimization models.

In terms of the four deterministic problems, each reference covers a different research stream. Ji and Luo (2017) put a special focus on finding an overall optimum regarding transportation and emission costs as well as transit times with a bi-objective optimization approach for a specific network with multiple sourcing and a single destination node. Results of a case study for a network in China reveal that the low-emission modes rail and barge are preferred to the road unless fast delivery requirements are present. A higher share of the more environmentally friendly modes can only be achieved by lower emission constraints. As a further approach of including environmental impacts Sun et al. (2019) analyze a hazardous materials routing problem. The reference is closely connected to Assadipour et al. (2016), who consider the risk exposure for a service network design with a variable structure. Sun et al. (2019) introduce a fuzzy set theory approach for modeling uncertainty regarding risk exposure in case of accidents more precisely than Assadipour et al. (2016). Fuzzy sets are a mathematical approach where elements can belong to different sets, expressed by a degree of membership (Zadeh, 1965). Based on this methodology, different risk exposure levels are assumed, ranging from most pessimistic to most optimistic assumptions, and incorporated into a Fuzzy population exposure model. Duan et al. (2019) incorporate heterogeneous user preferences regarding the value of time and the value of reliability. They developed a frequency-based service network design model, which they applied to a railway network in China. They estimate the value of time and reliability of the users from a stated preference survey and determine distinct user classes. The results show that by considering heterogeneous users, the total generalized cost can be reduced while the service level is improved. As the last deterministic approach, Heggen et al. (2019) is the only reference that integrates vehicle routing problems into the service network design identified in this review. The authors simultaneously solve corresponding vehicle routing problems for the drayage operations in the choice of different intermodal services. By the means of a case study for Western Europe, it can be shown that costs can be reduced if orders are not always assigned to the nearest terminal, as the efficiency of drayage operations could be increased for other terminals, more than compensating for the higher distance related costs.

Table 7: Problem characteristics and model formulations for dynamic service network design problems with given network structure

Reference	Problem characteristics				Model Formulation	
	Mode	Actors	Covered components	Stochastic parameters	Basic Approach	Decision Variables
Deterministic						
Ji and Luo (2017)	Not specified	Multimodal operator	Costs, transit time and emissions	-	Bi-objective mixed integer linear programming	- Selected transportation modes and transshipment nodes (binary)
Duan et al. (2019)	Rail	Multimodal operator	Cost-only	-	Mixed integer nonlinear programming	- Arc-based service frequency (integer) - Arc-based commodity flow (binary) - Commodity transfer (binary)
Heggen et al. (2019)	Road, Rail	Multimodal operator	Cost-only	-	Mixed integer linear programming	- Selected transportation services (binary) - Vehicle routing for drayage (binary)
Sun et al. (2019)	Road, Rail	Multimodal operator	Cost, early delivery penalties and risk exposure	-	Bi-objective Fuzzy mixed integer programming	Commodity flow (continuous)
Stochastic						
Puettmann and Stadtler (2010)	Road, Deep sea shipping	Multimodal operator and road carrier	Cost-only	Demand release time	Mixed integer linear programming with decentralized planning	Intermodal operator - Commodity flows (Assignment of orders to liner-services and carriers) - Additional capacity - Inventories Road carrier - Commodity flows (Assignment of orders to tours) - Additional capacity (Assignment of orders to additional capacity)

Reference	Problem characteristics				Model Formulation	
	Mode	Actors	Covered components	Stochastic parameters	Basic Approach	Decision Variables
Hui et al. (2014)	Road, air	Air freight forwarders	Cost and delay penalties	Processing Times	Two stage stochastic programming	First stage Initial Agent-activity-assignment (binary) Second stage Adjusted Agent-activity-assignment (binary)
Meng et al. (2015)	Road, rail and short-sea shipping	Multimodal operator	Cost-only	Demand Volume	Two stage stochastic programming	First stage Fixed capacity booking (integer) Second stage Commodity flow (integer)
Demir et al. (2016)	Road, rail and barge	Multimodal operator	Costs, delay penalties and emissions	Demand volume and transportation time	Mixed integer linear program	- Selected transportation services (binary) - Commodity flow (continuous)
Zhang and Pel (2016)	Maritime hinterland transportation	Multimodal operator	Costs, transit time and emissions	Demand release times	Simulation	Selected paths for each order
Hrusovsky et al. (2018)	Road, rail and barge	Multimodal operator	Costs, delay penalties and emissions	Transportation time	Simulation optimization	- Selected transportation services (binary) - Commodity flow (continuous)
Layeb et al. (2018)	Road, rail and barge	Multimodal operator	Costs, delay penalties and emissions	Demand volume and transportation time	Simulation optimization	Selected paths for each order
Sun et al. (2018)	Road, rail	Multimodal operator	Costs, delay penalties and emissions	Transportation time and capacity	Fuzzy chance constrained mixed integer programming	Selected transportation services (binary)
Zhao et al. (2018b)	Rail, deep sea shipping	Multimodal operator	Cost and delay penalties	Demand volume and transportation time	Chance constraint mixed integer programming	- Service choice (binary) - Commodity flow

Regarding stochastic approaches, six out of nine references include random transportation (or processing) times, either isolated (Hrušovský et al., 2018; Hui et al., 2014), in combination with random demand volumes (Demir et al., 2016; Layeb et al., 2018; Zhao et al., 2018b) or with random capacity of transportation services (Sun et al., 2018). The consideration of uncertainty is extended compared to stochastic service network design with variable network structure, for which the main focus is on stochastic demand. A possible explanation is a reduced model complexity per se, because the network design is exogenously given and not part of the optimization.

For the stochastic models, five different research streams can be distinguished. Puettmann and Stadtler (2010) is the only reference of the review, which studies a decentralized planning approach for different actors (multimodal operator and road carrier in the context of maritime transportation). The model considers uncertain demand release times. The authors develop an iterative information exchange procedure between the actors, where proposed transportation plans (commodity flow of the multimodal operators for deep sea services and drayage operations of the external road carriers) are exchanged, and coordination among the actors is reached.

Hui et al. (2014) study a special case of a service choice problem for an air freight forwarder shipment planning with stochastic processing times. Activities reflect the single transportation services along the transportation chain, which are assigned to the different freight forwarders by means of an agent-activity-assignment problem, reflecting a centralized planning approach for the coordination of the different forwarders. Cost reductions due to consolidation (assigning several activities of one stage of the chain to the same actor) and integration (assigning subsequent activities along the chain to the same actor) are considered, and therefore, non-linear cost effects are integrated.

Meng et al. (2015), Demir et al. (2016), and Sun et al. (2018) study mode and service choice decisions with various sources of uncertainty. Meng et al.(2015) and Demir et al. (2016) analyze an optimal booking of fixed capacities on different intermodal services when demand is uncertain so that sufficient capacity is available, but high capacity utilization is ensured as well. Demir et al. (2016) further include random transportation times and GHG emissions to find an overall optimum, which additionally ensures reliable and environmentally friendly transportation paths. Sun et al. (2018) introduce capacity uncertainty for rail services. In their model, demand is deterministic, but the available capacity for the different services is random. As in Sun et al. (2019), fuzzy variables are introduced for minimum, most possible, and maximum available rail capacities. Chance constraints ensure that sufficient capacity is present on the selected transportation paths at a given probability level.

Three references apply simulation or simulation optimization. Zhang and Pel (2016) present a simulation approach for synchromodal hinterland transportation. Synchromodality refers to an open-mode booking procedure in which customers do not define the transportation mode for their orders, and multimodal operators are completely free to organize the transportation processes to fulfill the predefined cost and time requirements of the orders. The authors provide results for a case study of the hinterland of the port of Rotterdam. Due to the synchromodal approach, service level, capacity utilization, and modal shift can be improved compared to an intermodal approach, where transportation modes are predefined. Hrusovsky et al. (2018) and Layeb et al. (2018) apply simulation optimization, where an optimization model is solved, and the resulting transportation paths are evaluated by a discrete-event simulation afterward. Hrusovsky et al. (2018) focus on random transportation times, whereas Layeb et al. (2018) extend this approach by additionally including random demand volumes.

As the last research stream, Zhao et al. (2018b) incorporate a chance-constrained mixed integer approach for intermodal container routing with random demand and transportation times. The chance constraints ensure that transportation paths are feasible with a given probability (connecting services must be caught at the respective terminals). Additional delay penalties in the objective function aim to reduce late deliveries as well.

In summary, two main findings for the dynamic service network design with a given network structure can be derived. First, stochastic approaches are much more covered than models with variable network structures, and they also incorporate uncertain transportation times more frequently. It can further be concluded that the latest stochastic references aim to integrate two random parameters (e.g., demand and transportation times) simultaneously to enhance decision support for multimodal operators. Second, overall, a broad scope of research has evolved, ranging from incorporating environmental impacts or heterogeneous users to the integration of vehicle routing and developing simulation-based approaches. However, as those models are tailored to specific problems in most cases, the development of generally applicable solution procedures for reducing computational times also for large networks by means of heuristics or combining simulation and optimization is rather in its beginnings, in contrast to the models for variable network structure.

After presenting the references on the dynamic service network design, the next subsection deals with the non-dynamic service network design.

4.4.1.3 Non-dynamic service network design with variable network structure

Problems in the category of non-dynamic service network design with variable network structure deal with the planning of offered transportation capacity in the network and the corresponding commodity flows without considering the time dimension. The references are summarized in Table 8 regarding their problem characteristics and model formulations. Most of the models are suitable for multimodal operators, which are not dedicated to a specific mode, with the exception of six references that explicitly consider rail (Gao et al., 2016; Lulli et al., 2011; Yaghini et al., 2013; Yang et al., 2011) or road and high-speed rail networks (Pazour et al., 2010; Tawfik and Limbourg, 2019). As for dynamic service network design with a given network structure, almost half of the references (8 out of 17) include uncertainty. Regarding model formulations, mixed integer programming is applied for the deterministic models, whereas the stochastic models include two-stage stochastic programming, fuzzy chanced constrained programming, and budget-/possibility-constrained programming. In terms of decision variables, most of the models (8 out of 17) apply binary variables for selecting transportation links to open and continuous variables for the resulting commodity flow, followed by arc- or path-based service frequency decisions (7 out of 17 references). Unnikrishnan et al. (2009), Watson and Woodruff (2011), and Sun et al. (2017) consider continuous variables for capacity decisions.

The main contributions of the presented models are in the methodological domain by providing more efficient metaheuristic solution procedures or improving exact methods. Regarding deterministic models, Zetina et al. (2019) incorporate an elastic demand function regarding the routing cost. They solve their path-based model with a hybrid matheuristic that combines a slope scaling metaheuristic and column generation. Wang et al. (2019) combine in a hybrid approach a matheuristic based on pricing with a local search algorithm. Yaghini et al. (2012), as well as Katayama (2019) introduce new metaheuristic approaches based on the simplex method and simulated annealing (Yaghini et al. 2012) and a greedy approach (Katayama 2019).

Table 8: Problem characteristics and model formulations for non-dynamic service network design problems with variable network structure

Reference	Problem characteristics				Model Formulation	
	Mode	Actors	Covered components	Stochastic parameters	Basic Approach	Decision Variables
Deterministic						
Pazour et al. (2010)	Road, Rail	Multimodal operator	Time-only	-	Mixed integer linear programming	- Opened transportation links (binary) - Commodity flow (binary)
Lulli et al. (2011)	Rail	Railway operator	Cost-only	-	Mixed integer programming	- Arc-based service frequency (integer) - Arc-based commodity flow (integer)
Yaghini et al. (2012)	Not specified	Multimodal operator	Cost-only	-	Mixed integer linear programming	- Opened transportation links (binary) - Commodity flow (continuous)
Yaghini et al. (2013)	Rail	Railway operator	Cost-only	-	Mixed integer linear programming	- Path-based service frequency (integer) - Path-based commodity flow (continuous)
Qu et al. (2016)	Not specified	Multimodal operator	Cost and emissions	-	Mixed integer programming	- Arc-based vehicle flow (integer) - Arc-based commodity flow (continuous)
Katayama (2019)	Not specified	Multimodal operator	Cost-only	-	Mixed integer linear programming	- Opened transportation links (binary) - Commodity flow (continuous)
Tawfik and Limbourg (2019)	Road, Rail	Multimodal operator and shipper	Revenue and costs	-	Bilevel - Mixed integer programming	Upper level - Arc-based service frequency (integer) - Service Price Lower level Path-based commodity flow (continuous)
Wang et al. (2019)	Not specified	Multimodal operator	Cost-only	-	Mixed integer linear programming	- Arc-based vehicle flow (integer) - Arc-based commodity flow (continuous)
Zetina et al. (2019)	Not specified	Multimodal operator	Revenue and costs	-	Mixed integer linear programming	Arc-based vehicle flow (binary) Path-based commodity flow (binary)

Reference	Problem characteristics				Model Formulation	
	Mode	Actors	Covered components	Stochastic parameters	Basic Approach	Decision Variables
Stochastic						
Unnikrishnan et al. (2009)	not specified	Shipper, Carriers	Cost-only	Supply and demand Volume	Two stage stochastic programming	First stage - Storage capacities (continuous) Second stage - Commodity Flow (continuous) - Inventories (continuous)
Crainic et al. (2011)	not specified	Multimodal operator	Cost-only	Demand Volume	Two stage stochastic programming	First stage - Opened transportation links (binary) Second stage - Commodity flow (continuous)
Watson and Woodruff (2011)	not specified	Multimodal operator	Cost-only	Demand Volume	Two stage stochastic programming	First stage - Opened transportation links (binary) - Transportation link capacity (continuous) Second stage - Activated transportation links (binary) - Commodity flow (continuous)
Yang et al. (2011)	Rail	Railway operator	Costs and empty capacity penalties	Capacities and costs	Fuzzy chance constrained programming	- Path-based service frequency (integer) - Path and arc assignment for commodities (binary) - Path-based commodity flow (continuous)
Crainic et al. (2014)	not specified	Multimodal operator	Cost-only	Demand Volume	Two stage stochastic programming	First stage - Installed transportation links (binary) Second stage - Commodity flow (continuous)
Gao et al. (2016)	Rail	Railway operator	Cost-only	Costs	Budget-constrained and possibility-constrained programming	- Arc-based service frequency (integer) - Arc-based commodity flow (continuous)

Comparable references that develop metaheuristic approaches dedicated to the stochastic problem are Crainic et al. (2011), Watson and Woodruff (2011), Crainic et al. (2014), and Rahmaniani et al. (2018). Further details regarding solution methodology are presented in Section 4.4.2.

Approaches dedicated to more specific problem instances are introduced by Lulli et al. (2011), Yaghini et al. (2013), Qu et al. (2016), and Tawfik and Limbourg (2019). Lulli et al. (2011) and Yaghini et al. (2013) are some of the few references that apply a service network design model in large real-world case studies. Lulli et al. (2011) optimize the network of a major Italian railway company. Their results point out that a model-based network design can result in a different network structure with lower costs. In the case study, the model suggests more direct services instead of the hub-and-spoke network structure incorporated by the railway operator, which can reduce costs by approximately 4%. Yaghini et al. (2013) introduce a train formation plan model (routing and frequency of trains), which additionally includes yard capacities in terms of number of trains and cars that can be assembled simultaneously. The authors solve the corresponding model instance for the Iranian railway network but do not provide figures for possible cost reductions compared to the current network design. Qu et al. (2016) is the only reference in this category that solves a green service network design problem, including GHG emissions, in addition to costs. Tawfik and Limbourg (2019) develop a bilevel model in which a multimodal service provider seeks to maximize his profits by setting the services´ tariffs and selecting their operating frequencies. At the lower level, the shippers react to the to the leader's strategy by choosing the services to be used.

For stochastic models, besides uncertain demand, capacities, and costs are introduced as further random parameters compared, whereas the latter is not considered in the other model categories. Yang et al. (2011) integrate uncertain costs into a fuzzy chance-constrained programming approach and derive three objective functions that should reflect the risk preferences of a decision-maker: a pessimistic objective where a minimum cost level should not exceed a given upper bound, an optimistic objective where a lower bound of the cost level should be minimized and a Hurwicz criterion objective which is a weighted sum of the pessimistic and optimistic objective. Gao et al. (2016) present two different model formulations for taking random costs into account. In a budget-constrained model, the probability for the costs to be lower than a given budget is maximized, whereas, in a possibility-constrained model, the budget to be reached with a given probability level is minimized.

Besides costs as a new random parameter, two further research streams can be identified for the non-dynamic service network design category. Unnikrishnan et al. (2009) analyze a multimodal network from the perspective of a shipper. He decides on storage capacities to be installed in his network and on corresponding network flows and inventories in each period by taking random supply and demand volumes of the nodes into account. The capacities for the network arcs are not part of the model. Instead, for transportation services, he can choose among a leader carrier and secondary competitive carriers. Sun et al. (2017) systematically analyze possible improvements which can be achieved by a stochastic model compared to a deterministic equivalent model with mean values for the random demand parameters. Different simplified approaches for solving the stochastic model with reduced computational complexity are presented. Further details are expounded in Section 4.4.3 (general characteristics of stochastic solutions and value of stochastic planning approaches).

In summary, the majority of the references for the non-dynamic service network design with variable network structure include stochasticity. Due to the limited model complexity by excluding the time dimension, the methodological contributions for solution procedures can be seen as a possibility for identifying network arcs to open generally, in a first step before detailed planning of the schedules. Especially for stochastic problems, this two-step procedure, in combination with the developed heuristic approaches, can be a way to tackle larger networks without excessive computational time.

4.4.1.4 Network flow planning

As the last category, the references dealing with network flow problems are presented in this section. Only four papers contribute to this field, all of them dealing with deterministic problems from the perspective of a multimodal or railway operator (see Table 9).

Table 9: Problem characteristics and model formulations for NFP

Reference	Problem characteristics			Model Formulation	
	Mode	Actors	Covered components	Basic Approach	Decision Variables
Deterministic					
Sun et al. (2016)	Road, rail	Multimodal operator	Cost and risk exposure	Bi-objective mixed integer programming	- Commodity flow (continuous)
SteadieSeifi et al. (2017)	Not specified	Multimodal operator	Cost-only	Mixed integer programming	- Vehicle flow (integer) - Loading unit flow (continuous)
Zhou et al. (2018)	Not specified	Multimodal operator	Cost and emissions	Mixed integer programming and bi-objective mixed integer programming	- Selection of mode-vehicle combinations and transshipment nodes (binary) - Commodity flow (continuous)
Abuobidalla et al. (2019)	Rail	Railway operator	Cost-only	Mixed integer programming	- Commodity flow (binary) - Block construction (binary) - Outsourcing (binary)

Sun et al. (2016) analyze the transportation of hazardous materials (as Assadipour et al. 2016 and Sun et al. 2019 with regard to service network design). Cost minimization for the multimodal operator and risk exposure for the population are integrated into a bi-objective mixed integer programming model.

SteadieSeifi et al. (2017) solve a complex network flow planning problem for perishable products. The authors include the flow of loading units and vehicles for transporting the products in a mixed integer model formulation. As balancing requirements and empty flow for loading units are integrated, this model already has a close connection to the operational planning level.

Zhou et al. (2018) analyze different mixed integer (cost minimization) and bi-objective mixed integer (cost and emission minimization) formulations for the network flow planning problem. The models include binary selection variables for possible mode-vehicle combinations of the network, which allows the integration of different vehicle types.

Abuobidalla et al. (2019) determine the trip plans for a railway operator by means of a nonlinear mixed integer formulation and thereby include the block assembly for railcars in their model.

4.4.1.5 Summary of all categories

As an overall summary, the state of research regarding problem characteristics and model formulations and the integration of stochasticity differ among the respective categories. The focus of the dynamic service network design with variable network structure is more on developing generally applicable heuristics and lowering computational times, whereas this is rather a research gap for the design with a given network structure. In this category, research has achieved more progress by including different uncertain parameters. Non-dynamic network design models provide a more abstract view of the planning and could be combined with dynamic models in a two-step procedure in the future. The non-dynamic models would provide a start solution with arcs to open and their respective capacities, which is the basis for deriving the exact schedules by means of dynamic models. Network flow planning models are less frequent. However, including stochastic elements would also be beneficial here, as none of the references in the survey has conducted this so far.

4.4.2 Solution approaches

After presenting the problem categories and respective model formulations, the solution approaches for the service network design and flow planning problems are expounded in detail in the following section. In Section 4.4.2.1, the solution approaches for the deterministic problems are presented, followed by approaches for the stochastic counterparts in Section 4.4.2.2.

4.4.2.1 Solution approaches for deterministic problems

Figure 23 provides an overview of the solution approaches for deterministic service network design and flow planning problems. The approaches can be divided into exact methods, matheuristics (heuristical procedures based on combining the exploration of the solution space derived by the mathematical problem formulation with metaheuristic approaches, Boschetti et al., 2009), and metaheuristics. Due to the complex problem structure, the majority of the models are solved heuristically (matheuristics and metaheuristics: 20 out of 35 deterministic models overall), whereby metaheuristics dominate against matheuristics.

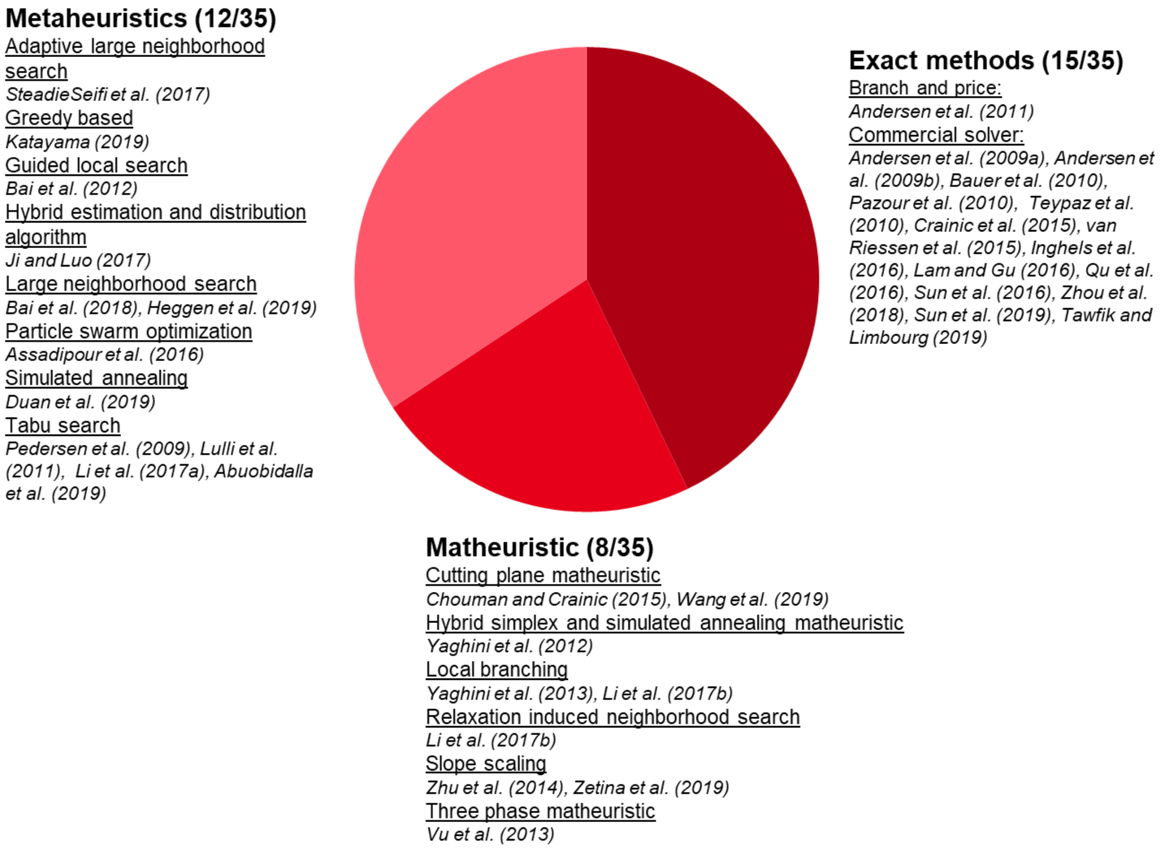


Figure 23: Overview of solution approaches for deterministic service network design and flow planning problems

In the following paragraphs, the solution approaches are presented regarding the respective model categories. A large research stream deals with generally applicable solution approaches for the dynamic service network design with variable network structure and consideration of asset management. Pedersen et al. (2009) introduce a Tabu Search as a metaheuristic approach, which outperforms commercial solvers on benchmark instances. A further improvement is achieved by Andersen et al. (2011), which is the only reference that develops its own solution approach based on exact methods. Their branch and price approach outperforms more simple exact methods like column generation and is capable of solving even larger network instances up to 50 services and 30 time periods. Bai et al. (2012) develop a guided local search approach, which is based on a tabu search and penalizes undesired features of the solution (in the case of service network design, opened arcs with high fixed costs) during the search procedure. Bai et al. (2018) introduce a large neighborhood search with a new arc-based neighborhood structure.

Besides those metaheuristic approaches, the problem can also be solved successfully by matheuristics. Vu et al. (2013), as well as Chouman and Crainic (2015), are able to further reduce computational times and increase network sizes up to 700 arcs and 400 commodities. Vu et al. (2013) incorporate a three-phase procedure containing a tabu search, a solution diversification, and a mixed integer program solver. The matheuristic of Chouman and Crainic (2015) is based on cutting planes. Further constraints for the mathematical problem are generated during the search procedure by defining arcs that must be included in the network design to provide sufficient capacity with regard to the given demand. Zhu et al. (2014) developed a matheuristic based on slope scaling. Li et al. (2017b) compare a local branching approach with a relaxation-induced neighborhood search. Both matheuristics are based on a branch-and-bound procedure in which the number of variables that may be changed in one iteration is limited. In a computational study for modified instances of Pedersen et al. (2009), the relaxation-induced neighborhood search provides superior results in terms of cost minimization and runtime. Three references develop metaheuristics for the dynamic service network design with a given network structure. Ji and Luo (2017) apply a hybrid estimation and distribution algorithm in which a probability matrix is introduced for different mode and service choice combinations. The probability matrix reflects promising solutions but also incorporates a random element for diversifying the solution space. The approach is superior to standard genetic algorithms regarding the evaluated instances. Heggen et al. (2019) integrate vehicle routing for drayage operations into the service network design. Therefore, the authors use a large neighborhood search with insertion and removal operators from respective solution approaches for vehicle routing problems. Duan et al. (2019) developed a simulated annealing based heuristic method to solve a frequency-based service network design model enhanced with heterogenous user values for time and reliability of the service.

Regarding the non-dynamic service network design with a variable network structure, four further heuristic approaches can be distinguished. Yaghini et al. (2012) incorporate a hybrid simplex and simulated annealing matheuristic, which combines a simplex approach for defining the neighborhood with a simulated annealing framework. Katayama (2019) tests a modified greedy algorithm, which improves a standard greedy approach with a capacity scaling and branch-and-bound procedure. Wang et al. (2019) present a hybrid algorithm which combines a local search with pricing and cutting techniques. Zetina et al. (2019) apply a hybrid matheuristic that combines a slope scaling metaheuristic with column generation to solve a path-based fixed-charge network design with elastic demand.

For the network flow problem, SteadieSeifi et al. (2017) introduce an adaptive large neighborhood search. The metaheuristic consists of different remove and repair operators for changing network paths of the orders and is capable of solving instances up to 2000 orders. Abuobidalla et al. (2019) developed a two-phase heuristic. A pre-processing procedure to generate potential car blocks is applied in the first stage. In the second stage, a tabu search is combined with a commercial solver.

In summary, a clearly dominant approach in terms of the presented heuristics cannot be identified. A noticeable fact is that the developed matheuristics perform well and are partially superior to metaheuristics in benchmarking studies. As the number of these approaches is significantly lower, further research should increase its efforts in this direction.

4.4.2.2 Solution approaches for stochastic problems

Figure 24 shows the solution approaches for the stochastic problems. Compared to the deterministic case, simulation can be introduced as a further category. In general, the computational effort for solving the stochastic models is high because the problems are (in most cases) NP-hard, and instance sizes of the problems increase. The latter is caused by representing the uncertainty by different scenarios (with regard to different demand or transportation time realizations), whereby each scenario is equal to a complete deterministic instance of the problem. Consequently, the application scope for exact methods is limited to rather small network sizes.

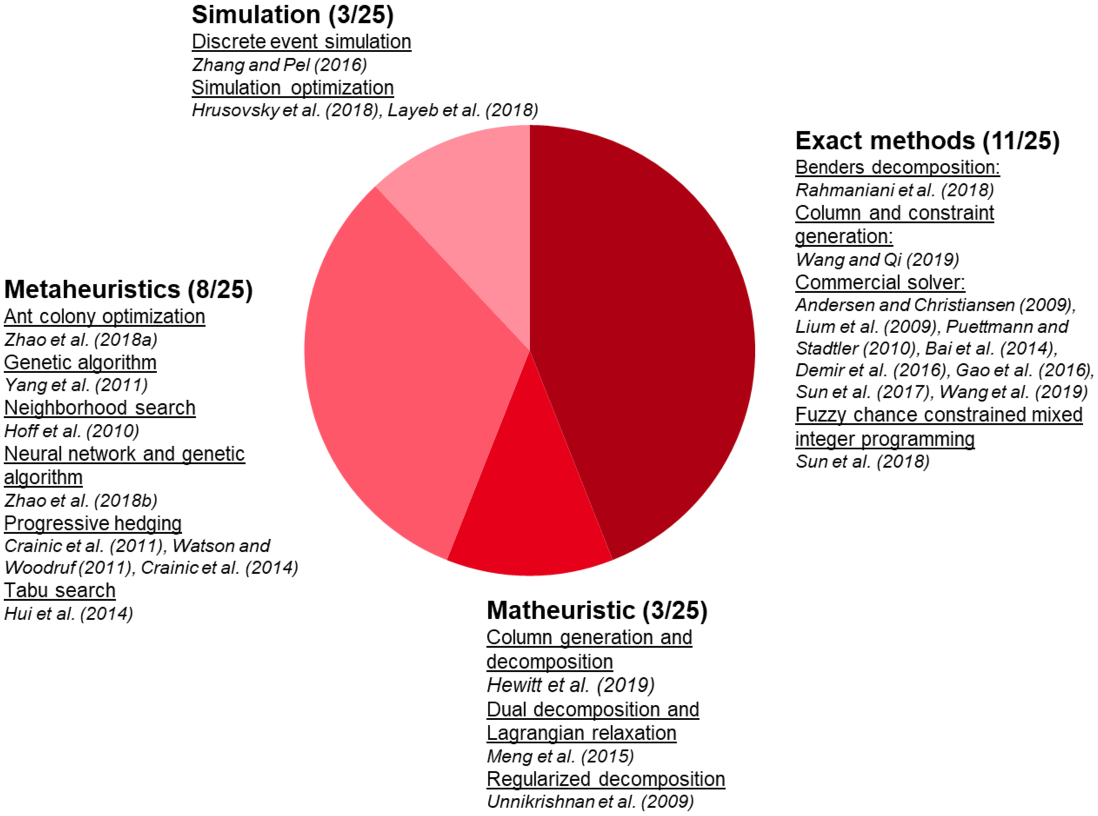


Figure 24: Overview of solution approaches for stochastic service network design and flow planning problems

With regard to the different problem categories, only three references study self-developed procedures for the dynamic service network design with a variable network structure and consideration of asset management. Whereas this research stream is the largest for the deterministic models, the approaches for the stochastic case are still rather in the beginning. Two references introduce heuristic approaches. Hoff et al. (2010) develop a neighborhood search with a specific neighborhood structure for the uncertain demand problem, consisting of the addition of arcs to vehicle paths with high transportation demand and terminal swap operations (changing visited terminals for the vehicles). Instances of up to 30 terminals and 90 demand scenarios can be solved. As a metaheuristic approach, Zhao et al. (2018a) present an ant colony optimization, which can solve the service network design with uncertain demand and transportation times. They test the heuristic for a case study network in China with 19 nodes. Hewitt et al. (2019) develop a column-generation-based matheuristic scheme, which decomposes the optimization problem across multiple dimensions for the strategic network design with resource acquisition and management. Wang and Qi (2019) introduce a column and constraint generation procedure as an exact approach in which the decision variables and feasibility or optimality constraints are added successively during the solution procedure. Their approach is dedicated to the robust programming formulation of the problem (minimizing cost for the worst possible case), whereas the other two approaches aim to optimize the expected cost value across all uncertain scenarios.

For the dynamic service network design with a given network structure, a broader range of solution methods can be identified. In terms of metaheuristics, Hui et al. (2014) apply a tabu search for the assignment of transportation tasks to different freight forwarders. Zhao et al. (2018b) train a neural network to approximate the impact of random demand and transportation times on the objective function value and solve the respective optimization problem with a genetic algorithm. Meng et al. (2015) rely on a matheuristic in the form of a dual decomposition and Lagrangian relaxation approach for the service network design, in which fixed capacity bookings should be determined for uncertain demand. Each random demand scenario is solved independently so that different fixed-capacity bookings are possible. Non-anticipative constraints are added during the solution process, which enforces a unified fixed capacity booking over all scenarios at the end of the search procedure. As a case study, a network in China with 19 nodes, 17 train routes, and 8 ship routes can be solved to optimality. A further approach is simulation optimization, which combines optimization procedures by standard solvers with a subsequent simulation experiment to evaluate the solution. Hrusovsky et al. (2016) combine a mixed-integer linear program with a discrete-event and agent-based simulation to include stochastic transportation times. In an iterative manner, selected transportation services and commodity flows are determined by optimization and simulated in the next step. Additional constraints are added to the optimization problem for shipments with high expected delays after each simulation run to reduce the probability that the respective transportation paths are chosen again. Layeb et al. (2018) extend simulation optimization to cover stochastic demand volumes as well. Both references indicate that simulation optimization can be suitable for analyzing larger problem instances compared to solely focusing on optimization.

Referring to non-dynamic service network design, Unnikrishnan et al. (2009) developed a matheuristic in the form of a regularized decomposition. The original problem is decomposed into a master problem and multiple sub-problems, which represent different demand scenarios with fixed capacity decisions for the network. The approach includes a distance measure in the objective function, which avoids solution spaces with a low probability of reducing overall costs are exploited extensively. Yang et al. (2011) introduce a genetic algorithm that is based on a set of potential paths for the origin-destination pairs of commodities. The genetic algorithm combines several potential paths for an overall design of the network, which is then evaluated by a simulation in terms of transportation costs. A further metaheuristic approach, which is also based on decomposing the problem into scenario-specific subproblems, is progressive hedging, applied by Crainic et al. (2011), Watson and Woodruf (2011), and Crainic et al. (2014). The approach is comparable to the dual decomposition and Lagrangian relaxation of Meng et al. (2015). Decisions on arcs to open in the network are determined independently for each demand scenario in the first step and are unified throughout the solution procedure by additional constraints. As an exact approach, Rahmaniani et al. (2018) provide a comprehensive evaluation of various acceleration strategies for a Benders decomposition algorithm. Benders decomposition is a special solution scheme for stochastic programs in which additional constraints are added iteratively. Their numerical study shows large improvements compared to a naive Benders procedure and to standard solvers, too.

In conclusion, comparable to the deterministic models, metaheuristics dominate over matheuristics. Certain heuristics based on the specific structure of the problem (like progressive hedging, dual decomposition, and regularized decomposition) are caused by incorporating the uncertain parameters in a set of quasi-deterministic scenarios. In contrast to the deterministic case, generally applicable metaheuristics for the dynamic service network design with variable network structures have not been developed as much. Moreover, simulation-based approaches are quite in the early stages and underrepresented compared to metaheuristics, which is a little bit surprising as simulation is a dedicated tool for covering uncertainty in planning.

As a large part of the presented solution approaches deals with handling the increased complexity caused by integrating stochasticity, the next subsection summarizes whether superior solutions can be achieved compared to a quasi-deterministic approach and, in consequence, justifies the increased effort.

4.4.3 Value of stochastic planning approaches

In this subsection, general characteristics of stochastic solutions are compared to their deterministic counterparts. The value of stochastic approaches in network planning and design is discussed afterward.

Nine references of the survey compare their stochastic with a deterministic And work out differences in the solution characteristics. Six references refer to stochastic dynamic service network design with variable network structure. For the models with asset management and stochastic demand, Lium et al. (2009) and Bai et al. (2014) conduct computational experiments to compare a deterministic solution with expected values to the solution derived by two-stage stochastic programming. The benefits of the stochastic solution depend on the correlation of the demand volumes. Lium et al. (2009) work out that the more uncorrelated or negatively correlated the demand volumes are, the higher is the solution quality gain compared to the deterministic approach. Those advantages are achieved by higher consolidation and higher flexibility. Consolidation relates to the tendency of the stochastic solution to route commodity flows over transshipment nodes for bundling them, although expected demand values would justify direct transportation. Flexibility is achieved by creating more different paths (in the transportation schedule) between origin-destination pairs.

However, Bai et al. (2014) show that savings of the stochastic solution are the highest for very uncertain and also for positively correlated demand and not as significant for uncorrelated demand. The deterministic solution tends to pair up positively correlated demand in commodity flow, leading to high outsourcing and/or rerouting (changes in transportation schedules of vehicles) as recourse action. Therefore, a stochastic solution approach is especially useful for environments with highly uncertain demand and high outsourcing and/or rerouting costs.

Sun et al. (2017) and Wang et al. (2019) compare three solution approaches (two-stage stochastic programming, skeleton, and upgrade), which incorporate stochastic demand to different degrees, with a deterministic approach. The stochastic solution can be compared to the deterministic one by the value of the stochastic solution (VSS), a commonly used measure introduced by Birge (1982), which calculates the expected value of using a stochastic model (or the expected losses of using a deterministic model, respectively).

A pure deterministic approach can lead to losses of up to 60% compared to the two-stage stochastic programming approach. However, it could be sufficient to solve the mixed deterministic-stochastic skeleton model for achieving acceptable solution qualities with lower computational time. In the skeleton approach, binary decisions on opening transportation arcs are determined by the deterministic model. Afterward, the stochastic program (with fixed binary variables) is solved to determine the capacity of the arcs and commodity flows. By the skeleton approach, 97% of the loss in the VSS can be recovered for the minimum cost transportation and the storage capacity problem and 31% for the minimum cost transportation schedule problem. In the upgraded approach, the deterministic model is solved, and the solution is taken as a lower bound on the capacity variables in the stochastic model. Hence, an upgrade does not reduce the computational complexity because the complete stochastic model still must be solved. It rather allows the analysis of structural differences in stochastic and deterministic solutions for explaining the VSS. By means of this analysis, Wang et al. (2019) confirm the results of Lium et al. (2009) that stochastic solutions provide more consolidation (paths with transshipments) and flexibility (more different paths opened in the network), which make them superior compared to deterministic approaches.

For the robust optimization of the dynamic service network design with variable network structure, Wang and Qi (2019) can also confirm the necessity of considering stochasticity in the network design. In numerical experiments, they identify increasing additional costs depending on the growing variability of demand for relying on the deterministic instead of the robust solution. Zhao et al. (2018a) contribute to the literature by additionally considering random transportation times. A case study for a network in China demonstrates that the stochastic solution determines completely different transportation paths compared to the deterministic approach.

Three references analyze the stochastic solution characteristics for the dynamic service network design with a given network structure. Meng et al. (2015) compare the solution of the two-stage stochastic programming to the deterministic solution with expected values for the random demand volumes. Their computational experiments show superior performance of the stochastic solution. Demir et al. (2016) is the only reference in the survey that compares the solutions for stochastic transportation times (and not only for stochastic demand volumes). The conducted computational study, based on a real-world case study, shows that considering uncertain transportation times leads to a higher value of the stochastic approach than considering uncertain demand volumes. The deterministic solution especially tends to produce infeasible routes in which the commodities cannot reach their final destination (or must then be transported by ad-hoc trucking, for example). Layeb et al. (2018) focus on the impact of shapes of the distribution functions of random demand and transportation times. Computational experiments reveal the importance of providing the model with information on distribution shapes and not only mean and variance of random parameters since solutions differ significantly. In consequence, stochastic models might require a comprehensive data collection of uncertain parameters to deliver satisfying solutions in real-world applications.

In summary, all references stress the value of incorporating uncertainty into the planning models. Significant gains compared to a deterministic approach could already be achieved by heuristic solutions, which combine stochastic and deterministic approaches. The most important feature of stochastic solutions, with regard to demand volumes, is the information on their correlations. Stochastic solutions show a higher consolidation and flexibility for better coping with an uncertain environment. Moreover, distribution functions for the random parameters seem to be necessary inputs to ensure a high-quality solution.

4.4.4 Fields for future research

After presenting problem characteristics, model formulations, and solution approaches and discussing the value of stochastic planning, in this last subsection, an outlook on future fields of research is given (referring to RQ 3). Five main fields can be identified, which are expounded in the following subsections.

4.4.4.1 Extending the scope to green service network design and flow planning models

Only a limited number of references have included environmental aspects in the models so far. As reducing GHG emissions is a main driver for promoting multimodal transportation, the state of research might not reflect this aspect adequately. The few models that integrate respective indicators stress the possibility of a modal shift from road to rail or barge transportation when limits on CO_2 emissions are decreased (Bauer et al., 2010, Inghels et al., 2016, Lam and Gu, 2016, Ji and Luo, 2017, Sun et al., 2019). However, this result is not surprising and an endogenous characteristic of the mathematical model. Statements regarding the economic impact for the operators under consideration of the trade-off between reducing emissions and possible efficiency losses (increases in cost or transit times) are rather scarce and partially contradicting. Sun et al. (2019) detect a high-cost increase in case of sharper emission constraints, whereas Lam and Gu (2016) even point out possible cost reductions caused by lower variable transportation costs of the modes rail and barge. According to this reference, efficiency losses are more likely caused by high transit times, even for time-critical demand. Bauer et al. (2010) analyze a service network problem that uses exclusively GHG emissions as an objective function. They conclude that significant GHG reductions can be achieved, but the monetary costs increase sharply.

In consequence, further research could concentrate more on analyzing concrete political measures like CO_2 taxes and their influence on the mode choice. The contribution of green network design and flow planning models could especially lie within the field of identifying concrete ranges in terms of efficiency losses in dependence on varying tax levels on CO_2 (or further pricing measures of GHG emissions). As the models incorporate the transportation processes on a detailed level, the possibilities for a modal shift can be determined more precisely for concrete network structures (compared to strategic models) under consideration of the decisions by the economic actors, which must weigh efficiency losses against higher fees for environmental damage.

4.4.4.2 Consideration of multi-actor planning

Only one reference (Puettmann and Stadtler, 2010) considers multiple actors by means of decentralized coordinated planning. This aspect is a further potentially highly interesting research stream because a single-actor planning approach can only cover the situation of a (large) operator owning all required transportation assets. However, a main characteristic of multimodal transportation in the real world is the interdependence between several actors who are responsible for one specific part of the transportation chain. Therefore, complex coordination of the actor-specific planning activities is necessary, including the organization of drayage operations of road carriers for the PPH and the management of terminal capacities with regard to the transportation schedules of different actors. The impact of information exchange and integration of the planning activities of different actors has not been studied extensively in network design and flow planning so far. As a concrete example, Heggen et al. (2019) stress the importance of coordinating drayage and long-haul service scheduling. However, in real-world networks, those parts of the transportation chain are frequently operated by different actors. More studies could investigate possible cost and transit time reductions, which could generate mutual benefits for all actors.

4.4.4.3 Changing the scope from cost minimization to profit maximization

Current research on network design and flow planning focuses on cost minimization as a prerequisite for fulfilling all occurring transportation requests. Only Andersen and Christiansen (2009), Teypaz et al. (2010), Tawfik and Limbourg (2019), and Zetina et al. (2019) incorporate revenue from fulfilling the transportation orders into their models, which extend the decision scope to the selection of the most profitable orders with regard to possible transportation plans. The simultaneous decision on orders to transportation and network design or flow planning could increase the profit of multimodal operators and, therefore, strengthen the position in a competitive environment with usually low-profit margins. Orders which require the offer of high-cost services can be excluded from the network. In a further extension of this approach, prices for different orders can be variable, and the customer's price-demand functions can be integrated. In contrast to the currently common approach of assuming a given amount of demand, those profit maximal network design or flow models would treat demand as a variable. In consequence, capacity allocations to and cost reductions for different relations would also be evaluated by possible demand increases and additional revenues. If the potential demand for some relations is high, it will increase the profit to further assign capacities to and reduce costs on those relations at the expense of lower capacities and higher costs on other relations with lower demand. The result could be a different transportation schedule compared to a cost-minimal network design or flow planning.

4.4.4.4 Integration of heterogeneous assets and loading unit management

A further future research stream could aim to extend the integration of heterogeneous assets and loading unit management. Whereas the first aspect is already covered by some references (among others Andersen and Christiansen 2009, Li et al. 2017a, Wang and Qi 2019), especially loading unit management is rarely considered. Both aspects are important for real-world applications. Allocating vehicles of different capacities to network paths is a key planning issue for multimodal operators. An additional contribution to this relation can be the inclusion of vehicle routing for the road mode, which is only incorporated by Heggen et al. (2019) so far. The currently dominant approach of modeling road transportation by network arcs with fixed assigned cost values neglects the fleet management issues, as road transportation costs are significantly determined by efficient routing to avoid empty haulage.

In terms of loading unit management, it can be beneficial to consider loading unit flow to fulfill balancing constraints already at the tactical level and not only in operative planning with fixed transportation schedules. A relevant amount of the overall flow in multimodal networks can be caused by empty loading units, especially because demand could be unbalanced in different directions. Thus, vehicle flow must be planned accordingly, and possibilities for integrating the empty loading unit flow into the schedule to fulfill the actual demand must be investigated in order to avoid additional costly transportation operations. As research has achieved progress in solving larger model instances, especially for the dynamic service network design with a variable network structure, it seems to be possible to cope with the additional model complexity caused by integrating both aspects.

4.4.4.5 Developing more sophisticated metaheuristics for stochastic models and increasing the amount of simulation studies

When comparing heuristic approaches for deterministic and stochastic models, a broader research stream in the deterministic field, specifically for the dynamic service network design with variable network structure and asset management, can be identified. Until now, it seems that the research streams for models without and with uncertainty have developed rather independently. As stochastic planning can significantly change network design (see Section 4.4.3), the existing approaches for the deterministic case should be developed further in order to cover larger instances of the stochastic counterparts. Additionally, random transportation times can be integrated more frequently, as the main focus of the stochastic dynamic service network design with variable network structure has been on random demand so far. Considering uncertain transportation times and delays is of comparable importance and allows the precise allocation of time buffers into the schedules for increasing reliability.

A further methodological research gap is the lack of simulation studies. Existing approaches demonstrate that superior solutions could be derived for the same problem instances compared to pure optimization models (Hrusovsky et al., 2018). Especially simulation optimization might be a promising way to analyze larger networks with stochastic elements, which is also stressed by other reviews (Crainic et al., 2018). Moreover, the extension of scope to profit maximization and inclusion of asset management and loading unit issues could also be integrated in stochastic models without suffering from excessive computational times.

The five main fields presented can be the basis for further research on service network design and flow planning. A conclusion regarding the current state of research and the limitations of the review are presented in the following last section of the paper.

4.5 Limitations and conclusion

The presented literature review has several limitations, which should be considered when interpreting the results. First, we limited the scope of the review to references that explicitly focus on service network design and network flow planning in multimodal transportation. The possibilities of transforming approaches from other research fields have not been investigated. General and more abstract approaches for network design problems, which are also applicable to telecommunication networks, could bear potentially interesting solution approaches for multimodal network design as well. Additionally, related fields in logistics and transportation that could cover partial aspects of multimodal transportation (vehicle routing, supply chain network design, deep sea liner shipping network design, city logistics) are excluded.

Moreover, the review focuses on network design and flow planning as important aspects of tactical planning. Further tactical planning problems (asset management, revenue management, crew planning) are only tackled if they are directly integrated into network design and flow planning models. Strategic and operational planning is also not covered. Specific reviews for the other tactical planning problems, as well as an overall up-to-date review on planning in multimodal transportations in total, could provide further insights, especially on possible interrelations to service network design and flow planning.

By considering those limitations, the main findings of the review can be concluded according to the RQs that were introduced. Regarding RQ 1 (classification of research regarding problem categories, model formulations, and solution approaches), service network design can be divided into dynamic and non-dynamic problems with and without a given network structure. A further division can be made in terms of the integration of asset management. The dominating model formulation is the mixed integer programming for deterministic models and two-stage stochastic programming for the stochastic case, which demonstrates the focus on optimization approaches compared to simulation. The majority of the solution approaches can be assigned to metaheuristics (without a clear dominating specific metaheuristics), whereas exact methods and matheuristics are less frequent. A large research stream, in terms of dynamic service network design with a variable network structure, is the development of heuristic approaches for deterministic problems with homogeneous assets.

Referring to RQ 2 (incorporation of uncertainty), the majority of the references for the dynamic service network design with variable network structure is deterministic. Stochastic approaches concentrate on integrating random demand into those models. For dynamic service network design with a given network structure and non-dynamic service network design, the larger part of the approaches incorporates stochastic elements. In terms of dynamic network design, random transportation times are also covered more frequently in the models with a given network structure than variable network structure. Specific heuristic approaches (like decomposition approaches or progressive hedging) for the special requirements of the stochastic problems are present in literature, and comparisons with deterministic equivalent solutions demonstrate the value of stochastic planning, which can result in different network designs and commodity flow paths.

In terms of future research needs (RQ 3), five main fields are presented. The importance of integrating environmental aspects (green network design and flow planning) can be stressed especially from the perspective of the society as a whole, whereas including profit maximization and asset as well as loading unit management more comprehensively could generate benefits for multimodal operators in terms of higher efficiency and profit margins. Extending the scope to multi-actor planning and the more frequent use of simulation studies can be an additional contribution to reducing current model simplifications and enhancing possibilities for real-world applications.

5 Study 2: Combined hub location and service network design problem[3]

In intermodal transportation, hubs are facilities that perform switching, sorting, connecting, and consolidating functions between many origins and destinations. Hub location problems (HLP) accordingly involve the location of hubs but include abstract network design decisions as well. In the past, the strategic location decision and the more tactical network design decision, in the form of a service network design problem (SNDP), have been considered separately. However, the SNDP is based on an existing hub network, and the HLP could benefit from a more detailed network design. For this reason, this paper presents the Combined Hub Location and Service Network Design Problem (C-HL-SNDP), which considers the strategic and tactical planning dimensions in an integrated manner. In a case study of a German intermodal operator, we show that integrated modeling can be used to produce very good and realistic solutions that generate added value. We compare the combined model with a classical HLP approach and perform a structural analysis of the solution properties. With this, we can show that the different consideration of economies of scale and economies of density leads to fundamentally different solutions.

5.1 Introduction

In the countries of the EU, road transportation still dominates the movement of goods, with a modal split of 76.5% compared to 18% by rail and 6% by inland waterway (EUROSTAT, 2018). To strengthen environmental protection efforts, an accelerated shift to environmentally friendly means of transportation such as rail or inland waterways plays an important role. By combining different modes of transportation, intermodal transportation can further help to minimize transportation costs and CO2 emissions and accelerate the shift in the mode of transportation. For this, efficient planning and operation of freight networks and transports are crucial.
Transportation networks are shaped fundamentally at the strategic planning level (SteadieSeifi et al., 2014). Since the decisions made there significantly influence performance, service levels, and transportation costs in the long term, these decisions should be thoroughly considered. One of these central decisions for freight transportation networks is the planning of hubs (Alumur et al., 2021). In general, two types of hubs can be distinguished in intermodal transportation: classification yards, also called shunting or marshaling yards, and transshipment yards.

[3] The content of this study is similar with only slight modifications to the paper Elbert, R., Rentschler, J., & Schwarz, J. (2023). "Combined Hub Location and Service Network Design Problem: A Case Study for an Intermodal Rail Operator and Structural Analysis". Transportation Research Record, 2677(1), 730-740. https://doi.org/10.1177/03611981221101391. Thus, in section the pronoun "we" refers to the authors of the paper.

Classification yards perform sorting, connecting, and consolidating functions. In transshipment yards, in addition to these functions, switching between modes of transportation, such as rail to road or road to an inland waterway, can take place. The location of hubs and the allocation of non-hub nodes to hub nodes strongly influence the transportation costs and service quality of a network. In most applications, HLPs aim to find the location of hub nodes and the allocation of demand nodes to these located hub nodes, thereby minimizing transportation costs or time (Alumur et al., 2012a). The assessment regarding the hub selection is rather abstract in most existing HLPs. Generalized assumptions neglect the time dimensions of services and demand and so do not reflect realistic requirements (Basallo-Triana et al., 2021). For an efficient design of the hub network, it is necessary to model and schedule commodity flows and vehicles not only by focusing on the costs they cause but also by considering the time they spend in hubs and traveling on arcs, as well as including varying transportation demands over the observed period of time (Alumur et al., 2021; Basallo-Triana et al., 2021).

One possibility to include the time dimension and to reflect real-world requirements more closely is the integration of the dynamic SNDP into the location decision. The SNDP includes decisions on transportation schedules and routes, which could, therefore, lead to more reliable and realistic results. Since, on the one hand, the HLP relies on a detailed assessment of hub placement, but on the other hand, the SNDP always relies on an underlying hub structure, it is natural to model them together.

The objective of this paper is to introduce and describe the Combined Hub Location and Service Network Design Problem (C-HL-SNDP) from the point of view of an intermodal operator. The intermodal operator intends to determine a set of hub locations for his network. As an assessment for the hub selection, a fixed service schedule over a given planning horizon is developed. Overall, the problem is to decide on the routes of the demand, the usage, location and allocation of hubs, and the number of trains operating between nodes. The objective is to minimize the overall costs for fulfilling all transportation demands, either by direct transportation or transportation through the hub network.

We test the C-HL-SNDP by conducting a real-world case study on the network of one of the largest German intermodal operators transporting commodities from the ports to the hinterland. To prepare for a network expansion, the intermodal operator is subjecting its current network to a fundamental analysis concerning the hub structure. In our case study, we determine the integrated hub selection and service decision as well as the transportation costs. For a network with three hubs, we perform an in-depth analysis to show that the integrated modeling and solving of the C-HL-SNDP leads to structurally different results and cost savings.

Formally, this paper answers the following RQ:

> **RQ1**: Can strategic (HLP) and tactical (SNDP) planning of a transportation network be combined to provide in-depth conclusions regarding network structure?
>
> **RQ2**: Can integrated modeling provide added value for a real-world use case?
>
> **RQ3**: Are there structural differences between the classical HLP and the combined problem?

The remaining parts of the paper are structured as follows: We start with a short review of existing literature about HLP, SNDP, and the combined problem. Afterward, we propose a novel model for the C-HL-SNDP. The model is tested on a real-world case study. After discussing the results of the case study, this work finishes with a short conclusion.

5.2 Literature review

In this section, we summarise the most important developments and current research trends in recent years. Although solutions to the SNDP can act as detailed assessments for the HLP and consideration of a combined strategic and tactical problem seems to be promising, most research focuses only on either the HLP or the SNDP (Alumur et al., 2021). Through the sequential analysis of the strategic and tactical planning levels, a variety of constraints are placed on the tactical level. Through integrated planning, more comprehensive results can be achieved. Accordingly, we structure the review of the literature by assessing the HLP, SNDP, and the combined problem separately and show research gaps motivating our paper and case study.

5.2.1 Hub location problems

Hubs serve as switching and consolidation facilities in many-to-many flow network systems (Alumur et al., 2012a). Therefore, HLP has a central function in intermodal transportation networks, here, hubs act as switching points between different modes of transportation (Limbourg and Jourquin, 2009). In addition, HLPs are also used in other transportation systems, such as air transportation or deep-sea shipping, or in other fields, such as telecommunications or neuroscience (Bassett and Sporns, 2017; Jaillet et al., 1996; Kim and O'Kelly, 2009).

Since the first research on HLP by O´Kelly (1986), numerous pieces of literature have been published. For a detailed review, the interested reader may be referred to (Alumur et al., 2021; Basallo-Triana et al., 2021; Contreras and O'Kelly, 2019)

Kara and Taner (2011) proposed a fivefold taxonomy to structure and present HLP in the form ϵ / ϕ / κ / λ / ω. The parameters thereby correspond to objective criterion, allocation structure, capacity, interhub connectivity, and other restrictions. For the objective function, a distinction is made between p-hub median, hub location with fixed cost, p-hub centre and hub covering problems. In addition, further distinctions are made with regard to the minimum, minimax, and cover versions of the objective. The allocation structure, single or multi, of non-hub nodes, is given by ϕ. The capacity restrictions at hubs or arcs are indicated by κ. A distinction is made between unconstrained, constrained at the hub and/or arc. The underlying network topology, indicated by λ, can range from complete to various substructures such as path, tree, ring, and star. The last indicator ω allows authors to describe the special circumstances of their model. Below, we briefly review the state of the literature on related problems and show similarities and differences to the problem we investigate.

Ph-median problems aim to locate hubs in the network in such a way that the transportation costs are minimal. According to Basallo-Triana et al. (2021), the objective function can consist of different components. Cost per transported unit is considered in almost all models, e.g., (Campbell, 1996). In contrast, fixed costs for setting up arcs or hubs are only analyzed in a fraction of the models (Campbell, 1994; O'Kelly, 1992). Cost savings can be achieved through economies of scale, economies of density, and economies of spatial scope on transports between hubs (Alumur et al., 2021; Aykin, 1995; Campbell, 1994). An efficient allocation of non-hub nodes to hub nodes is crucial to minimize transportation costs (O'Kelly, 1992).

In some models, commodities may be only transported through the hub network (Campbell, 1996). In other models, transports are not only allowed via hubs, but also direct connections between non-hub nodes are possible (Mahmutoğulları and Kara, 2015). In contrast to hub transports, the usage of direct connections is not discounted but rather penalized (Campbell and O'Kelly, 2012; Mahmutoğulları and Kara, 2015). Nevertheless, models that allow direct connection leads to more realistic modeling and cost savings. However, according to Basallo-Triana et al. (2021), models with direct transportation are only considered in about 30% of the studies and thus represent a minority.
They further divide the key modeling factors regarding the realism of the model into external and internal. External factors are exogenous to the system, such as data uncertainty, disruptions, and the interaction between actors and the environment. Meraklı and Yaman (2017), as well as Rostami et al. (2021), consider demand uncertainties, but also other relevant data in HLP modeling can face uncertainties. For example, transportation costs (Contreras et al., 2011; Rahmati and Neghabi, 2021) or the handling and travel time (Shang et al., 2021). One possibility for modeling uncertainties is with the help of a set of different scenarios. Each

scenario thereby represents one possible form of realization of the uncertain parameter and is considered with its probability of occurrence in the HLP model (Alumur et al., 2012b).
Internal factors, on the other hand, refer to the main elements of hub networks like hubs, transportation modes, and the physical network. The two most recent and comprehensive reviews (Alumur et al., 2021; Basallo-Triana et al., 2021) agree that the internal factors, in particular, are represented in a highly simplified way. They suggest several research directions for more realistic modeling:

Use of real data/incomplete networks: In the European context, transhipments between rail-road and rail-rail terminals are typical. The underlying networks are usually not complete due to topology and existing infrastructure. Therefore, it would be desirable to consider formulations with incomplete network structures that resemble the characteristics of the system under study. Deviating from this, the classical datasets on which the HLP is studied (i.e., CAB, AP, and Turkish datasets) have a complete network.

Dynamic nature of transportation systems/incorporation of time: Time and synchronization play a key role in economies of scale for transportation networks, and time is a crucial metric for quality of service in HLPs. Many existing formulations assume rigid physical structures that create a lack of flexibility in transportation activities. This could be improved by considering the dynamic nature of transportation systems, service frequencies, and flow synchronization by allowing for a change in hub connections at different periods during a planning horizon.

Integration of HLP with other problems: By adding more tactical questions and more application-specific features to HLP, they can be enhanced. Alumur et al. (2021) highlight in particular the links to the service network design and multi-commodity network flow research.

5.2.2 Service network design problems

SNDPs are tactical problems that aim to determine the schedule of services, the assignment of commodities to these services, and their routing through a network (Crainic, 2000). The demand for commodities must be served reliably and, if a time dimension is considered, also punctually (Crainic and Kim, 2007). Similar to HLP, the most common objective is to minimize costs, compromising variable and fixed transportation costs (Pedersen et al., 2009; Wieberneit, 2008). Detailed reviews can be found in (Crainic, 2000; Elbert et al., 2020; Wieberneit, 2008).

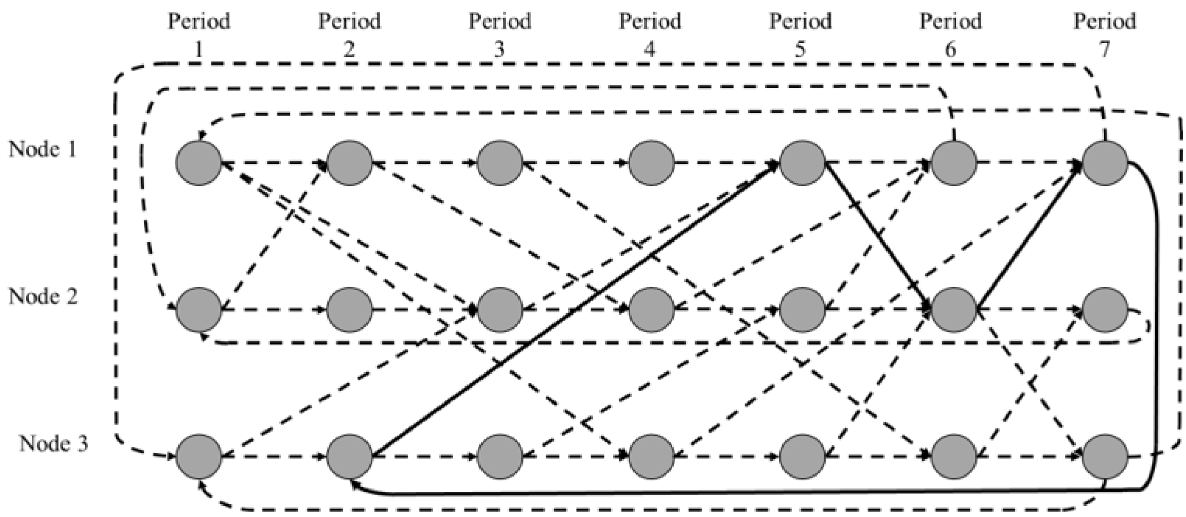


Figure 25: Time-Space Graph |own representation based on Pedersen et al. (2009)

Dynamic SNDP consider a temporal dimension, often represented as a time-space graph, see Figure 25 (Pedersen et al., 2009). The geographical network is replicated for every period in the planning horizon (e.g., a day, a week). The arc set consists of all possible connections between the nodes concerning geographical transportation links and minimum transportation time. A feasible solution constitutes a transportation route between geographical nodes in different periods (Lium et al., 2009; Pedersen et al., 2009; Wieberneit, 2008). Considering the temporal dimension permits the inclusion of factors like varying demand over different periods or temporal service networks (Elbert et al., 2020; Lium et al., 2009). To the best of our knowledge, a time-space graph representation hasn't been considered in the context of HLP so far.

SNDPs are frequently applied to intermodal networks (Braekers et al., 2013). Different transportation modes can, therefore, be represented in the time-space graph (van Riessen et al., 2015b). Even limitations or assignments for single vehicles and other assets can be considered in SNDP. The neglect of asset management in a model can cause inefficient usage of available resources and infeasible transportation plans (Andersen et al., 2009b). Asset management considers, for example, the number of vehicles in the available fleet or routing limitations of vehicles (Andersen et al., 2009a; Andersen et al., 2011; Teypaz et al., 2010). Most often, asset management is modeled by so-called design-balance constraints. These constraints enforce that the number of vehicles leaving a node in a period is equal to the number arriving. Current trends in SNDP literature consider, as proposed by Elbert et al. (2020b), are:

- Extending the scope to green service network design: Environmental aspects have so far been taken into account in only a few models (Bauer et al., 2010; Sun et al., 2016). Since reducing GHG emissions is one of the main drivers for promoting intermodal transportation, the state of research may not adequately reflect this aspect.
- Integration of heterogeneous assets and loading unit management: Only a few references cover heterogeneous assets and loading units (Andersen and Christiansen, 2009; Wang et al., 2019b). This could further enhance the benefit of the combined model.
- Stochastic models and metaheuristics: As in HLP, there are numerous models that consider uncertainties. Most research assumes the demand (Baubaid et al., 2021; Hewitt et al., 2019; Wang and Qi, 2020) or the travel time (Lanza et al., 2021; Müller et al., 2021a; Zhao et al., 2018b) to be stochastic. Like in HLP, uncertainties can be modeled as different scenarios where each scenario has a certain probability of occurrence (Hewitt et al., 2019; Jiang et al., 2021; Müller et al., 2021a). Stochastic planning can significantly change network design. To evaluate these highly complex models, sophisticated metaheuristics are necessary.

5.2.3 Combination of HLP and SNDP

The joint modeling and solving of HLP and SNDP leads to much more detailed and realistic solutions but, at the same time, to a significant increase in complexity. In the literature, there are a handful of combined models that explicitly consider both HLP and SNDP aspects. A short overview is given by Rothenbächer et al. (2016). They are also one of the first to study in-depth the integrated tactical planning of hub locations and the design of a frequency service network. For the SNDP, they use a path-based model and consider travel time constraints. Furthermore, they consider a set of real-world constraints, such as multiple transhipments of commodities at hubs, demand splitting, and outsourcing.

Some of the research gaps mentioned for HLP and SNDP thus remain unaddressed. In the next sections, we, therefore, present an integrated problem to address, among others, gaps such as the dynamic nature of transportation systems.

5.3 Model description and formulation

In the following section, we introduce the C-HL-SNDP as an arc-based mixed-integer linear program. The notation is summarized in Table 10. We assume an intermodal operator intends to determine hub locations for his network so that the total cost of transporting commodities through the network is minimal. The commodities are modeled by a given set of transportation demands. As an assessment for the hub selection, a fixed service schedule over a given planning horizon (e.g., one day, one week) is developed to determine the transportation cost. The planning horizon can be divided into discrete time steps of equal length (e.g., one day), resulting in a set of planning periods $T = \{1, \ldots, |T|\}$. A geographical intermodal network is represented by the directed graph $G_g = (N_g, A_g)$ with N_g denoting the set of geographical nodes and A_g denoting the set of geographical arcs (physical network connections between the nodes $i_g, j_g \in N_g$). The graph does not necessarily have to be complete, as individual arcs may be missing. Moreover, the transportation time $t_{(i_g,j_g)}$ on each geographical arc is given by the respective number of planning periods. The graph G_g can be transformed into a time-space graph representation $G = (N, A)$ of the network, see Figure 25. The node-set N contains each geographical node $|T|$ times, with one time-space node for each planning period. The set of directed arcs A defines the possible connections between all nodes $i, j \in N$ under consideration of the transportation times $t_{(i_g,j_g)}$ of the respective geographical arcs.

We further make the following assumptions to represent reality as best as possible and formulate the model. These assumptions were discussed in depth with industry partners and found to be a good representation of reality.

- The triangle inequality holds for all nodes $i, j \in N$ (in terms of transportation times and costs (Marín et al., 2006). Therefore, at most two hubs are used, since transportation via more hubs is always more expensive.
- There is no cost associated with opening a hub; the transshipment capacity of hubs is unlimited, and transshipment takes place immediately. This assumption is based on the fact that the intermodal operator rather leases capacity in hubs and does not operate them itself.
- A fixed cost f_{ij} is associated with each vehicle deployed on arc $(i, j) \in A$. These fixed costs are divided into a fixed service charge per train, which represents the costs for hub use, and a distance-dependent cost.
- Variable costs c_{ij}^k are the costs for transporting or holding one unit of the commodity $k \in K$ on the arc $(i, j) \in A$.
- A homogeneous vehicle fleet, each vehicle with the same capacity u, operates within the network. Multiple vehicles can travel on an arc $(i, j) \in A$. The service is called a transportation service in case of different geographical nodes $i_g, j_g \in N_g: i_g \neq j_g$ and a holding service in case of equal geographical nodes $i_g, j_g \in N_g: i_g = j_g$. In the case of a transportation service, the number of trains used in the planning period determines the

transportation capacity available on the arc. In the case of holding service, the capacity is unlimited.

- The transportation demand is given by a set of commodities K, which must be transported between the geographical origin nodes $o_g(k) \in N_g$ and destination nodes $s_g(k) \in N_g$ of each commodity $k \in K$. Some but not all Hubs also act as an origin or a destination of a commodity.
- The deterministic demand to be transported for each commodity $k \in K$ is $d(k) \in \mathbb{R}^{\geq 0}$ and the transportation can be split across multiple services.
- Fixed release $\sigma(k) \in T$ and due $\tau(k) \in T$ periods are given for each commodity $k \in K$ and make it possible together with their geographical origin $o_g(k) \in N_g$ and destination $s_g(k) \in N_g$ to directly assign corresponding origin nodes $o(k) \in N$ and destination nodes $s(k) \in N$ in the time-space graph for all commodities $k \in K$. Due to holding service, commodities can arrive early.

Table 10: List of notations used in the C-HL-SNDP model.

Notation	Meaning
Parameters	
A_g	Set of directed geographical arcs
N_g	Set of geographical nodes
$G = (N, A)$	Directed graph with N denoting the set of nodes and A denoting the set of arcs in the time-space graph
K	Set of commodities
$H \subset N$	Set of potential hubs
T	Set of planning periods $T = \{1, \dots, \lvert T \rvert\}$
$t_{(i,j)}$	Transportation time on each geographical arc
$d(k)$	Demand for commodity $k \in K$
$o(k)$	Origin node for commodity $k \in K$
s(k)	Destination node for commodity $k \in K$
$\sigma(k)$	Period t, from when commodity $k \in K$ can be transported
$\tau(k)$	Period t, until when commodity $k \in K$ must be delivered
u	Vehicle capacity
n_h	Number of open hubs to open
f_{ij}	Fixed cost for each vehicle deployed on arc (i, j)
c_{ij}^k	Variable costs for transporting or holding one unit of the commodity $k \in K$ on the arc $(i, j) \in A$
Decision variables	
$h_i \in \{0,1\}$	1, if hub i is open, $i \in H$, 0 otherwise
$x_{ij}^{tk} \geq 0$	Transported quantity of commodity k from node i to node j in planning period t
$y_{ij}^t \in \mathbb{N}_0$	Number of vehicles operating in arc $(i, j) \in A$ in period t

There are two possibilities for transporting a commodity: transportation through the hub network or direct transportation from origin to destination. A number of potential hubs are given by the set $H \subseteq N_g$ and the number of hubs to be used is n_h. When a hub is opened, it is kept open for the entire planning period. Since the intermodal operator does not operate the hubs but only purchases the service, no costs for hub opening are incurred. At any point in time, an unlimited number of trains may use a rail link.

Overall, the problem is to decide on which hubs h_i $i \in H$ to open the temporal allocation of terminals to hubs by determining the number of vehicles y_{ij}^{t} operating on arc $(i, j) \in A$ in period t, and the itineraries of the transportation demands by assigning them to a service x_{ij}^{tk}. The objective is to minimize the overall costs for fulfilling all transportation demands, either by direct transportation or transportation through the hub network.

With this notation, the C-HL-SNDP can be formulated as arc-based mixed-integer linear program:

$$min \sum_{(i,j)\in A} \sum_{t\in T} f_{ij} y_{ij}^{t} + \sum_{(i,j)\in A} \sum_{k\in K} \sum_{t\in T} c_{ij}^{k} x_{ij}^{tk} \qquad (0)$$

subject to

$$\sum_{i\in H} h_i = n_H \qquad (1)$$

$$\sum_{k\in K} x_{ij}^{tk} \le u y_{ij}^{t} \qquad \forall (i,j) \in A, t \in T, i \neq j \qquad (2)$$

$$\sum_{j\in N^{+}(i)} x_{ij}^{tk} - \sum_{j\in N^{-}(i)} x_{ji}^{tk} = \begin{cases} d(k) \text{ if } i = o(k) \\ -d(k) \text{ if } i = d(k) \\ 0 \quad \text{else} \end{cases} \qquad \forall i \in N, k \in K, t \in T \qquad (3)$$

$$\sum_{j\in N^{-}(i)} y_{ij}^{t} - \sum_{j\in N^{+}(i)} y_{ij}^{t} = 0 \qquad \forall i \in N, t \in T \qquad (4)$$

$$x_{ij}^{tk} \le d(k) h_i + d(k) h_j \qquad \forall (i,j) \in A, k \in K, t \in T, \; i \neq j, i \neq o(k), j \neq s(k) \qquad (5)$$

$$x_{ij}^{\tau(k)k} = 0 \qquad \forall (i,j) \in A, k \in K \qquad (6)$$

$$h_i \in \{0,1\} \qquad \forall i \in H \qquad (7)$$

$$y_{ij}^{t} \in \mathbb{N}_0 \qquad \forall (i,j) \in A, t \in T \qquad (8)$$

$$x_{ij}^{tk} \ge 0 \qquad \forall (i,j) \in A, k \in K, t \in T \qquad (9)$$

The objective function (0) minimizes the total cost, which is the sum of the flow cost of demands on the solution network plus the fixed-charge cost of the vehicles included in the design. Constraint (1) ensures that the predetermined number of hubs is used. Constraints (2) are capacity constraints. They limit the permissible flow on an arc depending on the vehicles employed operating on this arc. Constraints (3) are the flow conservation constraints and ensure that each commodity flows from its origin node to its destination node. The so-called design-balanced constraints (4) ensure that the number of incoming vehicles is equal to the number of outgoing vehicles. Constraints (5) prevent flow on arcs outside the hub network except for direct connections of the respective commodity. Constraints (6) ensure that a commodity can no longer be transported beyond its delivery deadline, which is equivalent to constraints (4, 5, and 6) in the deterministic model in Lium et al. (2009). The feasible domains for the decision variables are given in the constraints (7)-(9).

5.4 Case study

In the real-world case study, we analyze the network of one of the largest German intermodal rail operators involved in maritime hinterland transportation. In the following subsections, we describe the design of the case study, the network under investigation, the obtained results, and an in-depth analysis.

5.4.1 Design of the case study

According to the taxonomy introduced by Kara and Taner (2011), our problem can be described as a pH-median/multi/Arc/incomplete/direct problem in combination with an SNDP. Using our combined model, we simultaneously determine hub selection and transportation cost minimal network setup. We compare the results of the C-HL-SNDP model formulation with the classical approach of first determining a hub selection and then calculating a service network for the determined hub selection. To determine a hub selection, we use the model presented by Mahmutoğulları and Kara (2015). They model a pH-median/multi/U/full/direct problem and, therefore, share important aspects with our model. Their formulation corresponds to the classical HLP model formulation in that they consider only aggregate transportation flows as an assessment for hub selection. With our model, they share essential aspects such as direct transportation between non-hub nodes, loosening one of the general assumptions in the hub localization literature. Since the basic assumptions and decisions in both models are similar, the model of Mahmutoğulları and Kara (2015) can be used to determine a comparable hub selection. To calculate the service network, we then use our model to fix the before-selected hubs. By comparing these two approaches, we can evaluate the benefits of integrated planning.

5.4.2 Description of the network

The rail services connect 15 hinterland nodes in Germany, Austria, and Switzerland with five port nodes in north-western and southern Europe, two of them in Hamburg, see Figure 26. Currently, the operators' portfolio consists mainly of transports to the northern ports. In the course of a network expansion, the service to the western and southern ports is to be increased. To best prepare for this network expansion, the intermodal operator is subjecting its current network to a fundamental analysis concerning the hub structure. Since the intermodal operator offers services from the hinterland nodes to the ports and vice versa within a weekly periodical schedule, the SNDP is particularly suitable for the evaluation of the hub selection.

There are six potential hub nodes included in the hinterland nodes. These hubs have been selected together with the intermodal operator to guarantee sufficient handling and transshipment capacity. In our case study, we determine the hub selection, service decision, and transportation costs for one to four hubs. For a network with three hubs, we performed an in-depth analysis, as interviews with the intermodal operator revealed that this is the most realistic scenario. The intermodal operator must purchase the transportation capacities from a railway undertaking. Since these are primarily block trains and a service charge per train is incurred for handling the goods at the hub, regardless of the number of goods transported, fixed costs dominate the problem. The input data, in terms of demand, for the C-HL-SNDP is based on an average transportation week. The data was processed and anonymized for this case study. Thus, the underlying geographical network consists of 20 nodes, more than 300 arcs and more than 400 commodities. Please note that due to a non-disclosure agreement with the intermodal operator no absolute numbers can be provided.

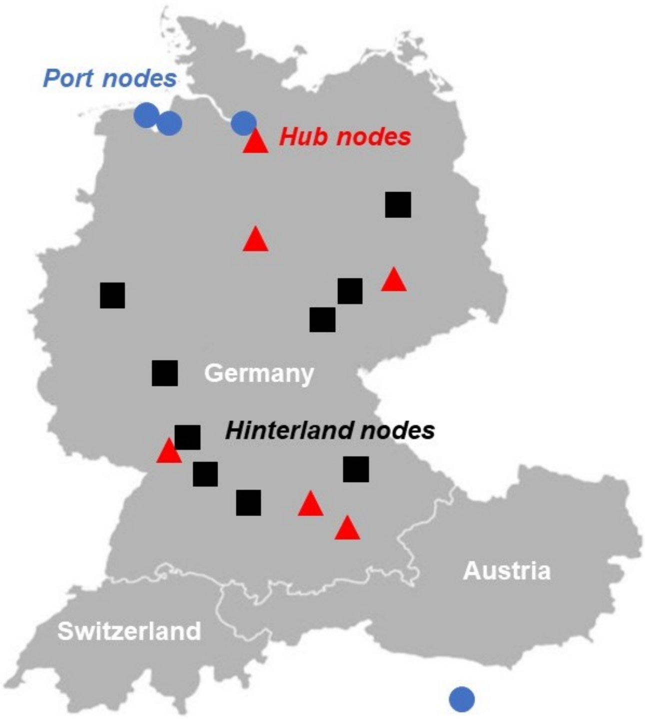


Figure 26: Geographical location of the nodes incorporated into the network of the intermodal rail operator

5.4.3 Results

To assess potential cost benefits by using the C-HL-SNDP, we compare the C-HL-SNDP with the classical approach of first determining a hub selection and then calculating a service network for the determined hub selection. Therefore, we solved the C-HL-SNDP and the p-hub median model by Mahmutoğulları and Kara (2015). To calculate the service network, we then use our model, which fixes the before-selected hubs.
To obtain the solutions, the two models are solved by the CPLEX MIP solver 12.10.0.0, a commercial solver for mathematical mixed-integer problems, to a given optimality gap (1%) on a personal computer (12 Intel i7 64-bit processors, 3.4 gigahertz, 128 gigabyte RAM) (IBM, 2021). To determine the hub selection, both models were solved four times, each time with a given number of hubs to open (one to four). According to Mahmutoğulları and Kara (2015), we have chosen a low discount factor on the inter-hub connections with $\alpha = 0.8$ and a low-cost increase for direct connections with $\beta = 1.5$ for the p-hub-median problem, in order to reflect the business model of the intermodal operator as best as possible and to achieve the greatest possible comparability between the models.

The performance of the two approaches is shown in Table 11. Columns "C-HL-SNDP" show the total cost of the C-HL-SNDP for one to four hubs and the relative savings that would be achieved by opening another hub. Columns "p-hub median" show the cost and savings for the hub combination determined by the p-hub median problem. The last column compares the two modeling approaches. The use of hubs can greatly reduce transportation costs. Since there are no costs associated with the opening of hubs in the model, the objective function naturally decreases as the number of hubs increases. However, it can be observed that this cost-saving is increasingly smaller.

Table 11: Results for C-HL-SNDP and p-hub median

#Hubs	C-HL-SNDP	C-HL-SNDP relative to #Hubs	p-hub median	p-hub median relative to #Hubs	C-HL-SNDP relative to p-hub median
1	1937022	-	1944320	-	-0,4%
2	1853185	-4,3%	1913727	-1,6%	-3,2%
3	1836459	-0,9%	1898529	-0,7%	-3,3%
4	1826714	-0,5%	1879539	-1,0%	-2,8%

The comparison of the C-HL-SNDP and the classical approach shows that by combining the HLP and the SNDP, a better solution, amounting to savings of up to 3,3%, can be determined consistently. This concerns both the absolute costs and the direct applicability for the intermodal operator. Hence, our first conclusion is that cost savings can be realized by utilizing the C-HL-SNDP.

To get to the core of this difference, we structurally analyze the two determined solutions for three hubs in the next section.

5.4.4 Structural analysis

A closer analysis of the solution characteristics explains the differences between the two approaches. Table 12 shows key solution characteristics. First is the assignment of non-hub to hub nodes. For example, in the C-HL SNDP, only one non-hub node does not use any hubs and performs all transportation directly. Eight non-hub nodes have exactly one access point into the inter-hub network. This compares to seven non-hub nodes with two to more access points to the inter-hub network.

Another interesting solution property is the proportion of demand that is transported directly via a single hub or via two hubs. Only in the latter case does discounting occur in the p-hub median model.

Table 12: Central solution characteristics for three hubs, obtained by C-HL-SNDP and p-hub median

Characteristic	C-HL-SNDP	p-hub median
Allocation of nodes to hubs		
Direct	1	1
Single-allocation	8	14
Multi-allocation	7	1
Share of transported commodities		
Direct	35,2%	8,1%
Via 1 Hub	58,7%	25.8%
Via 2 Hubs	6,1%	66,1%

The solution properties shown allow interesting conclusions to be drawn about the two ways of modeling. The assumptions underlying the respective model and their modeling are decisive and are reflected in the observed solution properties. Central to this is the mechanism by which the cost reduction through hubs is modeled. For this purpose, Alumur et al. (Alumur et al., 2021) distinguish between economies of scale and economies of density. Economies of density describe the reduction in costs per traffic unit due to an increase in traffic density with an unchanged network structure. In contrast, economies of scale take into account additional changes in the network. In practice, this is modeled in the classic HLP by representing economies of scale as cost reductions on inter-hub connections. In the C-HL-SNDP, economies of density are favored instead as a cost-reduction mechanism and are modeled by the higher utilization of capacity and, thus, the lower fixed costs per transported unit.

In the p-hub median model, two-thirds of all transports are carried over two hubs in order to benefit from the discounts on the interhub connections. To this end, 14 non-hub nodes use only the geographically closest hub to maximize the length, thus reducing the cost of interhub transportation. In the C-HL-SNDP, on the other hand, the majority of transportation takes place directly or via one hub. Direct shipments are preferred where there is enough demand to ensure high utilization of transportation capacity. Transports via one hub are used to bundle flows and reduce the number of connections. For this purpose, seven of the non-hub nodes use more than one hub. Interviews with the intermodal operator confirm this interpretation. Because the trains he contracts are block trains, he is heavily reliant on utilizing them to the fullest possible capacity. The different assumptions are also reflected in the geographical location of the hubs. In the p-hub-median model, the hubs are evenly distributed across the network since the aim here is to have the longest possible main haulage. In the C-HL-SNDP, the demand in an area is decisive. The higher the demand, the more likely it is that a hub will be placed there. This also explains the leap in savings when the second hub is opened in the C-HL-SNDP. There are two focal points of demand in the network. By opening a hub in each of them, the economies of density can be used most efficiently.

5.5 Conclusion and future research gape

In this paper, we investigated the integrated location placement and network design decision. In doing so, we addressed the research gaps identified in the HLP and SNDP literature. For this purpose, we developed a model combining HLP and SNDP (RQ1). In a case study of a German intermodal operator, we were able to show that very good and realistic solutions can be calculated by the integrated modeling, which generates additional value (RQ2). We compared the combined model with a classical HLP model and performed a structural analysis of the solution properties. We found that the different considerations of economies of scale and economies of density lead to fundamentally different solutions (RQ3).

Based on the results of this paper, several further research opportunities can be derived. The benefits of integrated modeling have been shown so far only for a few use case-specific data sets. In a detailed study, this should be generalized for different data sets. Also, the model could be extended to increase its practical applicability by adding constraints for a limited number of trains per link or limited transshipment capability at hubs. In addition, an efficient heuristic should be developed to handle the high complexity of the combined model. We plan to address these issues in the future.

6 Study 3: The Trans-Caspian Corridor – Bridging Asia and Europe[4]

Recent geopolitical developments like the Russia-Ukraine war, the US-China trade war, and China's Belt and Road initiatives have changed the transportation landscape of Central Asia. Classic transport corridors like the Silk Road through Russia have become unfeasible, and new alternatives are emerging.

This study explores the Trans-Caspian Corridor, connecting Asia and Europe via Kazakhstan and the Caspian Sea. Since this corridor is largely unexplored and research is scarce, we chose an inductive qualitative research design to develop a broad initial understanding and assess the current state of the corridor. We conducted 14 in-depth interviews with political authorities and logistics companies and analyzed them through a meticulous coding process. Based on this analysis, we identified five groups of stakeholders and distilled their ambitions in shaping the corridor in light of current geopolitical tensions. Moreover, we structured and explored five areas of strategic interest that influence the corridor: current and lasting interest, infrastructure and equipment, standardization and digitization, cooperation and coordination, and spillover effect.

The findings contribute to the scarce research on the Trans-Caspian Corridor with real-world insights. They serve as extensive analyses and, on this basis, create opportunities for future theorization about the corridor by suggesting a set of research propositions and associated areas of future research.

6.1 Introduction

Recent geopolitical developments like the Russia-Ukraine war, the US-China trade war, and China's Belt and Road Initiative (BRI) have changed the transportation landscape and threatened global shipping (Khan et al., 2023; Tamilselvan et al., 2024). Schindler et al. (2022) go as far as to declare a "new cold war," voicing the opinion that the unipolar international order led by the USA has given way to a multipolar order with a novel territorial logic. This "new cold war" is fought through the financing and construction of transnational infrastructure and transportation networks. China's BRI deserves special attention in this context, as it is arguably the most important nexus between transport and geopolitics (Lin, 2019; Sheng, 2023). First announced in 2013, the initiative seeks to bridge China with territories across Eurasia through various land-and-sea transport projects (Blanchard and Flint, 2017). One of those

[4] The content of this study is similar with only slight modifications to the paper Rentschler, J., Friedrich, F., Hummel, D., Elbert, R. “The Trans-Caspian Corridor – Geopolitical Implications and Transport Opportunities”. Currently under revision in a journal. Thus, in section the pronoun “we” refers to the authors of the paper.

projects that has come into focus recently is the Trans-Caspian Corridor (TCC), a transit pathway connecting Europe and Asia through Kazakhstan, the Caspian Sea, and the South Caucasus(see Figure 27). The Russia-Ukraine war has significantly heightened demand for the TCC, as geopolitical tensions make Northern Corridors (e.g., the Trans-Siberian Corridor) less viable (Blackwood et al., 2023). Furthermore, volatile sea freight rates rising from $2,000 per container in June 2020 to $15,000 a year later have driven logistics service providers (LSPs) to seek alternatives to the dominating traditional sea route (Almendral, 2021). Research on supply chain risks, such as conducted by Kwak et al. (2018), underscores the growing need for resilient logistics solutions to mitigate the disruptions caused by such geopolitical conflicts and economic uncertainties.

Figure 27: Main transport corridors from China to Europe | based on data from the Statistic Agency of the Republic of Kazakhstan (2022)

Recognizing this promising prospect and the present heightened level of attention in light of the Russia-Ukraine war, there exists a notable scarcity of research that systematically categorizes and scrutinizes the TCC.

A clear understanding of the ambitions of the stakeholders (China, Kazakhstan, European Union, Turkey, and diverse others) interested in the corridor is missing. Such an understanding is needed to assess the state of the corridor and establish areas of strategic interest. These areas can provide a framework for outlining measures for the corridor's development from its nascent stage. Moreover, they can serve as a foundation for developing fields for future research. This study aims to contribute to closing this gap guided by the following exploratory research questions:

- **RQ1:** What are the ambitions and motives of the different transport stakeholders involved in the TCC?
- **RQ2:** What are the areas of strategic interest fostering the development of the TCC into a mature transport corridor?

Given the limited knowledge of the TCC and the scarce research, we selected an inductive qualitative research approach and conducted 14 in-depth interviews to answer the research questions from collected rich, real-world data. We analyzed the data by means of open, axial, and selective coding, according to Corbin and Strauss (2015).
Our findings include the analysis of the ambitions and motives of the stakeholders and the development of five areas of strategic interest for freight transport along the TCC. Our study contributes to the theorization of the TCC by presenting a comprehensive overview of the TCC and its future development, summarized in five research propositions, and it suggests associated fields for future research.

The remainder of this paper is structured as follows: Section 6.2 provides the theoretical background. Next, we introduce our methodological approach in Section 6.3. In Section 6.4, our findings are presented along RQ1 and RQ2. In Section 6.5, we present our theoretical contribution and propose fields for future research. Finally, we conclude in Section 6.6.

6.2 Theoretical background

6.2.1 Theoretical perspectives of transport corridors

Rodrigue (2024a) defines transport corridors as an accumulation of flows and infrastructures of various modes, with their development linked with economic, infrastructural, and technological processes. Gálvez-Nogales (2014) outlines a corridor development model featuring five phases, each representing a progression towards more comprehensive and integrated development (see Figure 28). These phases evolve from basic transportation infrastructure to encompass logistical coordination, trade facilitation, economic diversification, and, ultimately, holistic growth corridors incorporating social, economic, and environmental dimensions.

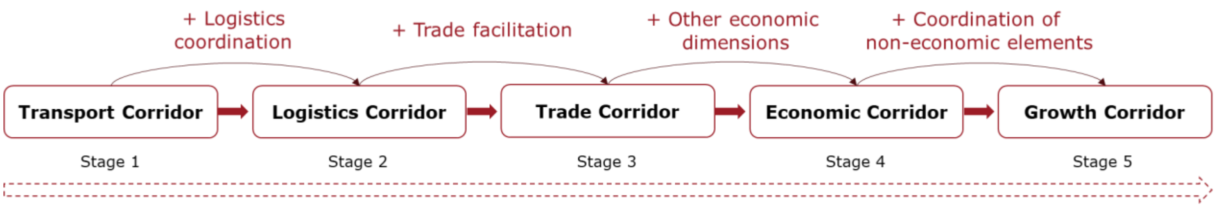


Figure 28: Corridor Development Path | own representation based on Gálvez-Nogales (2014)

Wilmsmeier et al. (2011) investigate the development of transport corridors of seaports in relation to inland terminals. In the Outside-In concept, inland nodes are used by the seaport to expand their hinterland. On the other hand, in the Inside-Out concept, corridor development and greater integration with the seaport are actively driven by inland intermodal terminals. Witte et al. (2014) suggest that paying more attention to inland ports as standalone entities in the context of the Inside-Out concept is essential. They highlight the significance of the spatial, economic, and institutional aspects of inland ports.

The relationship between port (or alternatively demand center) activity and local development is further investigated by Hidalgo-Gallego and Núñez-Sánchez (2023). In a case study on the impact of port activity on local employment in Spain, they find a strong positive correlation. Lastly, Qi et al. (2020) examine the spatial spillover effects of logistics infrastructure in China. They find that investments in logistical infrastructure can promote regional economic development, especially in developing countries along the BRI.
Beyond the basic need for functional infrastructure, Lin (2019) proposes a framework to jointly analyze transport geography and geopolitics. He emphasizes the necessity for more sustained research on three broad geopolitical strands: transport visions and imaginations, rule-making in transport, and militarism in transport. Using the example of the BRI, he argues that geopolitics is not merely a background fact "out there" affecting transport but rather an integral part of the asymmetrical production, organization, and impedance of transport. He underscores that these geopolitical frameworks and strategic actions not only influence transport decisions among states on a normative level but also impact the spatial possibilities and configurations of transport.

6.2.2 Research on the Trans-Caspian Corridor

Since the TCC is in a nascent stage, related research has been limited so far and conducted mostly in the context of the BRI. Sárvári and Szeidovitz (2016) broadly investigate the modern Silk Road, encompassing all possible transport corridors from China to Europe. They disregard the TCC as being too slow and impractical. Sternberg et al. (2017) analyze the impact of the BRI on Kazakhstan and Kyrgyzstan. They focus on geographical factors constraining infrastructure and recognize geopolitical contestation between Russia and China. More focused on the evolution of the TCC into a mature corridor is the research by Taisarinova et al. (2020), who attempt to assess how the China-Europe transportation demand affects the economic potential along the corridor. In an anthology, the Asian Development Bank collected studies that shed light on the TCC from different perspectives (Asian Development Bank Institute, 2021).

With the Russian invasion of Ukraine and the resulting decline in demand for the Northern Corridors, interest in alternative corridors increased, as did research on the TCC. Shortly after the start of the war, the USAID organization published a report in which they analyzed the changing landscape of Trans-Caspian trade in light of the unfolding conflict (USAID). The EU investigated sustainable transport connections between the Central Asian countries and the EU's extended Trans-European Transport Network and proposed actions for development (EBRD, 2023). Political organizations and think tanks likewise conducted an assessment of the TCC (Chang, 2023; Eldem, 2022). In a first scientific study since the outbreak of the war, Palu and Hilmola (2023) give an overview of the potential of the TCC.

6.2.3 Derived research gap

Given the scarcity of research dedicated to the increasingly relevant TCC in light of current geopolitical turbulences, there is a need to provide real-world insights into the ambitions and motives of the various stakeholders involved in the TCC and emerging areas of strategic interest for its future development. The transport corridor theory presented in Section 6.2.1 provides general models (e.g., the corridor development path by Gálvez-Nogales (2014) as well as the Outside-In and Inside-Out concepts by Wilmsmeier et al. (2011), but it is not suitable to distill the specifics of the TCC. The theoretical strands from Section 6.2.1 raise awareness for the understanding of geopolitics as an integral part of transport and for the relevance of spillover effects (Lin, 2019; Qi et al., 2020). These high-level insights from existing transport corridor theory can support us in discussing and embedding our findings (see Section 6.5.1), but are not the driver for our developing these findings by applying our methodological approach, as presented next.

6.3 Methodology

6.3.1 Research design and sample selection

We selected an exploratory qualitative research design due to the nascent stage of the TCC and the scarcity of existing research. For this purpose, we opted to apply the methodological practices of *grounded theory*, as advocated by Corbin and Strauss (2015). Grounded theory is appropriate for exploring new phenomena, such as the increasingly relevant TCC, from different angles to build theory by following a purely inductive logic. We embedded our study directly in the context of the TCC and collected data from a sample of 14 actors in in-depth interviews supplemented with public information.

We selected our sample aiming to cover a variety of perspectives on the TCC. Therefore, we considered different actors (logistics companies and political stakeholders) as well as different geographical perspectives (Central Asian and Western European). Note that the Kazakh perspective in its role as a connective link between Asia, in particular China, and Europe enabled us to understand the Central Asian situation. For the Western European perspective as the predestined sink of the corridor, we focused on Germany, based on its strong transport industry (The World Bank, 2023) and the authors' geographical affiliation.

We carefully selected actors for our sample in an overlapping and iterative process of collecting and analyzing data by applying a *theoretical sampling* approach (Mello et al., 2021). We used four approaches to identify suitable companies and authorities in this process: First, we partnered with the German-Kazakh University to benefit from their experience and local connections. Second, we gave a presentation at the conference "Logistics Forum," held at the German-Kazakh University, to promote our study among the participants from industry and academia. Third, we reviewed online recordings and lists of participants of the event "New Silk Road" dedicated to the TCC and hosted by the Ministry of Industry and Infrastructural Development of Kazakhstan. Fourth, we carefully followed up on the recommendations of companies/authorities in our sample. When establishing these contacts, we prioritized political authorities due to their influence on the strategic development of the TCC (e.g., by initiating funding and political measures) and logistics companies that can contribute to the growing relevance of the TCC by using this corridor for their global transportation flows. When analyzing the TCC from these perspectives, the port of Aktau emerged as a crucial inland terminal and bottleneck. Therefore, we opted to develop a deeper understanding of the port by enriching our sample with additional actors directly involved with the port.

Finding and contacting actors for our sample ceased when we had gained a broad and reflective understanding of the ambitions and motives of the stakeholders, emerging areas of strategic interest surrounding the TCC, and the specific role of the port of Aktau. We arrived at this point of *theoretical saturation* (as described in Manuj and Pohlen (2012)) when our sample counted 13 actors, the last actor contributing no significant new insights to the category systems that emerged from our data analysis. In sum, our final sample counts eight companies for assessing the overall TCC and five for in-depth insights into the port of Aktau. Nine actors are based in Central Asia, with a focus on Kazakhstan and three in Germany and Austria, guaranteeing, in sum, a balanced view. Moreover, the sample contains nine big and four small and medium-sized enterprises. The supplementary material provides additional details about the sample.

6.3.2 Data collection and analysis

We conducted 14 semi-structured interviews in the sample of 13 companies/authorities between September 2022 and November 2023.[5] We identified interviewees in management positions, our aim being to target strategic views on the TCC and its future development.

We developed a semi-structured interview protocol focused on gaining a holistic overview of the TCC and specific insights into the port of Aktau from the interviewees' perspective and structured it along four fields: political framework, infrastructure, integration and cooperation, and technology and market. The work of Cavallaro et al. (2020) and Lordieck and Corman (2021) assisted us in developing this structure, but neither guided us in our interviews nor influenced our open mind for exploring the TCC (see Mello et al., 2021). We piloted the interview protocol in a workshop with the German-Kazakh University in Almaty. However, based on Gioia et al. (2013) and in an effort to accommodate the different perspectives of the interviewees and our growing understanding, we kept the concrete questions flexible (see supplementary material for the final version of the interview protocol).

Seven interviews took place in person in Almaty, and seven were online video meetings. One of the authors conducted all the interviews. The interviews lasted, on average, 42 minutes. We triangulated the interviews with internal data and publicly available information about the companies collected via web searches.

We transcribed the interviews (585 minutes), resulting in 139 single-spaced pages of data. We used MAXQDA to analyze this data and apply open, axial, and selective coding, according to Corbin and Strauss (2015). The full coding process was conducted by one of the authors and intensively discussed among the team of authors to establish a consistent and mutual understanding of the corridor and its future potential. We developed two data structures, one for the stakeholders of the TCC and one for the areas of strategic interest and relied on the scheme of Gioia et al. (2013) for the visualization (see Figure 29 in Section 6.4.1 and Figure 30 in Section 6.4.2). Throughout our grounded theory approach, we adhered to a rigorous research design, as detailed in the supplementary material.

[5] We conducted two interviews with a representative from one authority, the first interview concerned the TCC and the second one focused on the port of Aktau.

6.4 Findings

6.4.1 TCC stakeholders and their motives

The distinct groups of stakeholders identified comprise China, Kazakhstan, the EU, Turkey, and several minor Other Stakeholders. These nations have a vested interest in the successful establishment of the TCC, aligning with their respective geopolitical ambitions. This section explores their specific motives justifying their ambitions, addressing RQ1. The results of the coding process can be seen in Figure 29 and selected codes are indicated by underlining.

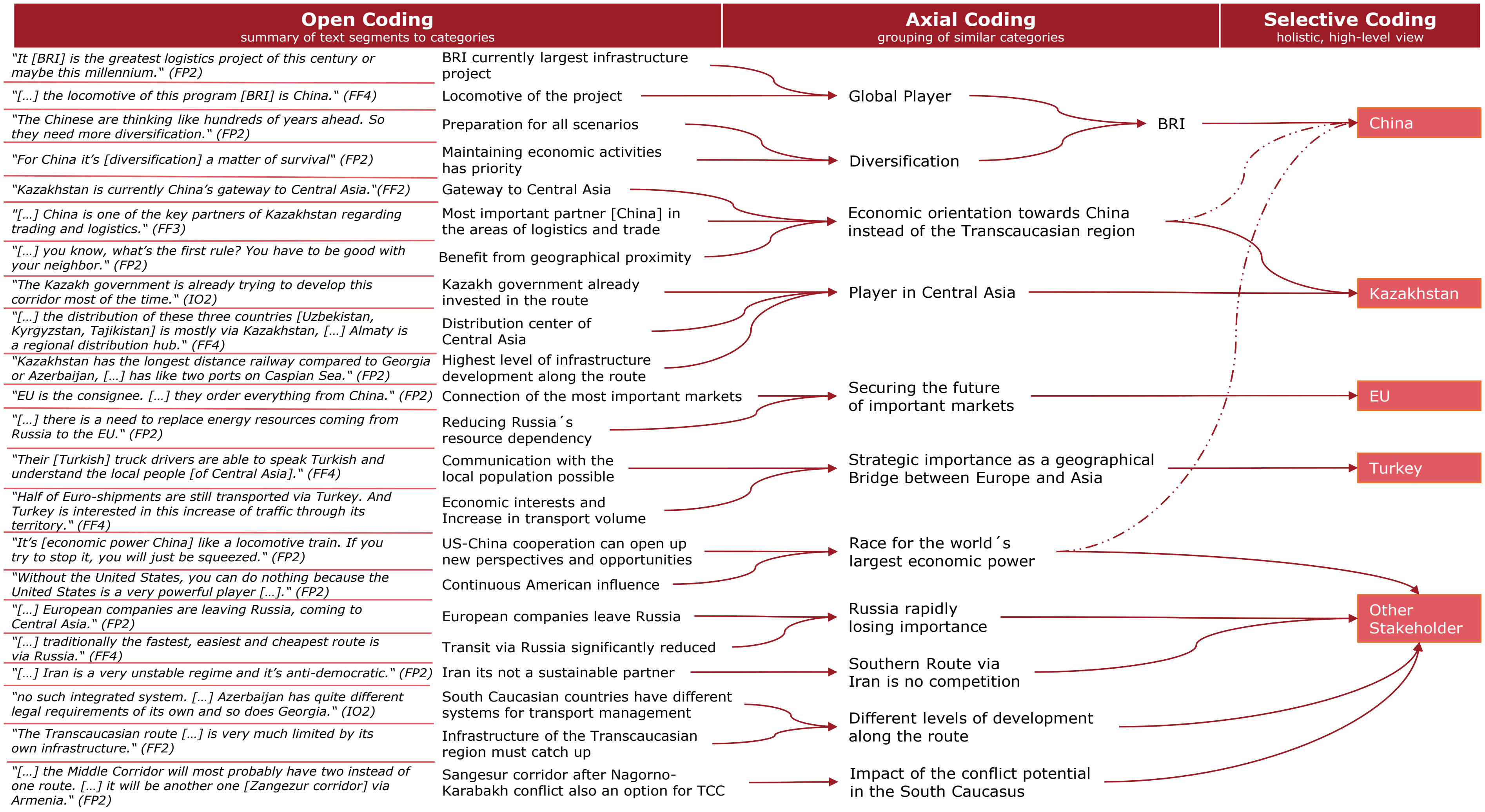


Figure 29: Coding results for stakeholders

6.4.1.1 China

China's active involvement in the TCC is conducted through the BRI. In this sense, interviewee FP2 vividly labeled the BRI as the "*greatest logistics project of this century or maybe this millennium,*" attributing China as a global player and the driving force behind the TCC. Nevertheless, diverse perspectives emerged in our interviews. Interviewee freight forwarder FF3, while acknowledging the strategic importance of the BRI, criticized its focus on the European-bound transit of goods, neglecting local Kazakh transport ("*China has decided that we need to increase the number of trains to Europe and decrease the number of trains to Kazakhstan.*" FF3).

Another reason for promoting the BRI is China's diversification strategy. Interviewees FP2 aptly described China as the world factory necessitating diversified sales channels and transport corridors to be prepared for all scenarios: "*For China, it [diversification in terms of trade corridors] is a matter of survival.*" Similarly, FP1 highlighted the need for varied corridors and China's long-term perspective: "*The Chinese are thinking hundreds of years ahead. They need more diversification.*"

In summary, China and its BRI project drive TCC growth through investments, transit, and ongoing interest. This is taken up by Kenderdine and Bucsky (2021), by suggesting policy measures for China, including transparent communication, local engagement, and cooperation with the EU.

6.4.1.2 Kazakhstan

Kazakhstan is central to the dynamics of the TCC, particularly in its economic orientation towards China. This mutually beneficial relationship is underlined by FF2's perspective of Kazakhstan as "*China's Gateway to Central Asia*." This view aligns with the overarching sentiment that trade with China is paramount for Kazakhstan ("*China is one of Kazakhstan's most important partners in trade and logistics.*" FF3).

Kazakhstan boasts the largest share of TCC infrastructure *("Kazakhstan has the longest distance railway compared to Georgia or Azerbaijan, […] has two ports on the Caspian Sea*." FP2), and the investments in infrastructure, such as the Horgos gateway, Aktau port, and central Kazakhstan's rail line, underscore its dedication to the corridor. In this sense, the corridor's transformative impact on Kazakhstan is further emphasized by Sattarov (2022).

6.4.1.3 European Union

The TCC holds profound implications for the EU's future strategies, particularly in securing important markets and strategic resources. Insights from FP2 highlighted the symbiotic interests of the EU in establishing the TCC: "*The EU is the recipient [profiteer] because it orders everything from China.*" The strong interest of the EU is driven by its role as the primary recipient of China's goods, with the TCC serving as a critical link to major markets. According to our interviewees, the EU recognizes the potential to reduce its dependence on Russian resources based on the TCC, as articulated by FP2: "*[…] there is a need to replace energy resources coming from Russia to the EU.*"

The Russia-Ukraine war has shifted EU interests, prompting the EU to explore Central Asia. Amidst this geopolitical shift, the EU acknowledges the strategic significance of connectivity and alternative corridors (European Bank for Reconstruction and Development, 2023).

6.4.1.4 Turkey

Turkey's strategic importance as a geographical bridge between Europe and Asia stems from its central position on the TCC. Presently, a substantial share of transported goods passes through its territory ("*Half of the Europe bound shipments are transported through Turkey. And Turkey is interested in this increase in traffic.*" FF4). Presenting an alternate perspective, interviewee FF4 suggested the feasibility of bypassing Turkey in favor of an alternative Black Sea ferry route between Georgia and Bulgaria ("*This route can be used without crossing Turkey right from Bulgaria to Poti, but it also has to use a ferry.*" FF4). Although an alternative perspective on bypassing Turkey is intriguing, the prevailing economic and operational realities firmly position Turkey as a key transport hub.

6.4.1.5 Other stakeholders

The US perceives the TCC project as an intricate facet of its overarching competition with China in its race to be the world's largest economic power ("*I think their [US] focus, number one – not enemy but competitor – is China.*" FP2). In light of China's ascendancy to an economic powerhouse, the prospects of the US outperforming China in the economic realm have significantly dwindled ("*It [China's economic power] is like a locomotive. If you try to stop it, you just get crushed.*" FP2). This reasoning advocates a pragmatic approach rather than a futile battle for supremacy – harboring potential for cooperative endeavors, as U.S.-China cooperation can open up new perspectives and opportunities.

Turning to Russia, the established benefactor of the historical efficiency of the Northern Corridor *("[…] traditionally the fastest, easiest and cheapest corridor is via Russia[…].*" FF4). However, Russia's conflict-induced disruptions of the Northern Corridor catalyzed the advent of the TCC. In this sense, the shift of European companies from Russia to the TCC, as expressed by FP2: "*[…] European companies are leaving Russia, coming to Central Asia.*" reinforces the importance of the TCC and the <u>diminishing importance of Russia</u>.

The South Caucasian nations face <u>infrastructure disparities</u> and diverse transport systems ("*The Trans-Caucasian corridor […] is very much limited by its own infrastructure.*" FF2). The <u>conflict between Azerbaijan and Armenia</u> holds implications for the corridor's future. The EU aims to prevent conflict escalation in collaboration with Turkey, promoting regional stability. However, ongoing tensions in the South Caucasus cast doubt on the TCC's potential as a robust conduit for cross-border trade (Mpoke and Nechepurenko, 2023).

An <u>alternative land transport route via Iran</u>, contingent upon Turkmenistan, faces challenges due to Iran's political instability and economic constraints ("*[…] Iran is a very unstable regime and it is anti-democratic.", FP2)*.

6.4.2 Areas of strategic interest

In the following subsections, we explore the areas of strategic interest shaping the development of the TCC into a mature corridor (RQ2). The following areas of strategic interest have emerged from the selective coding process: current and lasting interest, infrastructure and equipment, standardization and digitization, cooperation and coordination, and spillover effect. On this basis, we suggest a set of research propositions to reason for the necessary steps for further developing the TCC. The overview of the coding process can be seen in Figure 30. In this figure, the open codes are marked with a plus or minus sign to indicate their supporting or constraining impact on the development of the TCC.

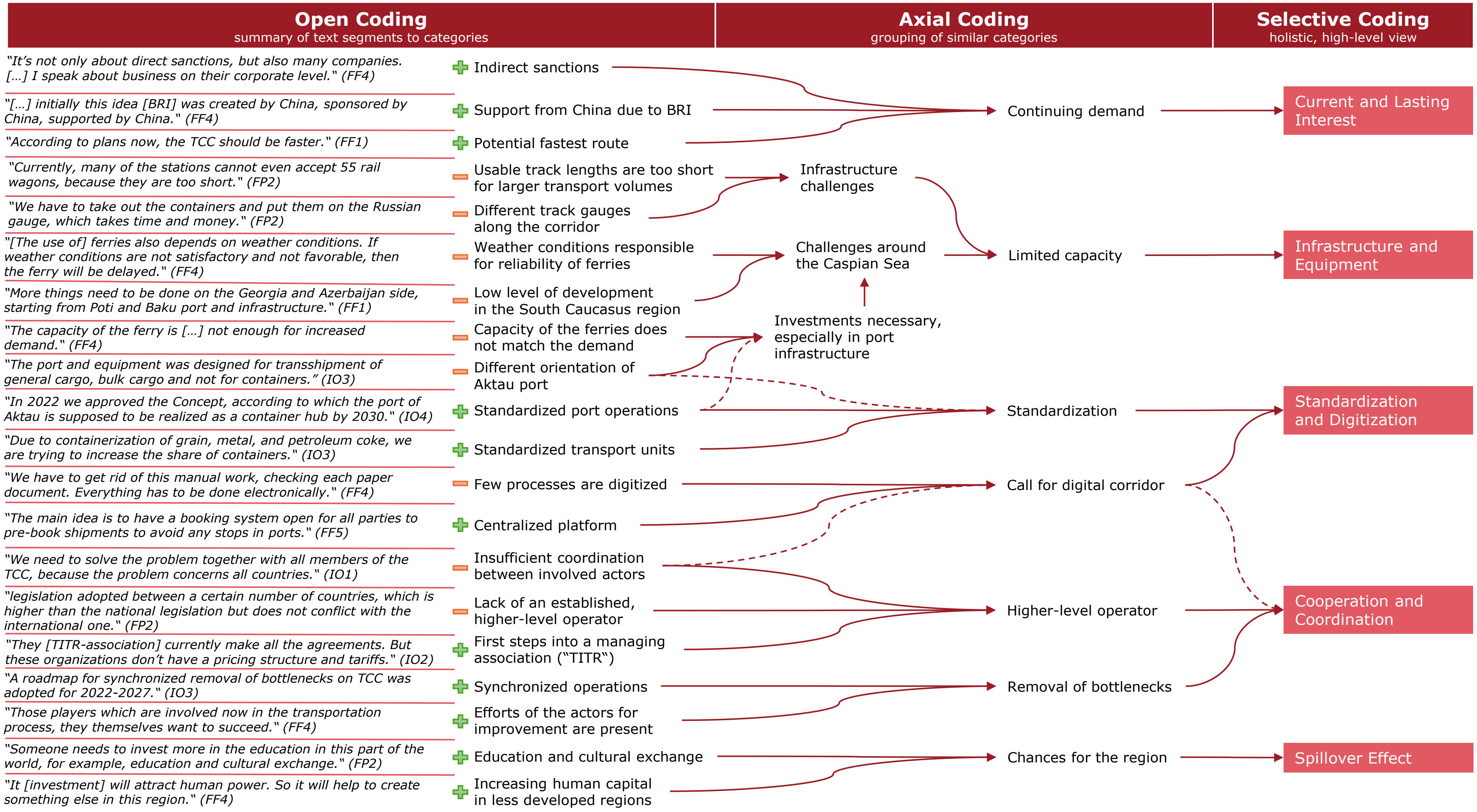


Figure 30: Classification of the areas of strategic interest

6.4.2.1 Current and lasting interest

The current and lasting interest in the TCC hinges on the continuing demand of its user base. Three key themes emerged:

First, interest in the TCC does not solely emanate from direct sanctions against Russia and Belarus but stems from their ripple effects as companies seek to mitigate the risks associated with geopolitical uncertainties ("*It is not just about direct sanctions. Many companies decide not to transport their goods through Russian, Belarusian, and definitely Ukrainian territory because they see a risk of war.*" FF4).

Second, the support from China due to BRI is a keystone in the progression and long-term relevance of the TCC. The BRI is identified as an initiative "*originated, funded, and endorsed by China*" (FF4), with a consistent commitment. China's substantial investment in infrastructure bolsters the viability of the corridor.

Thirdly, the TCC has the potential to become the fastest corridor, becoming more attractive for shippers. However, our interviewees emphasized the pragmatic view that it is more about potential than solidified outcomes *("According to plans now, this Trans-Caspian line should be faster.*" FF1). Hence, we propose:

> **Prop. P1:** To sustain the growth of the TCC, long-term demand beyond the current peak, support from the BRI, and the potential speed advantage have to be leveraged.

6.4.2.2 Infrastructure and equipment

FP2 highlighted the challenging conditions of infrastructure and equipment, especially around the Caspian Sea: "*[…] the cranes at the port of Aktau are old, they are weak. They have to be upgraded.*" Limited ferry capacity, coupled with weather-related delays, exacerbates tensions *("If weather conditions are not satisfactory and not favorable, then the ferry will be delayed.*" FF4) Kenderdine and Bucsky (2021) underscore the Caspian Sea as a connectivity bottleneck, while a generally low level of development in the South Caucasian region reveals infrastructure insufficiencies ("*More things need to be done on the Georgia and Azerbaijan side, starting from Poti and Baku port*." FF1).

Rail poses further infrastructure challenges due to differing track gauges, requiring transshipment of goods at the border ("*We have to take out the containers and put them on the Russian gauge, which takes time and money*." FP2). Furthermore, the usable track length of the outdated Soviet-era rail stations is too short for larger freight trains *("Currently, many of the stations cannot even accept 55 rail wagons, because they are too short.*" FP2).

The combined challenges lead to limited capacities along the corridor, aligning with the observations of Chang (2023). We therefore derive the following proposition:

> **Prop. P2:** To overcome the significant logistical challenges, investments in port and railway infrastructure and technological harmonization are necessary.

6.4.2.3 Standardization and digitization

Several challenges exist regarding standardized operations and equipment ("*The port and equipment was designed for transshipment of general cargo, bulk cargo and not for containers.*" *IO3)*. However, the actors involved are working to address these challenges ("*In 2022, we approved the Concept, according to which the port of Aktau is supposed to be realized as a container hub by 2030.*" *IO4)*.
Several interviewees called for more efforts to create a digital corridor and mitigate bureaucratic impediments. Manual processes, including paper-based documentation, persist ("*We have to get rid of this manual work, checking each paper document. Everything has to be done electronically.*" *FF4)*. Interviewees uniformly stressed the need for continuous digital infrastructure transcending individual border points ("*The main idea is to have a booking system open for all parties to pre-book shipments to avoid any stops in ports.*" FF5).
In the broader context, Eldem (2022) emphasizes positive strides in soft infrastructure development, and Chang (2023) underscores bureaucratic challenges, particularly customs and toll delays at borders due to multiple countries. Therefore, we propose:

> **Prop. P3:** To achieve seamless synchronization along the TCC, digitization must be strengthened, bureaucratic hurdles removed, and standardized operations must be implemented.

6.4.2.4 Coordination and cooperation

Addressing the lack of an established, higher-level operator, FP2 proposed the need for multiparty legislation to form a united regulatory framework transcending national boundaries *("legislation adopted between a certain number of countries, which is higher than the national legislation but does not conflict with the international one.*" FP2). To address this need, the local Kazakh "TITR" association has emerged as an entity in the last four years, aspiring to function as a central operator. However, its current maturation phase precludes the provision of specific pricing structures and tariffs, necessitating independent planning by companies *("They ["TITR"-associations] currently make all the agreements. But these organizations do not have a pricing structure and tariffs.*" IO2). Other interviewees would rather see the EU or China taking a leading role in the further development of the TCC.

Besides a central guiding entity, synchronized operations are necessary to remove bottlenecks and enable a seamless flow of goods *("A roadmap for synchronized removal of bottlenecks on TCC was adopted for 2022-2027."* IO3). IO1 and FP1 emphasized the need for cooperation and coordination along the TCC ("*We need to solve the problem together with all members of the TCC.*" *IO1;* "*Regional cooperation is essential for such a project.*" FP1). This view is shared by Palu and Hilmola (2023), and our insights coalesce into the proposition:

> **Prop. P4**: To foster the future development of the TCC, a guiding higher-level operator must be established, and joint efforts must be undertaken to remove the existing bottlenecks.

6.4.2.5 Spillover effect

Kenderdine and Bucsky (2021) highlight the prospects of the corridor for economic development and trade facilitation. However, the TCC extends its impacts beyond economics, offering regional growth opportunities and fostering a spillover effect. It can potentially advance education, cultural understanding, and cooperation ("*Someone needs to invest more in education in this part of the world.*" FP2). This presents a chance to uplift disadvantaged regions, focusing on holistic development beyond infrastructure.
In particular, inland terminals should be considered as they are seen as crucial linkages for efficient freight transport and corridor development (Witte et al., 2014). In this vein, we learned from our interviewees that investments in ports, such as those in Aqtau and Kuryk, can trigger a spillover effect ("*It [investment] will attract human power. So it will help to create something else in this region.", FF4)*. This notion is supported by Hidalgo-Gallego and Núñez-Sánchez (2023) and Bedoya-Maya et al. (2023). We thus propose:

> **Prop. P5:** Beyond merely economic aspects, the TCC can create opportunities for multifaceted, socio-economic growth. The port of Aktau can be a catalyst for this spillover effect and drive the Inside-Out development of the corridor.

6.5 Discussion

6.5.1 Theoretical contribution

The recent geopolitical developments underscore a critical juncture for the TCC. Consequently, this study aimed to provide a detailed examination of the implications of the TCC for international transport in the context of geopolitics. Our exploration delved into the motivations and ambitions of the stakeholders involved, and we systematically categorized areas of strategic interest.

These stakeholders and categories have been juxtaposed in Table 13 to illustrate their interrelationships and potential impact.

Table 13: Relationship between the stakeholders and the areas of strategic interest

	China	Kazakhstan	EU	Turkey	South Caucasus
Current and lasting interest					
Continuing demand	X	X	X	X	
Direct and indirect sanctions		X	X		
Support from BRI	X	X			
Infrastructure and equipment					
Challenges around the Caspian Sea		X			X
Low level of development in Central Asia		X			X
Standardization and digitization					
Continuous digital infrastructure	X	X	X	X	X
Standardization	X	X	X	X	X
Cooperation and Coordination					
High-level operator	X		X		
Synchronized processes and removal of bottlenecks	X	X	X	X	X
Spillover effect					
Opportunities for multifaceted, socio-economic growth		X			X

The varied perspectives presented herein form a comprehensive picture enabling the discussion of the TCC in light of the existing transport corridor theory, as established in Section 6.2.2:

The development of the TCC aligns closely with the stages outlined in the corridor development model by Gálvez-Nogales (2014). Initially, the TCC serves primarily as a transport corridor, linking major economic hubs like the EU and China. It also embodies elements of a logistics corridor, with ongoing efforts to enhance transport and storage efficiency, and exhibits characteristics of a trade corridor, connecting countries to significant markets despite facing major challenges categorized under the areas of strategic interest "infrastructure and equipment" (e.g., low levels of development in Central Asia) and "standardization and digitalization" (e.g., standardized processes and equipment).

Focusing on the geopolitical discourse, the TCC aligns with the geopolitical visions and strategic statecraft, according to Lin (2019). It is a pertinent example of how modern geopolitics play a crucial role in shaping transport corridors. Hence, the TCC is not merely a corridor for facilitating trade but a geopolitical strategy that enhances the connectivity of nations involved, particularly aligning with the interests of countries looking to diversify away from Russian influence in Eurasian trade. This reflects Lin's focus on the visions and imaginations that drive the establishment of such corridors and is essential for the continuing relevance of the corridor, as characterized in the identified area of strategic interest, "current and lasting interest" (e.g., the TRR as part of the BRI). Furthermore, Lin's point on rule-making resonates with the TCC through the establishment of treaties and agreements between participating states, such as China, the EU, and Kazakhstan, as demonstrated in the area of "cooperation and coordination." This is reflected in the need for a centralized authority with enhanced competencies in terms of pricing structures and overarching organization, as extracted from our interviews. Militarism, while not overtly pronounced in the context of the TCC, indirectly influences the strategic importance of the corridor. The TCC's significance in reducing dependency on the Northern Corridor, controlled by potentially adversarial states like Russia, underscores the militaristic underpinnings of such infrastructure projects as part of broader geopolitical strategies and ambitions, as demonstrated for the various stakeholders in Section 6.4.1.

Lastly, in the framework of Wilmsmeier et al. (2011), the TCC's development predominantly reflects an Outside-In approach, with major economic powers like China and Europe driving the strategic expansion (see Section 6.4.1.1. and 6.4.1.3). This macroscopic influence mirrors the role traditionally played by seaports. Conversely, Kazakhstan's proactive development around the port of Aktau exemplifies the "Inside-Out" model, with local initiatives aiming to enhance the corridor's efficiency and regional integration, as demonstrated in the area of “infrastructure and equipment.” The significance of inland ports, as highlighted by Witte et al. (2014) and Hidalgo-Gallego and Núñez-Sánchez (2023), underscores the role of the port of Aktau as a potential catalyst for economic and social development. We found evidence that improvements in this inland port can lead to "spillover effects" (see Section 6.4.2.5) that benefit the broader regional economy.

6.5.2 Further research fields

The strategic initiatives and developments along the TCC, underpinned by the theoretical frameworks, emphasize the transformative potential of the corridor for Eurasian trade. Nonetheless, these achievements prompt the need for further research to address the identified challenges. Per our propositions, we can delineate potential fields for future research, outlined in Table 14.

Table 14: Further research fields based on our propositions

Proposition	Further research fields
P1: Sustained interest and growth of the TCC	▪ How can the TCC maintain sustained demand and growth? ▪ What strategies can be implemented to maximize the long-term benefits of the BRI? ▪ How can the TCC effectively harness its potential speed advantage?
P2: Overcome logistical challenges	▪ What are the most effective strategies for infrastructure investments? How do they enhance efficiency and capacity? ▪ What are the economic and trade implications of addressing the lack of capacity and low efficiency of the TCC, and how do these improvements impact regional and global trade flows? ▪ How can public-private partnerships be leveraged?
P3: Seamless synchronization, standardization, and digitization	▪ How can technological harmonization across multiple countries and regions along the TCC be achieved? ▪ What specific bureaucratic hurdles and bottlenecks exist currently, and how can these obstacles be effectively addressed? ▪ How can digitization initiatives be further strengthened to streamline trade processes and reduce manual processes?
P4: Cooperation and coordination along the corridor	▪ How can stakeholder collaboration and communication be improved, and what role should international organizations and governments play? ▪ In what ways can the competencies of existing associations be expanded to establish a central, overarching entity that effectively drives regulation, standardization, and cooperation? ▪ What lessons can be learned from other international transport corridors or organizations that have successfully established organizational structures?
P5: Spillover effect and Inside-Out growth	▪ How can the TCC be strategically designed and managed to maximize its role as a conduit for economic and social change? ▪ What specific indicators and metrics can be used, measured, and monitored to assess the impact on cultural exchange, human development, and social progress?

6.6 Conclusion

The TCC links China and Europe through an integrated network of railway, road, and maritime components. Still in its developmental phase, the TCC faces intricate challenges.

Our methodology involved a qualitative analysis based on grounded theory through 14 interviews with key logistics companies and political authorities, primarily from Central Asia and Europe. Based on this analysis, we identified five groups of stakeholders and distilled their ambitions and motivations for shaping the TCC . Moreover, we structured and explored five areas of strategic interest that influence the TCC: current and lasting interest, infrastructure and equipment, standardization and digitization, cooperation and coordination, and spillover effect.

Our study has drawn extensively on the theoretical frameworks of Gálvez-Nogales (2014), Lin (2019), and Wilmsmeier et al. (2011) to analyze the development and strategic importance of the TCC within a broader geopolitical and transportation context. The model of Gálvez-Nogales (2014) allowed us to trace the corridor's evolution from basic transport infrastructure towards a holistic growth corridor. The insights of Wilmsmeier et al. (2011) into the "Inside-Out and Outside-In" development models helped us understand the dynamic interplay between large economic centers and local transport activities. The theoretical contribution of Lin (2019) further enriched our analysis by placing the TCC within the discourse of modern geopolitics and its impact on transport geography.

The contributions of this study offer a refined understanding of the corridor's transportation and geopolitical complexities and lay a foundation upon which future research can be built. The classification of areas of strategic interest, the development of research propositions, and the delineation of further research fields provide a structured framework for future investigations. As is natural for qualitative research approaches, the comprehensive analysis presented in our study is derived from the viewpoints of individuals. Although our focus centered on the viewpoints of Central Asia and Europe, a valuable next step entails delving into the Chinese and South Caucasian outlooks to enrich our comprehension. Furthermore, while we acknowledge the dominance of small and medium-sized freight forwards in the transportation industry, their unique concerns remain partially unexplored in our sample.

6.7 Appendix

Supplementary material A: Information about the companies and conducted interviews

Table 15: Information about the companies and conducted interviews.

Actor	No.	Company description	2022 annual revenue (in millions)	Number of employees (in 2022)	Headquarters	Interview type	Duration	Position of interviewee
Freight forwarder	FF1	Logistics and transport services (global and local)	10,000–25,000 €	50,001–100,000	Germany, branch in Kazakhstan	On-site at the company	00:24:15	Executive director
	FF2	Logistics and transport services (global and local)	1,000–10,000 €	5,001–10,000	Austria, branch in Kazakhstan	On-site at the company	00:31:40	Executive director
	FF3	Logistics and transport services (local)	n/a	51–500 [a]	Kazakhstan	Conference	00:35:19	Executive director
	FF4	Logistics and transport services (global and local)	50–100 €	1,001-5,000	Kazakhstan	On-site at the firm	00:57:00	Executive director
	FF5	Logistics and transport services (local)	n/a	51–500 [a]	Kazakhstan	Online Port focus	00:20:37	Executive director
	FF6	Logistics and transport services (local)	n/a	51–500 [a]	Kazakhstan	Online Port focus	00:35:32	Executive director
Infrastructure Operators	IO1	Railway company	1,000–10,000 €	>100,000	Kazakhstan	Online	00:27:00	Politician
	IO2	Support of infrastructure projects; technical and strategic consulting services	500–1,000 €	5,001–10,000	Germany, branch in Kazakhstan	Conference	00:44:21	Executive director
	IO3	Railway company	1,000–10,000 €	>100,000	Kazakhstan	Online Port focus	01:08:11	Executive director

	IO4	Port	10-50	51–500 [a]	Kazakhstan	Online Port focus	00:48:57	Executive director
	IO5	Infrastructure Company	n/a	1,001-5,000	Kazakhstan	Online Port focus		Executive director
Fnancial and Political Authorities	FP1	Financing of development projects in the Asia-Pacific region	10,000–25,000 €	1,001–5,000	Philippines	Conference	00:33:42	Researcher
	FP2	Investment fund	10,000–25,000 €	>100,000	Kazakhstan	Conference	01:02:36	Technical Consultant [b]
						Online Port focus	00:32:48	

[a]: SME according to EU recommendation 2003/361 (European Commission, 2003).

[b]: Internal data provided

Supplementary material B: Semi-structured interview protocol

General questions and background information about the company

1a) In which field / which company do you work?

1b) What position do you hold there?

1b) What do you mainly deal with in your daily work?

1c) How many years of experience do you have in logistics?

1d) How many years of experience do you have in the field of combined transport and use of the Trans-Caspian railroad corridor? What other corridors are used by your company?

1e) What points of contact did you have with combined transport/ Trans-Caspian rail corridor in this regard?

1f) What is the share of your company's business activity with combined transport & Trans-Caspian railroad corridor?

Political framework

2a) In your opinion, how does the current (world) political situation affect transportation on the China-Europe-China corridor?

2b) In your view, which global policies have the greatest effect (both positive and negative) on the China-Europe-China corridor and the Trans-Caspian rail corridor?

2c) What would you personally like to see in local (Kazakh) policy measures to promote the Trans-Caspian rail corridor?

Do you see any measures that go in a wrong direction? In your opinion, are there any limitations to the government's scope of action?

Infrastructure

3a) Which infrastructural conditions have the greatest effect (positive and negative) on the Trans-Caspian Railway Corridor?

3b) What would you like to see infrastructure providers do to promote the Trans-Caspian rail corridor in the future?

3c) How do you think infrastructure could realistically and quickly be improved? Do you think that the government has the sole responsibility here, or should private actors play a greater role?

Integration and cooperation

4a) What factors (both positive and negative) currently have the greatest effect on cooperation and communication between companies along the Trans-Caspian Railway Corridor?

4b) What would you like to see in terms of cross-company cooperation in the future?

4c) Do you think that cooperation between different countries and governments is on an upward or downward trend?

Technology and market

5a) In your opinion, which technological developments have the potential to increase the attractiveness of the Trans-Caspian Railway Corridor? What technological developments stand in the way of the Trans-Caspian Railway Corridor here?

5b) Think 10 years into the future ... How do you think the market and the Trans-Caspian railroad corridor will develop?

5c) Is the government able to introduce new technologies here? Do you think private actors need to be asked for support to speed up implementation?

Outlook

6a) In your opinion, which issues that have not been raised so far are still important for the development of the Trans-Caspian railroad corridor?

6b) Who else should we talk to?

Port Specific Questions

7a) Can you tell us how the port of Aktau has developed in the last 3-5 years?

7b) Who are the port's main customers and what type of goods are mainly transported?

7c) Have you noticed any changes in the customer structure or in the goods transported during this period?

7d) What was the short-term impact of the political situation on Port Operations?

7e) Where do you see the greatest challenges and growth potential for the Port of Aktau in terms of different types of cargo?

7f) (If the respondent is able to provide information) Are there already concrete plans or considerations for adapting the port infrastructure to future requirements?

7g) What could future cooperation with other ports on the Caspian Sea look like and what role could the port of Kuryk play in this?

7h) Are there any other ports that you see as a model for the development of the Port of Aktau?

Supplementary material C: Implemented quality measures

Throughout the methodological approach of our study, we ensured *credibility*, *dependability*, *confirmability*, and *transferability* that serve as established criteria for rigorous qualitative research, as summarized in Table 1. Halldórsson and Aastrup (Halldórsson and Aastrup, 2003) and Kaufmann and Denk (Kaufmann and Denk, 2011) provide guidance for fulfilling these criteria when applying grounded theory in the context of logistics/transportation and supply chain management research, as evident in our study.

Table 16: Implemented quality measures.

Criterion	Fulfillment	Measures implemented in this study
Credibility	Match between the interviewees' constructed realities and the researchers' representation (Halldórsson and Aastrup, 2003)	▪ Established chain of evidence from the data, to emerging categories, and to more abstract core categories ▪ Positioning of the study on the TCC within existing alternative trade corridors and initiatives as established in Section 6.2
Dependability	Dependability is concerned with the stability (i.e., the ability to replicate) of the study over time (Kaufmann and Denk, 2011)	▪ Following of an identical approach for each interview ▪ Use of a semi-structured interview protocol ▪ Standardized process of storing and analyzing the data using MAXQDA ▪ Transparent, multi-step coding process for the developed data structures
Confirmability	Confirmability is based on how the data itself can confirm the emergence of the findings (Halldórsson and Aastrup, 2003)	▪ Triangulation of data from interviews, internal data provided, and public sources (web searches) ▪ Intensive discussion of codes and the emerging data structures among the authors
Transferability	Transferability is concerned with the extent to which findings are applicable to other contexts (Kaufmann and Denk, 2011)	▪ Applied theoretical sampling logic for selecting the sample and reasoning that the sample appeared to be theoretically saturated with eight actors included ▪ Provided reasoning for selecting interviewees with strategic perspectives on the TCC ▪ Embedding of the study directly in the context of the TCC

7 Study 4: ETA forecasts in the pre- and post-haulage of intermodal transport[6]

Estimated Time of Arrival (ETA) forecasts can be used to dynamically adapt the route planning for the pre- and post-haulage of intermodal transport in response to delays on the main haulage. However, the quality of the ETA forecast depends on various factors. It changes over time and generally increases as the train under consideration approaches the destination terminal. It is not readily apparent to road hauliers if and when they should reschedule. Methodologically, this scenario gives rise to a dynamic and stochastic Pick-up and Delivery Problem with Time Windows (PDPTW) and clustered ETA forecasts, a complex optimisation problem that has not been addressed in the context of intermodal transport. We propose a simheuristic solution procedure to tackle the stochastic and dynamic nature of the problem. Further, we have conducted two simulation studies based on interviews with actors in the intermodal transport chain and reallife data. We examine the impact of clustered, dynamic and stochastic ETA forecasts by comparing the effectiveness of different re-optimization strategies. Further we conduct five parameter variation experiments. Our findings indicate that the integration of ETA forecasts leads to an average cost reduction of 7% compared to scenarios without such forecasts. Even basic forecasts prove beneficial, but higher-quality predictions yield superior planning outcomes, reducing the need for frequent adjustments. While waiting costs constitute a minor fraction of total expenses, they hold significant sway over solution structures, allowing road hauliers greater planning flexibility. Based on these findings, we derive actionable managerial insights and propose policy recommendations to optimise intermodal transport operations.

7.1 Introduction

From a societal perspective, intermodal transport increases the volume of the environmentally friendly modes of rail and inland waterway transport. It is, therefore, an essential pillar for achieving the emission reduction targets in the transport sector. Over the last few years, however, the modal split (in ton-kilometres) in the EU-28 countries has shown no significant changes, and the overall share of inland waterways and rail has declined (EUROSTAT, 2019). In order to increase the share of rail and inland waterway transport, the decision-makers (road hauliers, LSPs, shippers) responsible for choosing the mode of transport must be convinced that intermodal transport is advantageous in terms of cost and reliability compared to road transport (Arencibia et al., 2015). In this context, research among such decision-makers has shown that,

[6] The content of this study is similar with only slight modifications to the paper Rentschler, J.; Elbert, R. The impact of clustered, dynamic and stochastic estimated time of arrival forecasts on the pre- and post-haulage of intermodal transport – a simulation study. Currently under revision in a journal. Thus, in section the pronoun “we” refers to the authors of the paper.

in addition to cost, high mode reliability and in-transit visibility are the most influential factors for the modal shift (Elbert and Seikowsky, 2017; Li et al., 2020). However, in 2021, more than 41% of all freight trains in Germany were delayed for more than one hour, reducing reliability and increasing the need for in-transit visibility (Deutscher Bundestag, 2022). Decision-makers are therefore dependent on decision support systems that provide not only a comparison of transport costs and times but also integrate real-time information about delays in the main haulage of the intermodal transport chain into their planning. This real-time delay information is provided in intermodal transport through so-called dynamic and stochastic ETA forecasts. Dynamic thereby refers to the regular updating of the forecast, stochastic to the inherited uncertainty of the forecast quality (See Figure 31a).

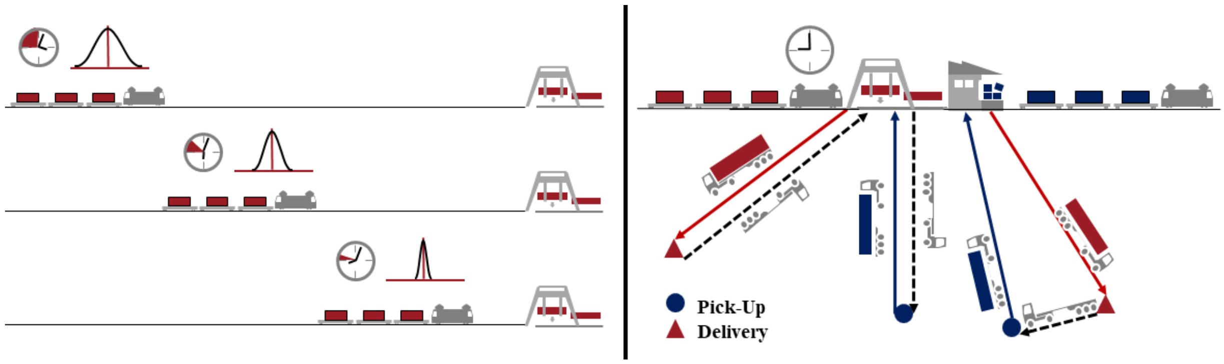


Figure 31: (a) Dynamic ETA forecasts; (b) Possible tours.

In passenger rail transport, ETA forecasts are well established and provide apparent benefits for individual travel planning (Grotenhuis et al., 2007; Hickman and Wilson, 1995). In rail freight, comparable, reliable ETA forecasts for the main haulage, also called release dates, have been difficult or impossible to obtain. The main reasons are the lack of information availability, limited data exchange, and inadequate forecasting methods (RailFreight, 2019). However, current research suggests that reliable ETA forecasts will soon be available for rail freight (Balster et al., 2020; Poschmann et al., 2019).

Several studies imply that dynamic ETA forecasts can add value to the Pre-and Post-Haulage (PPH) of intermodal transport. Bock (2010) shows that the use of real-time information and the continuous adaptation of transport plans with regard to dynamically incoming disturbances and requests improve road haulier transport networks. Wide (2020) examines the operational management of disruptions in transport chains. He shows that information and decision support systems can help planners decide on early recovery actions. Jacobsson et al. (2017) studied the information needed to be exchanged between intermodal terminals and road hauliers to improve access management. They find that the data exchange is currently poor or non-existent, leading to suboptimal processes in the terminal, vehicle waiting times, and possibly additional tours.

Therefore, effective use of ETA forecasts can allow transport decision-makers to streamline processes in the PPH of intermodal transport by rescheduling their vehicles to arrive at the terminal at a better time, reducing waiting and improving tour efficiency. In this paper, we investigate the impact of dynamic and stochastic ETA forecasts in the PPH of intermodal transport from the perspective of a road haulier. The road haulier owns their own fleet and must transport goods to and from the intermodal terminal. If delays occur in the main train haulage and the road haulier is informed of this by a corresponding ETA forecast, they must decide if and when the route planning of the PPH should be adjusted. If the road haulier adjusts the tours early and the arrival of the train is delayed further, waiting costs at the terminal and opportunity costs arise due to tours that could have been conducted during this time. If, on the other hand, the road haulier waits too long to adjust the route planning, costs are incurred due to suboptimal routes.

The PPH of intermodal transport can be described as a PDPTW. Commodities arrive at the terminal by train and need to be distributed, or they need to be collected in the surrounding area and transported to the terminal, where they are loaded onto an outbound train (Figure 31b). Certain time windows must be observed during which pick-up and drop-off are possible. While the locations and quantities of the commodities are known in advance, the arrival times of the incoming trains are announced via ETA forecasts. The ETA forecasts are frequently updated, and arrival information only becomes known over time. Thus, the problem is dynamic, also referred to as an online problem. Furthermore, the quality of the ETA forecast depends on various factors (e.g., infrastructure disruptions, accidents, weather), changes over time, and general increases as the train under consideration approaches the destination terminal (Figure 31a). Accordingly, the problem is also stochastic (Berbeglia et al., 2010).

The structure of the time windows further increases the complexity of the problem. Commodities from the surrounding area can be delivered to the intermodal terminal anytime. However, there are strict time windows for the pick-up of the commodities from the origin and the delivery to the recipient. The time windows for picking up commodities at the intermodal terminal are dynamic. After the train arrives, the commodities must be picked up within a certain time. In intermodal transport, an ETA forecast refers to the arrival of a complete train that can transport several commodities. Consequently, these commodities have the same predicted release date and are clustered. This results in a dynamic and stochastic Pick-up and Delivery Problem with Time Windows and clustered release dates (PDPTW-crd).

To summarise, we address three RQ.

RQ1: How do clustered dynamic and stochastic ETA forecasts impact the PPH of the intermodal transport chain?
RQ2: Which managerial insights can be derived for the decision-makers in intermodal transport?
RQ3: Which policy measures can be taken to foster the implementation of ETA forecasts in intermodal transport?

To answer these RQ, we formalise the problem as a dynamic and stochastic one-to-many-to-one PDP with time windows, clustered release dates, multiple capacitated vehicles, and the possibility to modify tours prematurely. To solve the PDPTW-crd, we propose a simheuristic solution procedure combining simulation and heuristic-based components (Chica et al., 2020). The simulation component uses Monte Carlo sampling, while the heuristic component is based on a biased-randomised algorithm (Grasas et al., 2017). We then extend this solution procedure with a rolling horizon framework to cope with the dynamic aspect of the problem. Finally, we propose two computaitional studies based on real-life data to analyse the impact of the clustered dynamic and stochastic ETA forecasts on the PPH of intermodal transport. First, we compare the solution strategies to determine the most appropriate strategy. Then, we introduce a parameter variation experiment to analyse the influence of the individual parameters and deduce which measures could be taken to increase the attractivity of intermodal rail transport. We find that when incorporating ETA forecasts into routing decisions, a potential cost reduction of around 7% on average can be achieved. Of notable significance is the substantial reduction in waiting costs facilitated by accurate ETAs. While waiting costs constitute a minor fraction of total expenses, they hold significant sway over solution structures, allowing road hauliers greater planning flexibility. Regarding the cluster size, we can observe that larger clusters lead to higher costs.

The remainder of the paper is structured as follows: Section 7.2 summarises the relevant state of research for ETA forecasts in intermodal transport and transport routing problems with ETA forecasts. Section 7.3 introduces the problem as a PDPTW-crd. Section 7.4 describes the solution methodology for the PDPTW-crd and the extensions on how to cope with real-time information. The instance generation process, based on real-world data, is introduced in Section 7.5. Afterwards, the computational experiments are conducted in Section 7.6. Section 7.7 covers the discussion and policy recommendations. We conclude in Section 7.8.

7.2 State of research

Intermodal transport involves the seamless integration of multiple transport modes, where goods are contained within a standardised unit and are not directly handled during transfers between modes on their transport from origin to destination (Crainic et al., 2018). The analysis of intermodal transport networks mostly takes place at the strategic and tactical level in the form of HLP and SNDP (SteadieSeifi et al., 2014). Uncertainty and dynamics regarding demand and travel times are increasingly being incorporated into the modelling and analysis (Alumur et al., 2021; Elbert et al., 2020). Goel (2010) and Zhang et al. (2018) demonstrate the network-level benefit of reliability improvements on the one hand and the value of in-transit visibility on the other. Ultimately, this leads to a new field of transport, namely synchromodality, a "real-time, dynamic and optimised intermodal transport" (Rentschler et al., 2022).

7.2.1 ETA forecasts in intermodal transport

While ETA forecasts are common in public transport and passenger traffic, they are novel in rail freight, and research on their computation and impact is sparse (Reich et al., 2019). Barbour et al. (2018) use support vector regression to predict the arrival times of freight traffic on US railroads based on the characteristics of the train, the network, and the properties of potentially conflicting traffic on the network. For a 140-mile section of track located primarily in Tennessee, USA and a generally sparse rail network, they can show an average improvement of 14% compared to a naive prediction.

In the maritime transport chain, there is a strong need for cross-actor systems that enable greater insight into delays and their consequences. To address this gap, Poschmann et al. (2019) exploit the high potential of artificial intelligence and develop a data-based cross-actor ETA prediction for the landside processes of the maritime transport chain. Together with different actors in the maritime transport chain, they investigate process-related characteristics in terms of benefits, applications, and feasibility for ETA development. They develop a prototype for a single rail relation, enabling the prediction and proactive communication of disruption effects. Balster et al. (2020) use machine learning to calculate reliable ETA predictions for sea freight containers in the intermodal transport chain. Their proof-of-concept shows the possibilities and limitations of a practice-oriented implementation of machine learning to improve reliability in transport networks. As benefits and areas of application of the ETA forecast, they identify early support for operational decision-making problems and improved capacity management. Although similar benefits are frequently mentioned, these benefits remain unquantified. In particular, the operational application of dynamic and stochastic ETA forecasts in the PPH of intermodal transport is missing.

7.2.2 Pick-up and Delivery Problems

The PPH of intermodal transport can be described as a PDP (Berbeglia et al., 2010). According to Kall and Wallace (1995), PDPs can be classified as static/dynamic and deterministic/stochastic. The PDPTW-crd is a dynamic and stochastic problem as ETA forecasts are updated frequently over time and have a certain probability of being accurate. An overview of dynamic and stochastic vehicle routing, as well as PDPs, is given by Berbeglia et al. (2010), Ojeda Rios et al. (2021), Mor and Speranza (2020), and Psaraftis et al. (2016). In general, dynamic and stochastic information is related to the emergence of new orders (Santos and Xavier, 2015), spatial distribution (Macharet et al., 2018), uncertain demand (Goodson et al., 2016), or temporal information (Bian and Liu, 2018; Köster et al., 2018). However, in the PDPTW-crd, these pieces of information are known beforehand and are certain. Instead, the release date of the commodities to be transported and, correspondingly, the time windows, are dynamic and stochastic.

Until now, related transport routing problems with dynamic ETA forecasts have been studied in the context of urban same-day delivery and ride-hailing. Most closely related to our setting are Archetti et al. (2018b, 2020b), Klapp et al. (2018a, 2018b), and Ulmer et al. (2019) regarding the update of the ETA forecast with focus on urban same-day delivery, as well as Srour et al. (2018) and Györgyi and Kis (2019), concerning the transport setting in the ride-hailing context. A summary of the relevant characteristics is given in Table 17.
In the same-day delivery context, the delivery of parcels from a depot to receivers is considered. Parcels arrive at the depot throughout the day, and each parcel has its own ETA forecast. These ETA forecasts are known in the corresponding literature as the release date, the time a parcel becomes available for transport. To plan the delivery, a travelling salesman or vehicle routing problem must be solved. Tours are assigned to a single, uncapacitated vehicle. These tours must be executed entirely and cannot be cut short prematurely, should new information on the release dates become available.

Klapp et al. (2018b) study the dynamic dispatch waves problem, a vehicle routing problem in an urban setting, but all receivers are on a line. Delivery requests arrive dynamically throughout a service day. The decision-maker has spatial information on a set of known requests and a set of future requests. He has to decide whether or not to dispatch the uncapacitated vehicle and, if so, which subset of open requests to serve to minimise expected vehicle operating costs and penalties for unserved requests. When dispatched, the vehicle must complete all assigned requests and cannot return to the depot prematurely. The problem is modelled as a Markov Decision Process and solved through dynamic programming for the deterministic case and a priori policy for the stochastic case. Klapp et al. (2018a) extend this problem setup to a general network. In contrast, Ulmer et al. (2019) allow the preemptive return to the depot in their dynamic same-day delivery problem to integrate dynamic requests better. To solve the problem, they present an anticipatory assignment and routing policy.

Archetti et al. (2020) studied the travelling salesman problem with stochastic and dynamic release dates. In this problem, a road haulier has to deliver parcels from one depot to their receivers. Spatial information and demand are known beforehand. The parcels arrive at the depot throughout the day and can be delivered to the receivers after arrival. The arrival time is called the release date, and information on the release date is stochastic and dynamic. The problem is modelled as a Markov Decision Process. The aim is to serve all receivers and minimise the total time, consisting of travel and waiting time. The problem is solved through a static approach and a re-optimisation approach. The static approach provides fast results, whereas the re-optimisation approach provides high-quality solutions in accordance with the frequency of re-optimisation. A more general overview of the problems faced in the urban setting is given by Boysen et al. (2021).

In the ride-hailing context, Srour et al. (2018) studied a one-to-one pick-up and delivery problem with time windows and advanced information on the time windows. The pick-up and drop-off locations of the service requests are known in advance, but the precise time at which the service is required is only revealed at one point during operations. Passengers inform the service provider about their transport needs in advance, specifying the pick-up and delivery location as well as an estimated time when the service is needed. During operations, the passenger informs the service provider once about the actual time the service is required. They develop a sample scenario and compare different routing strategies to accommodate these time realisations while designing and updating the routes. They show that even if uncertain, advance information can provide benefits in the form of shorter time windows and lead times. Györgyi and Kis (2019) developed a new probabilistic solution approach for the problem. By leveraging the cost structure, they can effectively solve the problem through a single minimum cost flow problem at each decision point.

In summary, research on the impact of dynamic and stochastic ETA forecasts on the PPH of intermodal transport is rather scarce. Only deliveries and no pick-ups are considered in the urban same-day delivery context. In ride-hailing, the ETA is only updated once and not dynamically. Moreover, central characteristics of intermodal transport, such as order structure or vehicle capacity, increase the complexity of the problem. In the urban or ride-hailing setting, each parcel and passenger has a separate ETA forecast. In intermodal transport, an ETA forecast refers to a complete train that can transport several commodities. These commodities also have the same predicted arrival time and are therefore clustered, resulting in the PDPTW-crd. With our contribution, we want to address these research gaps.

Table 17: Related publications and most important characteristics

TSP – Traveling Salesman Problem, PDP – Pick-up and Delivery Problem

	Archetti et al. (2018)	Archetti et al. (2020)	Klapp et al. (2018b)	Klapp et al. (2018a)	Ulmer et al. (2019)	Srour et al. (2018)	Györgyi and Kis (2019)	This Paper
Setting	Urban	Urban	Urban	Urban	Urban	Ride-Hailing	Ride-Hailing	Inter-modal
Problem	TSP	TSP	1-m PDP	1-m PDP	1-m PDP	PDP	PDP	1-m-1 PDP
Fix demand and spatial information	x	x			x	x	x	x
Number of vehicles	1	1	1	1	1	n	n	n
Capacity restriction						1	1	1
Dynamic route modification					x			x
Dynamic ETA	(x)	x				Once	Once	x
Stochastic ETA		x	x	x	x	x	x	x
Time windows						x	x	x
ETA Cluster								x

7.3 Problem description

This section introduces the simulation model incorporating a dynamic and stochastic Pick-up and Delivery Problem with Time Windows and clustered release dates around one intermodal terminal. We were guided by the simulation model development process from Manuj et al. (2009), which was developed specifically for simulation models in the logistics and supply chain context in order to ensure scientific rigour. All our assumptions were validated in expert interviews with industrial partners. For a more general approach to model stochastic and dynamic vehicle routing problems, we refer to Soeffker et al. (2022).

A network is represented by the directed graph $G = (V, A)$, with V denoting the set of nodes and A denoting the set of arcs. Each arc $(i, j) \in A$ is associated with deterministic transport time $t_{i,j}$ and cost $c_{i,j}$. The set of nodes V consists of the depot v_0, the intermodal terminal v_1, and a node for every customer of a transport service $V_C \subset V$. Commodities are given by the set K. Each commodity $k \in K$ must be transported between a pick-up location node $o(k) \in V$ and a delivery location node $\mathrm{s}(k) \in V$. Commodities have to be transported either from a customer or the depot $o(k) \in V_C \cup v_0$ to the intermodal terminal v_1 or from the intermodal terminal to a customer. No commodities are transported between customers. Customers may have multiple commodities both to be picked up and delivered.

A limited fleet of homogeneous vehicles M operates within the network to transport the commodities. We assume a capacity of $q = 1$ for every vehicle since the transport units (e.g., containers) used in intermodal transport take up the total capacity of a vehicle. Full-truckload is typical for road and road-rail long-distance transport in Europe (Rivera and Mes, 2019; UIRR and UIC, 2020) and, therefore, a relevant case for the PDPTW-crd. At the beginning of the planning horizon, typically a day, each vehicle starts at the depot v_0 and must return to the depot at the end of the planning horizon.

For each commodity $k \in K$, time windows are given at the pick-up $[\epsilon_{o(k)}, l_{o(k)}]$ and at the delivery $[\epsilon_{s(k)}, l_{s(k)}]$ locations. Vehicles can arrive early but are not served outside the time window. If vehicles do arrive early, waitingcost c_w must be paid per unit of time. There is no cost for spending time at the depot, as drivers can conduct other productive tasks. Time windows are soft – commodities can be delivered after the time window closes, but a linear fine c_l must be paid depending on the delay. The pick-up time windows for commodities with pick-up at the intermodal terminal, $o(k) = v_1 \forall k \in K$, have a fixed length $l - \epsilon$ and start as soon as the train carrying the commodity arrives at the depot. Therefore, these time windows have a dynamic start. This modelling reflects reality, as commodities have to be picked up within a certain period of time after their arrival in order to decongest the terminals. Other time windows are fixed but have a specific structure, as described in Table 18.

Table 18: Structure of the time windows.

Time Window	Description
Transport from the customer to the intermodal terminal	
$[\epsilon_{o(k)}, l_{o(k)}]$ time window at the pick-up location $o(k) \in V_C$	Short pick-up time window of 2 hours.
$[\epsilon_{s(k)=1}, l_{s(k)=1}]$ time window at the intermodal terminal	Delivery and pick-up of commodities at the intermodal terminal are possible throughout the day.
Transport from the intermodal terminal to the customer	
$[\epsilon_{o(k)=1}, l_{o(k)=1}]$ time window at the intermodal terminal	Length $l - \epsilon$ of the time window is between 2-4 hours, The time window starts as soon as the train arrives.
$[\epsilon_{s(k)}, l_{s(k)}]$ time window at the delivery location $s(k) \in V_C$	Medium-sized with 2-4 hours.

For a vehicle $m \in M$, a tour starting and ending at the depot and not visiting the depot in-between is called a route r_m. A route consists of the transport of one to several commodities. A pick-up and delivery plan is the set of all routes. The objective is to transport all commodities and minimise the cost. Total cost include travel costs, the costs for violating time windows, and waiting costs at the intermodal terminal and customers. A summary of the notations is given in Table 19.

Table 19: List of notations.

Notation	Meaning
V	Set of nodes
A	Set of directed arcs
$G = (V, A)$	Directed graph with V denoting the set of nodes and A denoting the set of arcs
K	Set of commodities
M	Set of vehicles
q	Vehicle capacity
C	Set of clusters
$t_{i,j}, c_{i,j}$	Transport time and cost on the arc $(i, j) \in A$
c_w	Waiting costs at the intermodal terminal and the customers
c_l	Delay cost
$o(k)$	Origin node for commodity $k \in K$
$s(k)$	Destination node for commodity $k \in K$
$[\epsilon_{o(k)}, l_{o(k)}]$	Time window at the pick-up location of commodity $k \in K$
$[\epsilon_{s(k)}, l_{s(k)}]$	Time window at the delivery location of commodity $k \in K$
$\tilde{r}_k^t$	Release date of commodity k at time t
β	Parameter of the geometrical distribution

The PDPTW-crd is characterised by its stochastic and dynamic aspects. The ETA forecasts of the trains translate to the release dates of the commodities to be transported from the intermodal terminal to the customers. These release dates are assumed to be stochastic, representing delays of the trains in the main haulage. A certain knowledge about the forecast quality, e.g. the mean forecast error and its variance, is assumed at all times. The forecast and its quality evolve over time and are assumed to improve the nearer the train is to the intermodal terminal. Updated information about the forecast becomes available in irregular time intervals, representing the dynamic aspect. A detailed description of the trains and ETA forecasts is given in Section 7.5.2.

The commodities can be divided into different subsets. The notation for the classification of commodities and release dates is inspired by Archetti et al. (2020).
Depending on the time t, some commodities $k \in K$ may have already been transported. Therefore, we call this set of commodities $K_t^{served} \subseteq K$. Further, we distinguish the unserved commodities that are $K_t^{unserved} = K \backslash K_t^{served}$, based on the commodity type and available information for their release date. Commodities for which all information is known at the time t are called $K_t^{known} \subseteq K_t^{unserved}$. K_t^{known} can be further divided into commodities to be transported from the customer to the intermodal terminal as they are independent of the arrival of the trains, and all relevant information is fixed at the beginning of the planning horizon. Accordingly, we call them $K_t^{fixed} \subset K_t^{known}$. For commodities that are to be transported from the intermodal terminal to the customer and have already reached the intermodal terminal, the release date has passed, and the customer can be served. The set of these commodities with a certain release date in the past is called $K_t^{released} \subseteq K_t^{known}$. The set of commodities which still have to arrive by train at the intermodal terminal, we call K_t^{future}. The stochastic release date for these commodities is dynamically updated as new train information becomes available.

To summarise: $K = K_t^{served} \cup K_t^{unserved}$; $K_t^{unserved} = K_t^{future} \cup K_t^{known}$ and $K_t^{known} = K_t^{fixed} \cup K_t^{released}$ at any time t.
We denote the release dates of commodities $k \in K_t^{unserved}$ at time t as $\tilde{r}_k^t$. We can further distinguish between the types of commodities.

- If $k \in K_t^{fixed}$, the release date is the start of the planning horizon $\tilde{r}_k^t = 0$.
- If $k \in K_t^{released}$, the release date is fixed to the time the train carrying the commodity arrives at the intermodal terminal $\tilde{r}_k^t = r_k$.
- If $k \in K_t^{future}$, $\tilde{r}_k^t$ is a random variable with information on the release date at time t. This information includes the predicted arrival time and the distribution of the forecast error at time t. Thereby, $\tilde{r}_k^t$ is dynamically updated whenever new information becomes available.

The trains delivering the commodities to the intermodal terminal travel independently from one another. Therefore, we assume that the release dates of commodities on different trains are independent. However, a train can carry a multitude of commodities so that a group of commodities can have the same release date r_c. Such a group is called a cluster $c = \{k \in K \vee \tilde{r}_k^t = r_c\}$, and C is the set of clusters.

7.4 Solution methodology

We solve the PDPTW-crd based on a simheuristic solution procedure. Simheuristics, the combination of simulation and heuristics, have been used to extend metaheuristic frameworks, especially in stochastic problem settings (Grasas et al., 2017; Herrera et al., 2021; Juan et al., 2018; Reyes-Rubiano et al., 2018).

Our simheuristic solution procedure consists of two components: an optimisation component is used to search for promising solutions, and a simulation component is used to evaluate the promising solutions in a stochastic environment. First, the constructive multi-start optimisation component is introduced in Section 7.4.1. Then, in Section 7.4.2, we describe the simulation component. How routes are modified once they are started is illustrated in Section 7.4.3.

To account for the dynamic nature of the problem, we incorporate the offline algorithm into a rolling horizon framework that re-solves the problem again at different points in time with the updated information. First, Section 7.4.4 introduces the rolling horizon framework in which the simheuristic solution procedure is embedded. Then, in Section 7.4.5, we propose different solution strategies.

7.4.1 A biased randomized algorithm for the static and deterministic PDPTW

A biased randomized algorithm (BRA) is used to solve the static and deterministic PDPTW (Estrada-Moreno et al., 2019; Herrera et al., 2021). The BRA consists of a fast constructive heuristic, followed by a cost-saving logic (Clarke and Wright, 1964) while building the routes for each vehicle.

Suppose an unlimited fleet of vehicles at the depot. Then, generate a feasible dummy route for each commodity by connecting the depot with its pick-up location and delivery location, followed by a vehicle return to the depot, e.g., a roundtour for each commodity. The vehicle leaves the depot at a random start time to arrive during the time window at the pick-up location.

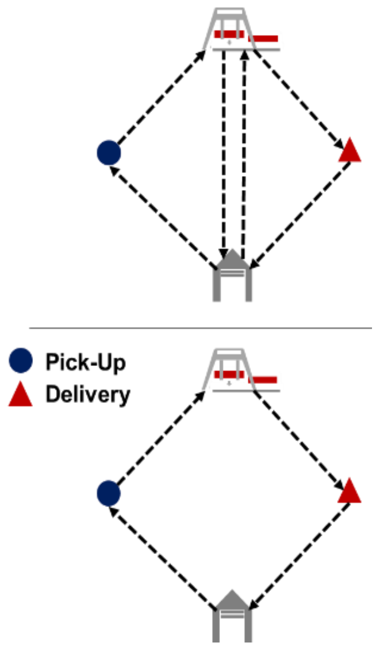


Figure 32: Merging of two routes

Create a cost-savings list of route merges and sort it from higher to lower savings. The merges at the top of the list represent routes that are close together in a spatial and time window sense. Therefore, these routes are good candidates to be merged. On the other hand, the merges at the bottom of the cost-savings list represent routes that are not close; thus, including them in the same route will only lead to moderate savings. Therefore, it is necessary to ensure that only permissible routes and route merges are generated. An example is given in Figure 32, where two routes are merged.

Start an iterative route merging process. In each iteration, the merge at the top of the cost-savings list is selected, and the corresponding routes are merged into a new one. Update the cost-savings list. The process concludes when no more suitable merges are left.

This algorithm is deterministic and greedy. This myopic behaviour leads to the same solution each time the algorithm is executed. To overcome this limitation, randomness is introduced into the merge selection process of the algorithm (step 3). The constructive heuristic is extended into a BRA by employing a skewed probability distribution. Grasas et al. (2017) give a survey about using skewed probability distributions for the randomisation of heuristics. They argue that theoretical distribution functions are especially suited as they are easy to tune, and the analytical expression allows fast computation times. Further examples of the use of skewed probability distribution are given by Belloso et al. (2019) and Festa et al. (2018).

We choose the geometric distribution to induce the biased-randomised behaviour within the heuristic. Since the geometric distribution function has only one parameter $\beta \in (0,1)$, it is particularly suitable for the simple tuning of the algorithm. Whenever β is close to 1, the algorithm approaches the greedy behaviour of the myopic constructive heuristic. For a β close to 0, the randomness in the merge selection is similar to the uniform probability distribution, and each merge is selected with the same probability no matter the savings it contributes. Values in-between can produce a more beneficial behaviour, as some level of randomness is introduced into the heuristic without sacrificing the logic behind the concept of saving costs. With this BRA, it is possible to produce a multitude of solutions and select the best one found.

7.4.2 Simulation framework to account for stochasticity

The BRA is then incorporated into a simulation framework to assess the quality of the generated solutions in a stochastic environment and use the feedback to guide the search process. The solution procedure, depicted in Figure 33, starts by generating a feasible initial solution (initSol) through the deterministic version of the constructive heuristic (Herrera et al., 2021). So far, the cost of this solution corresponds to the scenario where all information is deterministic. To deal with the stochastic nature of the main haulage and the associated ETA forecasts, a Monte Carlo Simulation (MCS) is used to obtain an overview of the behaviour of the solution under stochastic conditions (Rabe et al., 2020). As simulation runs are time-consuming, a large number of solutions are checked, and the problem has to be solved repeatedly, only a few simulation runs are conducted to obtain a rough estimate (Rabe et al., 2020). This initial solution is then assigned as the best solution (bestSol) found up until now. An iterative procedure aims to improve this best solution in a given amount of time or number of iterations. Therefore, the biased-randomised algorithm generates a new solution (newSol) in each iteration. As skewed probability distributions are employed in the third step of the algorithm, a random behaviour is induced into the algorithm. Each run yields a new solution to diversify the exploration of the solution space and make it less greedy. When such a newly found solution outperforms the current best solution in terms of deterministic cost, an MCS is started to check the performance of the newSol in a stochastic environment. If the newSol also outperforms the bestSol there, the bestSol is updated. The search for a new solution terminates when a predetermined time or number of iterations is reached.

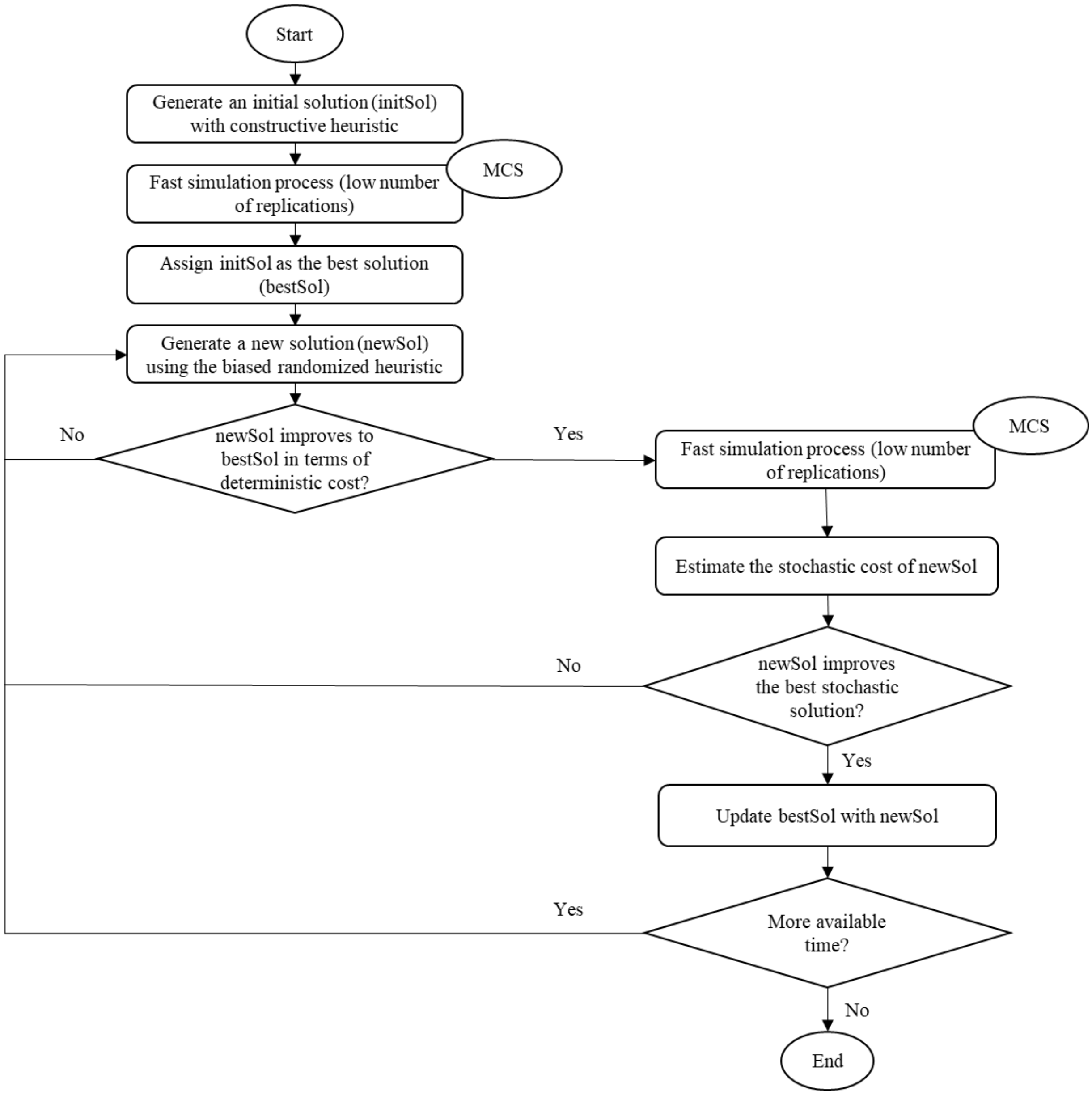


Figure 33: Conceptual diagram of the simulation framework to account for stochasticity. |own representation based on Herrera et al. (2021)

7.4.3 Dynamic modification of started routes

With vehicle capacity $q = 1$, due to the typical full-truckload in intermodal transport, there are only a limited number of possible actions a vehicle can perform (see also Figure 31). The vehicle can either

- pick up a commodity at the intermodal terminal and deliver it to its destination, or
- pick up a commodity at its origin and deliver it to the intermodal terminal,

or a combination of the two,

- leave the intermodal terminal with a commodity, deliver it to its destination, travel from there to a pick-up location and then deliver the commodity to the intermodal terminal.

Therefore, a vehicle route consists of a sequence of actions applied to the commodities assigned to this route. To account for the dynamic nature of the problem, we allow the modification of routes that have already started. A route modification is possible whenever the pick-up and delivery plan is updated. A started route of a vehicle can be modified, while a started leg of a route must be finished. Possible route modifications we consider are:

- After travelling to the pick-up location, it would be possible to leave the vehicle empty, travel to another location where the pick-up is more urgent, and transport this commodity. This modification is beneficial at the terminal should the announced train be suddenly delayed.
- Remove a commodity from the route and assign it to another route or start a new route. This is beneficial if the availability of a commodity is delayed, and the delivery of all other commodities in the route would be held up.

7.4.4 Rolling horizon framework

To deal with the dynamic and stochastic aspects of the pick-up and delivery problem with clustered release dates, we extend the introduced BRA into a simheuristic with a rolling horizon framework. Figure 34 shows the conceptual diagram of the rolling horizon framework.

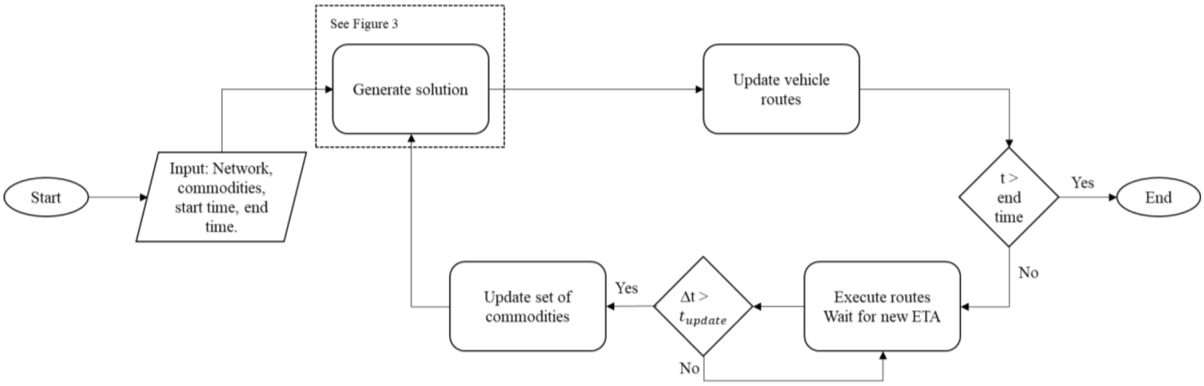


Figure 34: Conceptual diagram of the rolling horizon framework

We start at the beginning of the planning horizon $t = 0$ and generate the first feasible solution with the BRA, indicated in the highlighted box in Figure 34. In particular, the PDPTW-crd is solved with the information available at time t: the currently available information about the ETA forecasts and the set of unserved commodities $K_t^{unserved}$. After generating a solution, the vehicle routes are updated.

After the first pick-up and delivery plan is generated, an iterative procedure starts. As long as there is time left, the simulation waits for an update. An update could be new commodities becoming known or a change in the ETA forecasts. When an update becomes known and at least a predefined time interval t_{update} has passed since the last calculation of a pick-up and delivery plan, the set of commodities still to be delivered $K_t^{unserved}$ is updated, and a new solution is calculated with the available information.

7.4.5 Solution strategies

Five different solution strategies are considered to evaluate the impact of the dynamic and stochastic ETA forecast on the PPH in intermodal transport.

- Perfect information: In this strategy, we assume knowledge of the exact arrival time of all trains as soon as they are created. Commodities become known once a day. The problem is solved once a day when the commodities become known.
  With the perfect information on the train arrivals, we are able to create a best-case solution. This approach allows us to determine how the dynamic strategies compare to the best possible solution.
- Ignore: This is the most straightforward way to incorporate ETA forecasts and reflects what a service provider without sophisticated decision support tools and information would do. No updated ETA forecasts are incorporated into the decision process. Instead, the service provider solves the optimisation problem once at the beginning of the day with the scheduled arrival times of the trains. He doesn't employ any dynamic strategies should new information become available. This strategy serves as a baseline to determine the value of the stochastic and dynamic information (Berbeglia et al., 2010).
- Blind: This strategy reflects the situation in which no advanced ICT systems or ETA forecasts are available. The road haulier refrains from integrating refined dynamic and stochastic information into the planning. Instead, they wait for the train to arrive at the intermodal terminal. As soon as they are informed about the arrival of the train, they plan the distribution of the commodities and update the pick-up and delivery plan.
- Reactive: In this strategy, the PDPTW-crd is solved every time an ETA forecast is updated, e.g. $t_{update} = 0$, representing a fully dynamic strategy. The solutions must be generated quickly to update the pick-up and delivery plan in real-time.
- Batch_t_{update}: Since short-sighted strategies fail to address the interdependencies of the complex problem and lead only to an unsatisfactory pick-up and delivery plan, another strategy is proposed. This strategy re-optimises the whole pick-up and delivery plan when at least one ETA forecast has been updated and at least a predefined time interval $t_{update} > 0$ has passed. With this strategy, on the one hand, several updates of ETA forecasts can be taken into account simultaneously. On the other hand, buffering allows a longer running time for the simheuristic solution procedure.

7.5 Instance generation

In the following section, we describe the instance generation procedure. First, we explain how we obtained instances based on interviews with intermodal transport practitioners. Then, we describe how the individual train trips and corresponding release dates are created and updated over time.

Figure 35: Map of depot (yellow), intermodal terminal (red), and customer locations (blue) in central Europe

7.5.1 Instance description

In order to create relevant test instances as close to real life as possible while still being generalisable, we interviewed one large road haulier, one intermodal rail operator, and two terminal operators (all located in Germany). From those interviews, we derived in-depth knowledge regarding the underlying processes and were able to validate our model. Furthermore, we have received several datasets describing all relevant processes around a German intermodal terminal for two months. These datasets include all arriving and departing trains, the corresponding ETA forecasts, and the commodities transported by the road haulier. These datasets built the foundation for our instance generation.

The examined intermodal road/rail terminal, located in western Germany, is one of the largest intermodal terminals in Germany and is a central start and end point for intermodal transport in Germany and Europe (Granzow, 2024). Germany itself is also the primary hub for intermodal transport in Europe. The relations presented in Section 7.5.2 are typical intermodal relations and connect Germany to the most important intermodal trading partners in Europe (EUROSTAT, 2022). Furthermore, the selected case is comparable with other terminals, their order structure, and ETA forecasts, so the results can be transferred and generalised.

We derive generalised distributions and parameters to generate instances based on the datasets provided by our interview partners. A summary of the basic parameters is given in Table 20. The depot of the road haulier v_0 is located about 30km from the terminal v_1. We consider 35 different customer locations V_C with a distance to the terminal of between 4km and 400km, each with a probability to be included in the instance based on the generalised data from the road haulier (Figure 35). A time horizon of twelve hours is considered to model a whole business day. In a single instance, we consider 14 business days. Costs are taken from the literature (Bicker, 2014; Layeb et al., 2018). Furthermore, a generalised process for commodity generation and the corresponding time windows is devised. At the beginning of each day, we randomly generate a set of commodities. These commodities are categorised into two groups: those necessitating transpor from the nearby vicinity to the terminal and those delivered to the terminal via train and then on to the customer. Customer locations are probabilistically determined based on the dataset distribution. Subsequently, the corresponding trains are devised. Initially, the point of departure of the train is identified, followed by the determination of its capacity, e.g. the cluster size. Commodity allocation to the train continues until full capacity is reached. This process iterates until all commodities are allocated to trains. Time windows for commodities are then generated in accordance with the structure outlined in Table 18.

Table 20: Parameters for the instance generation. Left fixed parameters, Right parameter sets

Parameter	Value	Parameter	Value
Planning horizon	12h/14 days	Number of commodities	$s \in \{8-12; 15-25\}$
Min./max. length of time windows	2h – 12h	Cluster size	$c \in \{1-3; 2-6\}$
Number of customer locations (|V|)	35	Degree of dynamism	$\delta \in \{0.25, 0.5, 0.75\}$
Number of vehicles (|M|)	5/7		
Vehicle cost	0.82€/km		
Waiting cost	60€/h		
Late fees	100€/h		

Each instance is denoted as $I_{s\_\delta\_c}$. The size of the instance, e.g., the created commodities each day, is indicated by s. We differentiate between small instances with 8 to 12 commodities per day and large instances with 15 to 25 daily commodities. The degree of dynamism, the share of commodities arriving by train, is denoted by the parameter $\delta \in [0,1]$, indicating the rate of commodities with a dynamically updated ETA forecast (Larsen, 2001). We choose to generate instances with $\delta \in \{0.25, 0.5, 0.75\}$. Finally, the size of the clusters, the number of commodities per train, is denoted by c. We consider small clusters with 1 to 3 commodities per train or large clusters with 2 to 6 commodities.

Therefore, we test instances with $s \in \{8-12; 15-25\}, \delta \in \{0.25, 0.5, 0.75\}$ and $c \in \{1-3; 2-6\}$, leading to twelve instance sets with different characteristics. For each set, we generated ten instances, leading to a total of 120 different instances. All instances used for the computational experiments can be downloaded at Rentschler (2024).

7.5.2 Train and ETA forecast generation and updating

We consider three highly frequented intermodal relations embodying unique transport characteristics and delay profiles in order to represent a broad range of real-world intermodal relations in Central Europe. The specific characteristics are summarised in Table 21. The first relation from Verona (Italy) to Cologne (Germany) covers a long distance and crosses the Alps. The relation serves as a conduit for half of the transported commodities in our model, frequently experiencing delays ranging from 2 to 6 hours. The second relation from Cerbère (France) to Cologne exhibits a moderate frequency of delays, but when they occur, they are high and can extend up to 10 hours. These delays often manifest in the later stages of the trip, mimicking real-world challenges at border crossings. Conversely, trains on relation three from Malmö (Sweden) to Cologne cover a medium distance and tend to maintain punctuality or occasionally arrive earlier than scheduled.

Table 21: Overview of the train relations

Number	Relation	Share	Distance	Delay frequency	Delay duration
1	Verona - Cologne	50%	1,150km	High	Medium
2	Cerbère - Cologne	30%	1,250km	Low	High
3	Malmö - Cologne	20%	950km	Low	Low

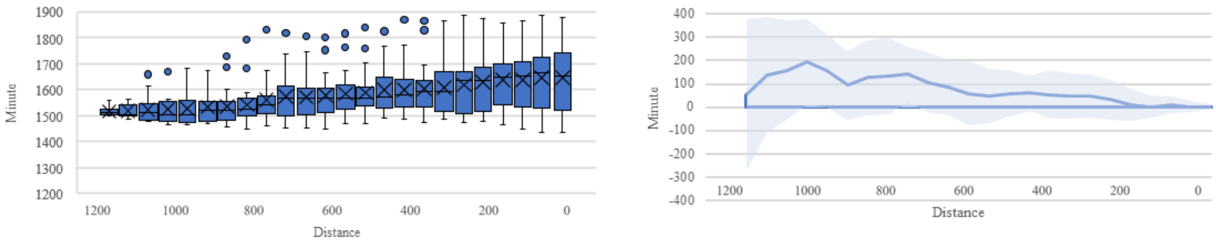
Based on the datasets provided by the intermodal operator, we derive generalised distributions to generate the trains and ETA forecasts for each relation. We split the process into two distinct stages to allow for more detailed modelling. Firstly, we simulate trains and their trip. Then, we generate the ETA forecasts for each train.

We start by generating individual train trips utilising a random walk process. At every 50km interval, the speed of the train for the subsequent 50km is determined. This speed is derived from a triangular distribution, providing a probabilistic framework for the travel dynamics of the train. Triangular distributions are widely used in business and logistic simulations, providing a suitable approach to consider uncertainty (Lombard et al., 2018; Moosavi and Hosseini, 2021). Consequently, the travel time of each train is continually updated by accounting for the time required to traverse the preceding 5km. Additionally, the model incorporates the possibility of occasional stoppages, thereby enabling a comprehensive representation of various disturbances. By utilising the triangular distribution in conjunction with the stoppage probability, our model captures detailed train characteristics while retaining generality to simulate a multitude of trains.

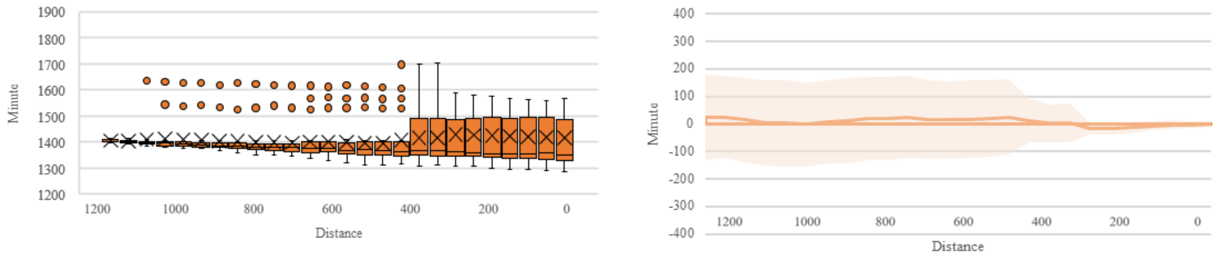
ETA forecasts are stochastic and dynamic as they are never accurate and are communicated irregularly. Calculating the "true" ETA is accomplished by dividing the remaining distance of the train trip by the theoretical mean speed of the specific train. This theoretical mean speed is based on the underlying triangular distribution and stoppage probability. To model different quality levels of the forecast, we introduce a random error term. This error term is based on draws from a Gaussian distribution with mean $\mu = 0$ and a standard deviation σb based on historical data. As the train approaches the intermodal terminal, the standard deviation σ of the Gaussian distribution decreases, signifying an improvement in the accuracy of the forecast as the train nears its destination. The standard deviation is adjustable by the parameter b to model various forecast qualities. The error term is based on the moving average of the last three draws to ensure a smoother forecast and minimise abrupt fluctuations.

In order to give an idea of the trains and ETA forecasts, we provide an example in Figure 36. We simulate 20 trains and the corresponding ETA forecasts for each relation. On the left side of the Figure is the "true" arrival time of the trains during the trip without error term, e.g., $b = 0$. To consolidate the information, we show a boxplot summarising the information for all 20 trains at every 50km interval. We can see the characteristics of each relation reflected in the simulated trains. The boxplots for relation 1 show a steady increase in the arrival time and its variance. Both are incurred due to the frequent and medium delays. For relation 2, we can observe a constant arrival time with low variance for the major part of the trip, but in the end, several high delays occur. Relation 3, on the other hand, remains punctual or even early during the whole trip.

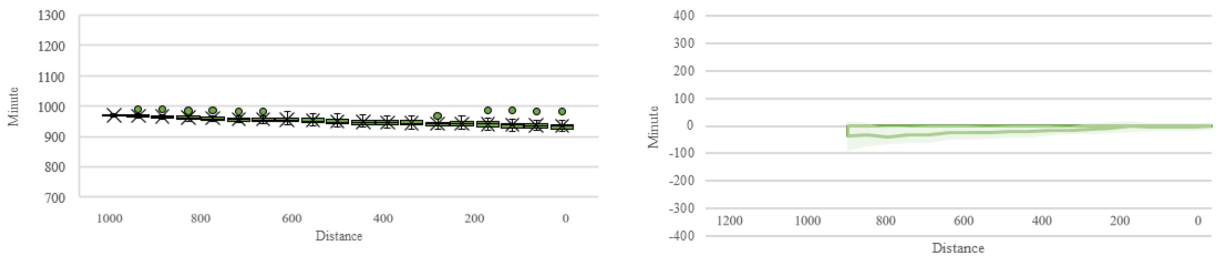
On the right side of the Figure, we see the accuracy of the ETA forecast ($b = 1$) during the train trip. The ETA forecast arrival time is deduced from the actual arrival time of the train to determine the forecast error. The solid line describes the mean forecast error, and the shaded area is the standard deviation. The nearer a train comes to the terminal, the more precise the ETA forecasts become. For relation 1, we observe a high mean error and a wide variance of the forecast quality at the beginning of the trip. This indicates that frequent delays are difficult to predict. Relation 2 displays a low mean error throughout the trip but also a high variance initially. This suggests that the long and late delays are difficult to predict in the earlier parts of the trip. The forecast error for relation 3 shows a low mean error and low variance, as is to be expected.



Train trips and ETA accuracy of relation 1



Train trips and ETA accuracy of relation 2



Train trips and ETA accuracy of relation 3

Figure 36: Left – "True" arrival time for 20 trains per relation. Right – Accuracy of the ETA forecast for each relation.

7.6 Computational experiments

Using our simheuristic solution procedure and real-time strategies, we analyse the impact of clustered dynamic and stochastic release dates on the PPH of the intermodal transport chain. In Section 7.6.1, we compare the different re-optimisation strategies. First, the value re-optimisation is shown by comparing the "ignore" strategy results, where the problem is solved at the beginning of each day when the commodities become known and only with the scheduled arrivals of the trains, with the other strategies. Then, we determine the efficiency of the different re-optimisation strategies by comparing them to the solution identified by the perfect strategy, where all information regarding train delays is known beforehand. This is followed by analysing the different costs and several key performance indicators (KPIs), such as the number of commodities per route and dynamic modifications of started routes. We close with an in-depth analysis of the Batch 60 strategy, as this strategy is used to conduct the subsequent parameter variation experiments in Section 7.6.2. In this set of experiments, we investigate which measures could be taken to increase the attractivity of intermodal rail transport. Concretely, we conduct five sets of experiments in which we vary central parameters such as waiting and delay costs, the number of available vehicles, length of the time windows, and different quality levels for the ETA forecast with varying severance of train delay.

The simulation and the solution procedure are implemented in the 8.8.6 AnyLogic University Simulation Software 8.8.6. AnyLogic is a well-established software known for its application in addressing stochastic and dynamic challenges within logistics (Juan et al., 2018; Karaaslan et al., 2018; Masoud et al., 2020). Verification of the simulation model relies primarily on various system performance statistics, whether in real-time or tally format, gathered by the model. Additional verification methods such as code walk-throughs, visual confirmation using model animations, and trace analysis were consistently implemented throughout the research process to ensure accuracy. Moreover, continuous validation of the simulation model occurred over the 24-month research period, involving project partners engaged in diverse functions within intermodal transport, covering all facets of the transport chain.
The parameters of the biased randomised savings algorithm have been set to 500 iterations, and the parameter for the geometrical distribution has bent set to $\beta = 0.75$ as preliminary tests for different parameter settings could not show a significant improvement in terms of lower objective function values for higher maximum iterations. The results are computed as averages over all 120 instances, and costs are given in euros.

7.6.1 Strategy comparison

Table 22: Results of the different solution strategies

Strategy	Total cost	Value re-optimisation	Gap	Cost KM		Cost Wait		Cost Late	
Perfect	56,661	30.7%	-	31,467	57.4%	580	1.0%	24,613	41.7%
Ignore	81,730	-	44.2%	31,376	41.0%	12,893	15.7%	37,459	43.3%
Blind	62,313	23.8%	9.9%	33,242	55.3%	149	0.3%	28,921	44.5%
Reactive	58,377	28.6%	3.0%	31,597	56.0%	1,318	2.2%	25,461	41.8%
Batch 30	58,262	28.7%	2.8%	31,473	56.0%	1,421	2.4%	25,367	41.6%
Batch 60	57,964	29.1%	2.3%	31,404	56.0%	1,524	2.6%	25,035	41.4%
Batch 90	58,319	28.6%	2.9%	31,392	55.7%	1,563	2.6%	25,363	41.7%
Avg	61,947	28.2%	10.9%	31,707	53.91%	2,778	3.8%	27,460	42.3%

We begin our analysis by exploring the efficacy of the different re-optimisation strategies compared to the static approach, also known as the value of re-optimisation. Re-optimisation involves dynamically solving the problem based on updated information, while the static approach entails solving the problem at the initial point of time when the commodities become known each day without further adjustments. In our case, this is equivalent to comparing the various solution strategies with the ignore strategy. The comparison reveals a substantial improvement in solution quality across all re-optimisation strategies. In particular, the results in the third column of Table 22 illustrate that re-optimisation offers an average improvement of solution quality of 28.2%. Moreover, dynamic strategies, including Blind, Reactive, and Batch, exhibit significant cost reductions, increasing with the sophistication of the strategy. This further underscores the value of incorporating dynamic ETA forecasts in intermodal transport planning and execution.

Building upon the insights gained from our assessment of the value of re-optimisation, we redirect our attention towards conducting a detailed analysis of the different solution strategies. In this endeavour, we turn to the average percentage gap of each strategy compared to the solution identified by the perfect strategy with all information regarding train delays known beforehand (column four in Table 22). The Blind strategy performs reasonably well, notably reducing waiting costs. Despite its simplicity, Blind, as a relatively conservative strategy, underscores the potential benefits of even marginal dynamic information in optimising intermodal transport operations. Although the Reactive strategy demonstrates good performance, its solution quality is somewhat compromised due to shorter computation time and limited information. This limitation restricts the complexity of achievable solutions. Its practical applicability is also questioned due to challenges in disseminating updated information to drivers. The set of Batch strategies emerges as the most promising approach, striking a delicate balance between utilising real-time information and re-optimisation. By leveraging updated data while minimising the number of re-optimisations, Batch 60 achieves notable improvements in solution quality and cost efficiency.

A closer examination of the different costs in the objective function offers valuable insights into the economic implications of different strategies. The costs for kilometres driven are similar across all strategies and account for an average of 54.0% of the total cost. The Blind strategy deviates from this with slightly higher KM costs. This is due to the fact that commodities are only assigned after the train arrives, which is why more routes have to be driven. Waiting costs account for an average of 3.8% of total costs and vary between the different strategies. The Blind and Perfect strategies, in particular, have inherently minimal waiting costs. Conversely, strategies such as Batch and Reactive incur relatively high waiting costs, primarily due to risk-averse planning resulting from the MCS evaluation. Delay costs are responsible for a significant proportion of the total cost. They are particularly pronounced in the case of the Blind strategy, as the conservative allocation strategy is considered in addition to the train delays. In contrast, strategies like Batch 60 demonstrate the ability to mitigate delay costs effectively, highlighting their effectiveness in managing time-sensitive transport operations.

In addition to cost-related metrics, various KPIs are considered to provide an in-depth evaluation of the different strategies (Table 23).

Table 23: KPIs for different solution strategies

Strategy	Reoptimisation	Routes	Commodities per Route	Dyn. Mod.
Perfect	14.0	110.5	1.8	2.9
Ignore	14.0	107.4	1.9	4.6
Blind	56.9	133.8	1.5	0.3
Reactive	1,133.1	111.2	1.8	2.3
Batch 30	653.9	108.9	1.9	1.7
Batch 60	327.2	107.1	1.9	1.9
Batch 90	218.2	107.0	1.9	1.8
Avg	345.3	112.3	1.81	2.2

The frequency of reoptimization varies significantly across strategies, with an average of 345 reoptimizations. Notably, Reactive conducts the highest number of reoptimizations at 1,133.1, while Ignore and Perfect optimise only once a day when commodities become known, resulting in 14 reoptimizations each. Blind strategy reoptimises whenever a train arrives, or new commodities become known, resulting in a moderate reoptimization rate of 56.9. Strategies employing Batch processing exhibit a steady reduction in reoptimizations, with Batch 90 having the lowest frequency at 218.2.

On average, 112.3 routes are required to deliver all commodities. However, the Blind strategy deviates from this average due to the necessity of planning more routes, as commodities are assigned only upon train arrival. The number of commodities per route is closely linked, with solutions aiming to minimise empty tours by combining transport to and from terminals.

Dynamic route modifications are relatively infrequent across all strategies, averaging 2.2 modifications. This is attributed to the ability to adjust plans before route commencement. However, the Ignore strategy stands out with a higher number of modifications, reflecting its attempt to compensate for poor information availability. The high frequency of modifications observed in the Perfect strategy can be attributed to the availability of comprehensive information regarding train arrivals, contrasted with the unveiling of commodities only at the beginning of each day. This combination necessitates route adjustments to accommodate new commodities alongside the complete knowledge of the arrival of trains started the previous day.

In the remaining parts of the paper, we will use the Batch 60 strategy for further analysis. This choice is motivated by its ability to yield good results with a low number of time-consuming reoptimizations and its alignment with real-world operational strategies. Subsequently, we will delve deeper into examining the impact of the various instance parameters under the Batch 60 strategy.

Table 24: Detailed results for the Batch 60 strategy

Instance Size	Degree of Dynamism	Cluster Size	Cost	Cost KM		Cost Wait		Cost Late	
Small	25%	Small	32,146	21,609	67.8%	559	1.7%	9,977	30.5%
		Large	31,504	21,530	69.2%	487	1.5%	9,486	29.3%
	50%	Small	39,424	21,657	55.1%	1,161	2.9%	16,605	42.1%
		Large	38,926	21,799	56.5%	1,088	2.8%	16,037	40.7%
	75%	Small	44,497	21,324	48.3%	1,504	3.4%	21,667	48.3%
		Large	44,824	21,482	48.0%	1,476	3.3%	21,865	48.7%
	Avg		38,554	21,568	57.5%	1,046	2.6%	15,940	39.9%
Big	25%	Small	66,400	41,890	64.1%	1,039	1.6%	23,470	34.4%
		Large	68,023	42,340	63.1%	1,116	1.7%	24,567	35.2%
	50%	Small	74,943	40,917	54.7%	2,140	2.9%	31,886	42.4%
		Large	78,258	41,522	53.3%	1,991	2.5%	34,744	44.2%
	75%	Small	85,742	40,280	47.2%	2,806	3.3%	42,655	49.5%
		Large	90,882	40,503	44.8%	2,920	3.2%	47,458	52.0%
	Avg		77,375	41,242	54.5%	2,002	2.5%	34,131	43.0%
Avg			57,964	31,404	56.0%	1,524	2.6%	25,035	41.4%

Table 24 is structured according to instance parameters and follows the logical structure in which the instances are generated. It provides a comprehensive overview of the implications associated with different commodities per day, degree of dynamism and cluster size.

It is evident that larger instances incur higher costs compared to smaller instances. Moreover, both small and large instances exhibit a notable cost increase as the proportion of commodities transported by rail (high Degree of Dynamism) rises. Specifically, there is a proportional increase in the overall cost of 40.3% for small instances and 31.4% for large instances. Remarkably, while the costs for travelled kilometres remain relatively constant, waiting costs almost triple, and delay costs double as the degree of dynamism increases. Consequently, the proportion of kilometre costs to total cost decreases accordingly.

The impact of cluster size is less straightforward, particularly evident in small instances with 25% and 50% dynamism. In those cases, small clusters lead to a slight cost increase compared to larger clusters (2.0% and 1.3%, respectively), especially in delay costs. However, in small instances with 75% dynamism, small clusters decrease cost by 0.7%. In contrast, the impact of cluster size is more definitive in large instances. Larger clusters lead to a substantial rise in total cost by an average of 4.3%. While the costs for travelled kilometres may slightly increase, delay costs see a significant uptick (average of 8.3%), especially in instances with a high degree of dynamism. This tendency can be attributed to the congestion caused by the simultaneous arrival of numerous commodities, which poses challenges in their distribution. In the real world, this is a particular challenge for smaller road hauliers with limited vehicle capacity that cannot be quickly augmented.

7.6.2 Parameter variation experiments

In five parameter variation experiments, we investigate how intermodal rail transport can become more attractive in order to achieve a significant shift of orders from road to rail. Our instance generation procedure and the underlying data enable us to draw conclusions representative of a real-world setting as the case study analyses three highly frequented intermodal road-rail relations in Central Europe. The results not only provide managerial insights for intermodal actors, but can also be an estimate for politics when assessing the potential for this modal shift.

We conduct our analyses by modifying delay costs, waiting costs, number of available vehicles, length of the time windows, and severity of train delays in combination with different quality levels for the ETA forecast. A detailed description of the varied parameters and levels can be seen in Table 25. The different quality levels for the ETA forecast and the varying severity of train delays are considered in combination in order to assess the mutual dependencies. The other parameter variations are considered independently from one another to reduce computational effort and allow for clarity in the analysis. We use the same instance generation procedure and characteristics described in Section 7.5 but use different seed values.

Table 25: Parameter and levels.

Experiment	Parameter	Levels	Steps
1	Train delay (Mean and Variance) Accuracy of ETA	9	Low, Medium, High Low, Medium, High
2	Waiting cost	5	0.5 €/min, 1 €/min, 1.5 €/min, 2 €/min, 2.5 €/min
3	Delay cost	5	0.5 €/min, 1 €/min, 1.5 €/min, 2 €/min, 2.5 €/min
4	Number of vehicles	5	3/5, 4/6, 5/7, 6/8, no limit
5	Time Window length	6	0.75, 1.0, 1.25, 1.5, 1.75, 2.0

ETA & Train

Table 26: Results for varying train punctuality and ETA forecast quality

Train Delay	ETA Acc.	Cost	Cost KM		Cost Wait		Cost Late		Routes	Dyn. Mod.	Com. Wait	Com. Late
High (Avg 465 min)	Low	94,031	32,776	37.6%	2,495	2.6%	58,759	59.8%	115.1	6.8	31.1	94.9
	Med	93,000	32,671	37.9%	2,072	2.1%	58,256	60.0%	112.5	2.8	29.1	94.0
	High	92,216	32,652	38.2%	1,616	1.7%	57,947	60.2%	112.3	1.3	24.7	94.1
	Avg	93,082	32,699	37.9%	2,061	2.1%	58,321	60.0%	113.3	3.6	28.3	94.3
Med (Avg 235 min)	Low	62,246	32,475	54.7%	2,241	3.5%	27,529	41.9%	112.6	5.6	33.2	85.2
	Med	60,276	32,309	55.8%	1,543	2.5%	26,423	41.7%	109.1	1.9	31.9	84.3
	High	59,414	32,269	56.5%	1,102	1.8%	26,041	41.8%	108.7	0.6	27.2	84.3
	Avg	60,645	32,351	55.6%	1,629	2.6%	26,664	41.8%	110.1	2.7	30.8	84.6
Low (Avg 84 min)	Low	47,683	31,895	69.1%	1,912	3.9%	13,875	27.0%	111.3	3.3	29.7	70.9
	Med	46,153	31,793	70.8%	1,114	2.5%	13,245	26.7%	108.7	1.3	28.0	69.2
	High	45,443	31,692	71.6%	921	2.1%	12,829	26.4%	107.7	0.6	25.3	68.9
	Avg	46,427	31,793	70.5%	1,316	2.8%	13,317	26.7%	109.3	1.7	27.6	69.6

In this section, we explore variations in both the punctuality of trains and the quality of ETA forecasts. We have decided to analyze these two parameters in combination as we suspect they are strongly interrelated.
The punctuality of the train is varied by manipulating the underlying triangular distribution, with adjustments made to the mean speed and spread of the minimal and maximal speed to simulate different travel behaviours with varying degrees of punctuality. The quality of the ETA forecast is modelled by varying the error term σb, reflecting forecast accuracy, with $b \in \{0, 1, 2\}$.

The average delay of the observed trains, from the least punctual to most punctual category, is 465 minutes, 235 minutes, and 84 minutes, respectively. This is reflected in the total cost, which amount to €93,082 for least punctual trains, €60,645 for moderately punctual trains, and €46,427 for most punctual trains (Table 26). The analysis reveals a clear correlation between train punctuality and total cost, with less punctual trains incurring higher costs. While costs for travelled kilometres remain relatively constant, they exhibit a slight decrease of 2.8% as trains become more punctual. This trend suggests that more tours are needed to compensate for delayed trains, as evidenced by the increased number of required routes from 109.3 to 113.3. Moreover, waiting costs experience a substantial reduction of 36.1% as trains become more punctual. However, their proportion of total cost increases, indicating a higher relative impact on overall expenses. Unsurprisingly, delay costs undergo the most significant change, decreasing by approximately 77.2% and their proportion of total cost shifts accordingly. As trains become more punctual, the number of dynamic route modifications decreases due to increased predictability, leading to less frequent adjustments in plans.

In general, ETA forecasts significantly reduce overall cost, as can be seen in the comparison of the different strategies conducted in Section 7.6.1. If we compare the blind strategy, in which the tours are only planned and executed when the trains arrive at the terminal, with the Batch 60 strategy, in which tours are planned every 60 minutes based on ETA forecasts and tours can start before the train arrives, we can see a reduction in total cost of 7.0%. This reduction can be described as the value of ETA forecasts in general. We now focus on the impact of the different degrees of accuracy of the ETA forecasts, which we perform on the separate delay levels of the trains. Regardless of train punctuality, accurate ETA forecasts consistently result in significant improvements compared to inaccurate forecasts, averaging €2,295 in cost savings. On all delay levels, more accurate ETA forecasts not only lead to slight savings in kilometre costs, but also result in substantial reductions in waiting costs and delay costs. Particularly striking is the relative saving of 45.9% in waiting costs, accompanied by a decrease of 17.8% in the number of commodities incurring waiting costs. For severely delayed trains, the reduction even reaches 20.6%. Conversely, the number of commodities incurring delay costs remains relatively stable. Overall, accurate ETA forecasts enable a reduction in the number of routes needed to deliver commodities across all levels of train punctuality by 3.4 saved routes on average. This reduction is facilitated by increased predictability, as evidenced by the decrease in the number of modifications needed for initiated routes by 84.4%.

If we take a closer look at the different delay levels, we notice that the relative cost savings vary. When trains are punctual, high-quality ETA forecasts lead to a saving of 4.7%. However, if the trains are very delayed, the absolute savings are equally high, but the relative savings only amount to 1.9%. We interpret this as an indicator that although ETA forecasts can help to improve tour planning in the PPH, the haulier's room for manoeuvre to use them effectively is limited. The largest cost blocks of PPH are either fairly fixed (costs for kilometres driven) or cannot be influenced (delay costs caused by late trains). However, the haulier can use ETA forecasts to reduce the waiting costs incurred. Of the average savings (€2,295) due to more accurate ETA forecasts, 43.7% (€1,003) are attributable to savings in waiting costs. Accordingly, we will analyse the impact of waiting costs in more detail in the next section.

Waiting Costs

Table 27: Results for varying waiting costs

Wait Cost	Cost	Cost KM		Cost Wait		Cost Late		Routes	Dyn. Mod.	Com. Late	Com. Wait	Share of Wait Com.	Avg Wait
2.5	61,031	32,587	55.5%	1,279	2.0%	27,164	42.4%	113.9	3.2	85.5	17.8	8.7%	28.8
2.0	60,692	32,539	55.7%	1,284	2.1%	26,868	42.2%	113.1	2.7	84.5	20.8	10.2%	32.0
1.5	60,472	32,434	55.8%	1,415	2.3%	26,623	42.0%	111.2	2.6	84.8	25.2	12.4%	36.9
1.0	60,276	32,309	55.8%	1,543	2.5%	26,423	41.7%	109.1	1.9	84.3	31.9	15.7%	48.6
0.5	60,076	32,086	55.7%	1,594	2.6%	26,396	41.7%	105.8	1.5	84.2	42.9	21.2%	74.3
Avg	60,379	32,342	55.8%	1,459	2.4%	26,577	41.9%	109.8	2.0	84.5	30.2	14.9%	48.0

When waiting costs vary between 2.5€/min and 0.5€/min, the overall total cost decrease only slightly by 1.6%, which is not entirely surprising given the low proportion of waiting costs of 2.4% of the total cost (Table 27).

The trend in costs incurred for waiting is intriguing. Despite a decrease in costs per minute waited, total waiting costs increase from €1,279 to €1,594. Conversely, there are slight decreases in both delay costs and costs for travelled kilometres. A closer look at the other KPIs suggests that while waiting costs have a minimal absolute impact on costs, they strongly impact the solution structure. An indicator of this is the number of routes driven, which decreases from 113.9 to 105.8 with decreasing waiting costs. The solution becomes less reactive, as evidenced by fewer dynamic route modifications. This hypothesis is further supported by the doubling in the number of commodities waiting, suggesting a more resilient planning. The average waiting time for these commodities increases even more significantly.

Managerial insight derived from these findings suggests that despite waiting costs constituting only a small portion of total cost, road hauliers exhibit sensitivity to these costs, likely due to their implications extending beyond direct waiting expenses. Specifically, they encompass the opportunity costs associated with tours that could have been completed during idle periods, a factor not explicitly addressed in our model. Furthermore, our analysis highlights that road hauliers possess agency in actively managing waiting costs, in contrast to the other cost blocks, a key aspect for operational efficiency. This is further supported by the effect ETA forecasts have on waiting costs, as could be seen in the first experiment.

Delay Cost

Table 28: Results for varying delay cost

Cost Delay	Cost	Cost KM		Cost Wait		Cost Late		Routes	Com. Late	Share of Late Com.	Avg Delay	Com. Wait	Share of Wait Com.	Avg Wait
2.5	74,871	32,541	46.2%	2,159	2.8%	40,170	50.9%	109.7	83.9	40.3%	186.0	36.8	18.2%	58.8
2.0	66,651	32,421	51.2%	1,818	2.7%	32,413	46.1%	109.4	84.8	40.7%	186.0	34.1	16.9%	53.8
1.5	57,470	32,182	58.0%	1,414	2.4%	23,873	39.6%	108.5	84.5	40.7%	184.0	30.5	15.0%	46.1
1.0	48,944	31,894	66.7%	944	1.9%	16,106	31.4%	107.9	85.7	41.4%	183.1	24.8	12.2%	38.3
0.5	40,154	31,044	78.2%	541	1.3%	8,568	20.5%	105.2	89.8	43.7%	185.7	17.4	8.5%	31.8
Avg	57,618	32,017	60.1%	1,375	2.2%	24,226	37.7%	108.1	85.7	41.4%	184.9	28.7	14.2%	45.7

With varying costs per delayed minute, we can observe highly dynamic behaviour that impacts several aspects (Table 28). The total costs decrease almost linearly with decreasing costs for delays. This trend is largely influenced by the significant impact of delay costs, which constitute an average of 37.7% of total costs. As the costs per delayed minute decrease, the total costs for delays also linearly approach zero (Figure 37).

The effects on the costs incurred for driven kilometres and waiting are of particular interest. These two cost blocks decrease in tandem with delay costs. As delay costs diminish, road hauliers become more flexible in tour planning and actively exploit this flexibility. In the hypothetical scenario where delays incur no penalties (though unrealistic given that even in the absence of monetary repercussions, reputational harm may ensue), road hauliers could optimise tours without regard for delays. The reduced costs for delays and enhanced flexibility lead to a decrease in routes from 109.7 to 105.2 and a rise in the delayed commodities from 83.9 to 89.8. In line with the observations of the first two experiments, the road haulier uses this room for manoeuvre to influence the incurred waiting costs. With diminishing costs for delays, the share of commodities that have to wait and the average waiting time decrease as well.

Managerial insights derived from this analysis suggest that flexibility or tolerance towards delays in PPH operations helps to make operations cost-effective and efficient for road hauliers. However, without incentives for punctuality, road hauliers may exploit this flexibility. Therefore, in negotiating the conditions for the PPH, road hauliers should prioritise the minimisation of penalties or costs associated with delays.

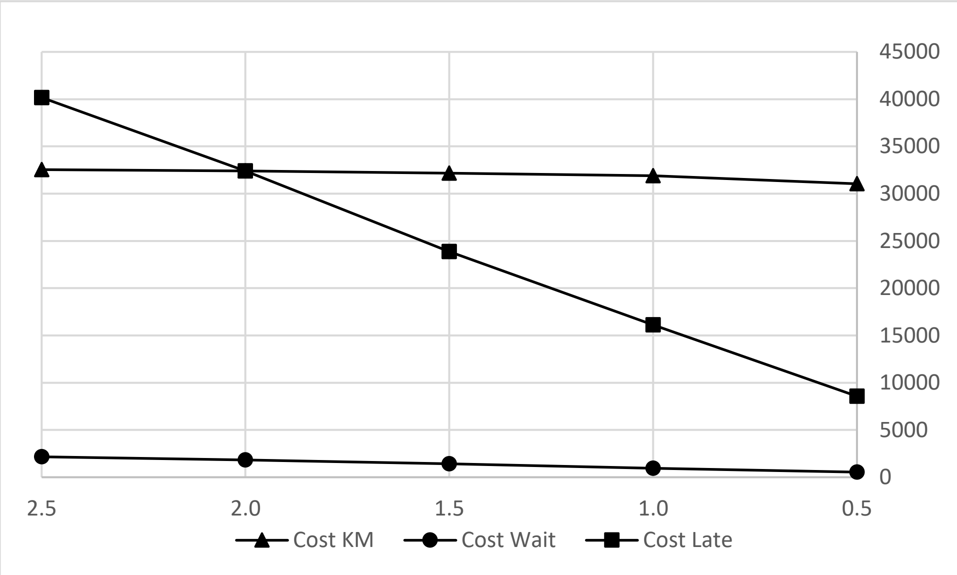


Figure 37: Trends in the individual cost types under varying delay costs

Available Vehicles

Table 29: Results for varying number of available vehicles

Vehicle	Cost	Cost KM		Cost Wait		Cost Late		Routes	Com. Late	Share of Late Com.	Avg Delay	Com. Wait	Share of Wait Com.	Avg Wait
3/5	88,796	32,444	38.7%	1,286	1.5%	55,065	59.8%	117.5	137.3	66.6%	234.6	24.9	12.3%	52.5
4/6	67,497	32,398	50.6%	1,443	2.2%	33,655	47.3%	112.3	102.2	48.8%	192.8	29.5	14.6%	49.7
5/7	60,276	32,309	55.8%	1,543	2.5%	26,423	41.7%	109.1	84.3	40.5%	185.0	31.9	15.7%	48.6
6/8	58,271	32,298	57.4%	1,605	2.7%	24,366	39.9%	107.9	77.4	37.5%	185.9	32.9	16.2%	49.1
No Limit	57,305	32,255	58.0%	1,595	2.7%	23,454	39.3%	107.2	73.5	36.0%	188.5	33.9	16.6%	46.9
Avg	66,429	32,341	52.1%	1,495	2.3%	32,592	45.6%	110.8	95.0	45.9%	197.3	30.6	15.1%	49.4

By increasing the number of vehicles, the total cost decrease, but not linearly (Table 29). There is a big jump in cost savings after increasing the number of vehicles from 3/5 to 4/6, indicating a minimum number of vehicles required to conduct the PPH properly. After 6/8 vehicles, there is no further significant decrease (Figure 38).

The costs for driven kilometres remains constant, as the distance to be driven remains the same but is distributed among more vehicles. Conversely, the number of travelled routes decreases significantly from 117.5 to 107.2. The increase in vehicles reduces the pressure to drive many short routes and allows more commodities to be loaded in one route. Surprisingly, waiting costs increase slightly. This indicates that with more vehicles, more risk-averse or resilient planning can be conducted, which may result in arriving a few minutes early. This is also reflected in the number of commodities that need to wait, which increases from 24.9 to 33.9, although the average waiting time decreases. Delay costs decrease as well, but there is a limit. If the trains are delayed, no compensation is possible by adding more vehicles.

From a managerial perspective, small haulage companies are particularly challenged by delays in the main haulage. Few vehicles promote a strongly reactive approach and hinder resilient planning. However, even large haulage companies with a large fleet (and purchasing capacity on the spot market) face challenges because not all delays in the main haulage can be offset. Nevertheless, a larger fleet enables resilient planning, which overall leads to cost reduction even when waiting costs increase.

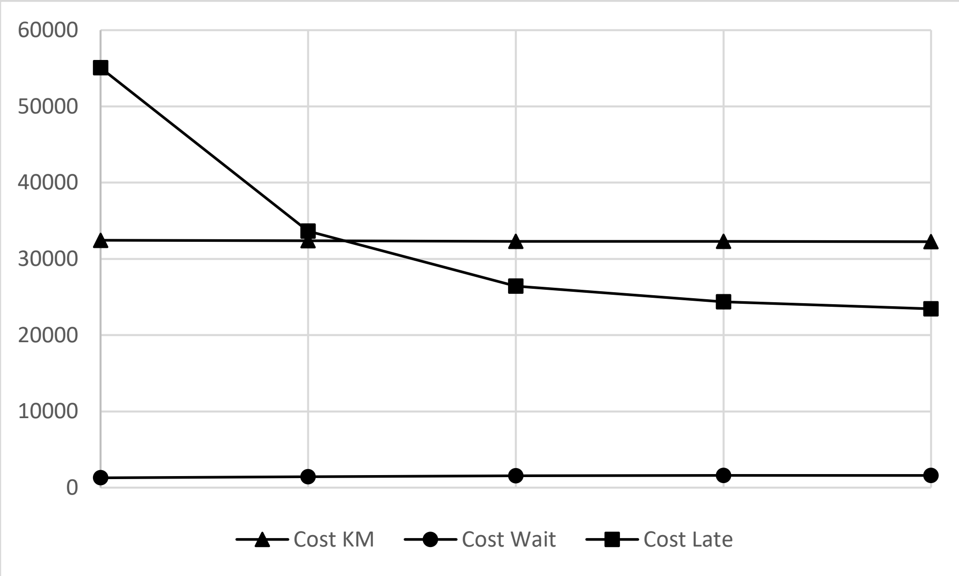


Figure 38: Trends in the individual cost types under varying number of vehicles

Time Window Length

Table 30: Results for varying time window length

TW Length	Cost	Cost KM		Cost Wait		Cost Late		Routes	Com. Late	Share of Late Com.	Avg Delay	Com. Wait	Share of Wait Com.	Avg Wait
0.75	66,342	32,544	51.4%	1,670	2.5%	32,127	46.1%	114.2	95.5	45.9%	198.0	35.1	17.4%	46.7
1	60,276	32,309	55.8%	1,543	2.5%	26,423	41.7%	109.1	84.3	40.5%	185.0	31.9	15.7%	48.6
1.25	55,015	32,042	60.3%	1,439	2.6%	21,533	37.2%	105.0	74.2	35.7%	170.9	28.5	14.0%	51.8
1.5	50,705	31,838	64.7%	1,298	2.5%	17,568	32.8%	102.5	66.3	31.8%	156.2	25.9	12.8%	50.5
1.75	46,984	31,644	68.9%	1,137	2.4%	14,202	28.7%	100.3	57.8	27.8%	145.0	22.3	10.9%	52.0
2	43,941	31,471	73.1%	1,020	2.3%	11,449	24.7%	98.4	49.6	23.7%	137.1	19.5	9.5%	52.4
Avg	53,877	31,975	62.3%	1,351	2.5%	20,550	35.2%	104.9	71.3	34.2%	165.3	27.2	13.4%	50.3

We vary the time window length by scaling the original time windows. Longer time windows help reduce all costs, with delay costs benefiting the most, decreasing by two thirds (Table 30, Figure 39). Waiting costs also decrease by one third. Longer time windows allow for more efficient tours, resulting in a reduction in the number of required tours from 114.2 to 98.4. Similarly, the number of commodities experiencing delay or waiting decreases, although the average waiting time increases slightly. From a managerial perspective, longer time windows facilitate flexibility and lower costs in PPH operations.

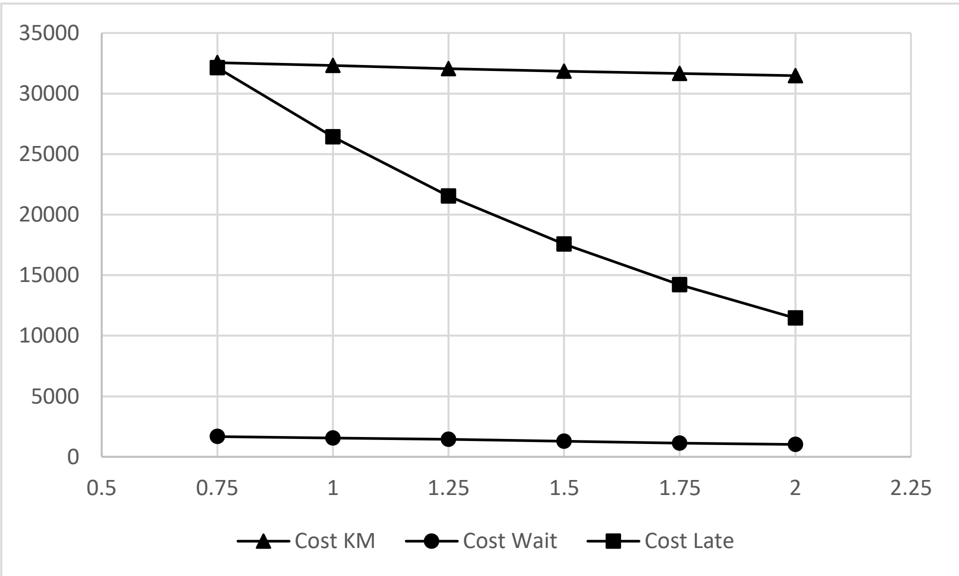


Figure 39: Trends in the individual cost types under varying time window lengths

7.7 Discussion and policy implications

Exploring the integration of dynamic and stochastic ETA forecasts into the PPH of intermodal transport unveils promising insights into operational efficiency. Our analysis indicates a potential cost reduction of around 7% on average when incorporating ETA forecasts into routing decisions. Interestingly, even basic forecasts prove beneficial, but higher-quality predictions yield superior planning outcomes, reducing the need for frequent adjustments. Of notable significance is the substantial reduction in waiting costs facilitated by accurate ETAs. While waiting costs constitute a minor fraction of total expenses, they hold significant sway over solution structures, allowing road hauliers greater planning flexibility. However, it is worth noting that tours that could have been conducted during waiting periods are only considered indirectly in this model.

While lower cost rates for delays or kilometres bring considerable operational savings, they remain challenging to influence due to the composition of fixed expenses such as salaries and amortisation. Negotiations could potentially lead to a more favourable delay cost rate, fostering more efficient route planning and leading to reductions in both waiting and kilometre costs.

Regarding the cluster size, we can observe that larger clusters lead to higher cost. This stems from two primary factors. Firstly, larger clusters necessitate waiting and subsequent delays when more commodities arrive simultaneously than available vehicles, which is particularly impactful for small road hauliers with limited fleets reliant on optimal fleet utilization. Secondly, smaller clusters diffuse the risk of delays, minimizing the impact of individual train delays on multiple commodities. As a result, redistributing commodities across more trains could be a pertinent strategy for road hauliers, despite the increased planning and coordination efforts involved.

It is important to acknowledge that our results are specific to the case study we have examined. Nevertheless, this case study holds broader relevance as it mirrors many similar intermodal relations across Europe, particularly those characterized by medium transport distances and those traversing the Alps.

In light of these findings, it becomes evident that dynamic ETA forecasts hold significant potential to reshape intermodal transport operations, offering avenues for cost optimization and enhanced efficiency. Therefore, we have derived several actionable policy measures that could further strengthen the integration of dynamic ETA forecasts within intermodal transport systems.

Standardization and Collaboration: Establishing industry-wide standards for dynamic ETA forecasting systems and fostering stakeholder collaboration could improve data sharing and interoperability. This would ensure that different players in the intermodal transport chain can effectively communicate and coordinate based on accurate and reliable ETA information.

Investment in Infrastructure: Infrastructure improvements, such as the development of smart transport networks and the integration of Internet of Things (IoT) devices along transport routes, could facilitate the collection and dissemination of real-time data. This would enhance the accuracy of ETA forecasts and enable more efficient management of intermodal transport operations.

Encouraging the Adoption of Dynamic ETA Forecasting Technologies: Policymakers could incentivize the adoption of advanced dynamic ETA forecasting technologies by providing subsidies or grants to logistics companies. This would promote the use of real-time data and analytics to enhance route planning and optimize resource allocation.

Training and Education: Providing training programs and educational initiatives for logistics professionals on the use of dynamic ETA forecasting tools and techniques could enhance their skills and competencies. This would empower them to leverage these technologies effectively to optimize routing decisions and mitigate the impact of delays in intermodal transport.

Policy Support for Research and Development: Policymakers could allocate funding for research and development initiatives aimed at advancing the capabilities of dynamic ETA forecasting systems. This could involve collaboration between academia, industry, and government agencies to develop innovative solutions for enhancing the reliability and accuracy of ETA predictions.

7.8 Conclusion and further research

In this paper, we analyse the impact of clustered dynamic and stochastic ETA forecasts on the PPH of the intermodal transport chain. We model the processes in the PPH and the trains transporting the commodities as a simulation incorporating a dynamic and stochastic Pick-up and Delivery Problem with Time Windows and clustered release dates. Commodities must be transported to the intermodal terminal from the surrounding area or arrive by train at the intermodal terminal and be transported to customers throughout the planning horizon. These commodities arriving by train have known delivery locations, but the actual arrival times are uncertain. A dynamic and stochastic ETA forecast announces the arrival of a train at the terminal. However, these forecasts are inherently inaccurate and have varying degrees of accuracy at different times. In principle, the quality of this forecast increases the closer the train is to the depot. As a train transports many commodities, this results in clustered release dates of these commodities.

To solve this dynamic and stochastic optimisation problem, we propose a simheuristic solution procedure that combines simulation and heuristic-based components. With a biased randomised savings algorithm we generate solutions for the PDPTW-crd. These solutions are then evaluated in a Monte Carlo sampling to account for the stochastic nature of the problem. We extend this solution procedure with a rolling horizon framework to cope with the real-time aspect of the problem and introduce five different solution strategies.

We propose a realistic case study in Central Europe based on real-world data, including one intermodal terminal and three major intermodal relations. Our results demonstrate that the value of dynamic ETA forecasts is high because re-optimisation, based on updated information, can significantly reduce overall costs compared to a static planning approach. Moreover, the Batch 60 strategy emerges as the most practical approach, striking a delicate balance between utilising real-time information and re-optimising. In a parameter variation experiment, we analyse which measures could be taken to increase the attractiveness of intermodal rail transport. By varying central parameters such as waiting and delay costs, the number of available vehicles, length of the time windows, and different quality levels for the ETA forecast und varying severance of train delay, we are able to gain managerial insights and derive policy implications.

We conclude by taking up the RQs posed in Section 7.1 and briefly summarising the answers. First, our goal is to determine how clustered dynamic and stochastic ETA forecasts impact the PPH of the intermodal transport chain. We find that ETA forecasts lead to an average cost reduction of 7% compared to situations where no ETA forecasts are used. Therefore, even basic quality forecasts prove beneficial, but higher-quality predictions yield superior planning outcomes, reduce the number of tours that have to be driven, lower the need for frequent adjustments of the tours, and generally decrease wait and delay time.

Building on this, we develop managerial insights for decision-makers in intermodal transport. A deeper analysis of the cost structure reveals that while waiting costs constitute a minor fraction of total expenses, they hold significant sway over solution structures, allowing road hauliers greater planning flexibility. While costs for kilometres driven or delays make up most of the total expenses, they are challenging to influence due to their composition of fixed expenses such as salaries and amortisation. Negotiations could potentially lead to a more favourable delay cost rate or longer time windows for delivery and pick-up, fostering more efficient route planning and leading to reductions in both waiting and kilometre costs as well.

Finally, we formulated several practical policy recommendations to enhance the seamless integration of ETA forecasts within intermodal transport systems. With industry-wide standards for dynamic ETA forecasting systems and infrastructure improvements, such as the development of smart transport networks and the integration of Internet of Things (IoT) devices along transport routes, data collection, the calculation of ETA forecasts and communication and coordination could be improved. Incentives through subsidies or grants could improve the adaption of ETA forecasts further. Last but not least, training and education of professionals and policy support for research and development could enhance skill in usage and improve acceptance of ETA forecasts.

There are several avenues for extending this research. Firstly, enhancing the modelling of the PPH could involve incorporating the transport of commodities between customers in the vicinity of the intermodal terminal, in addition to transporting them to and from the terminal. Moreover, instead of deterministic travel times on road arcs, stochastic travel times could be considered to represent delays and congestion realistically. Furthermore, conducting additional case studies on relations with diverse characteristics, such as maritime hinterland transport, could offer further insights into the efficacy of dynamic ETA forecasts. Additionally, the need to investigate the quality of the forecast itself should be pursued as better ETA forecasts have been shown to yield improved outcomes. Lastly, in terms of methodology, exploring the transfer of exact algorithms for the PDP to the PDPTW-crd and evaluating them against the presented simheuristic solution procedure could provide valuable insights.

8 Study 5: Synchromodal transportation – The future of intermodal transportation?[7]

Synchromodal transportation (SMT) is a novel multimodal transportation concept. It builds on a collaboration of shippers and logistic service providers to enable real-time switching between transportation modes and mode-free transportation bookings, enabling more flexible and sustainable freight transportation. This paper summarizes the current state of research since 2010 by means of a systematic literature review. A comprehensive taxonomy consisting of five dimensions and 13 categories for both qualitative and quantitative papers is developed. The results reveal a mixed picture, with high consistency in geographical areas of synchromodal transportation implementation and suitable modeling of operational disruptions and uncertainties. However, compared to multimodal or road transportation, there is little alignment in the forms of collaboration, network organization, or the advantages of synchromodal transportation. Finally, the main fields for future research are identified, namely business, legal, technological, modeling, and awareness.

8.1 Introduction

The EU freight transportation industry is responsible for 25.8% of the total GHG emissions, a major factor driving climate change (Eurostat - Statistics Explained, 2021). Existing multimodal freight transportation concepts have not been able to counteract the radical ecological changes. Inland freight modal split within the EU consisting of 77.4% road freight in 2020 shows that neither the goal of a substantial modal shift nor comprehensive decarbonization of the transportation sector was advanced in recent years (Eurostat - Statistics Explained, 2022).

Promoted by the European Commission, SMT is a new, promising freight transportation concept. It originated in 2010 in the Netherlands (Tavasszy et al., 2010). The revolutionary concept changes the process and organizational forms of existing multimodal freight transportation concepts. It can be defined as the "synchronization of physical resources, business processes, and the parallel use of transportation modes in a mode-free way to offer shippers a more flexible and sustainable means of freight transportation." (Agbo et al., 2017). In this context, synchromodal transportation can be seen as a further development of

[7] The content of this study is similar with only slight modifications to the paper Rentschler, J.; Elbert, R.; Weber, F. Promoting Sustainability through Synchromodal Transportation: A Systematic Literature Review and Future Fields of Research. Sustainability 2022, 14, 13269. https://doi.org/10.3390/su142013269. Thus, in section the pronoun “we” refers to the authors of the paper.

intermodal transportation concepts, in which the actors in the transportation chain actively work together in a cooperative network in order to plan transportation processes flexibly and to be able to switch between transportation modes in real-time according to the available resources (Pfoser et al., 2016; SteadieSeifi et al., 2014).

SMT has the potential to increase the attractiveness of more sustainable transportation modalities and thus significantly improve the modal shift. Cost and resource efficiency, as well as reliability and resilience of transports, are guaranteed by unprecedented transparency of freight transportation, intensive connectivity of infrastructure, and an in-depth collaboration of all actors involved. However, there is no single universal understanding of SMT. Substantially contrasting emphases are detected in various definitions such as the one by Ambra et al. (2019b): " Structured, efficient and synchronized combination of two or more transportation modes." or Acero et al. (2022): "A multimodal transportation planning system, wherein the different agents involved in the supply chain work in an integrated and flexible way that enables them to dynamically adapt the transportation mode they use based on real-time information from stakeholders, customers, and the logistic network."

As SMT entails profound operational, technical, and business changes, this paper aims to bundle and align existing research approaches. Therefore, a systematic literature review (SLR) is conducted. A conceptual elaboration of SMT is developed, which distinguishes it from previous transportation concepts. Synergies within research on SMT are explored to establish a well-founded and exhaustive overview of the topic. Furthermore, this paper extends the current body of literature. While Acero et al. (2022) elaborate on the innovative factors of SMT, they focus on integrating SMT into the supply chain. The SLR presented by Delbart et al. (2021) examines intermodal and synchromodal transportation problems but lacks a paper categorization tailored to the innovative features of SMT and their mathematical representation. The SLR conducted by Pfoser et al. (2021), which examines antecedents, mechanisms, and effects of SMT, is most similar to this paper. However, their paper focuses solely on the qualitative properties of SMT, disregarding quantitative research, without establishing an individualized taxonomy for qualitative and quantitative papers.

Therefore, there is still a significant research gap in terms of understanding synchromodality holistically, developing a taxonomy to bundle all relevant qualitative and quantitative literature on synchromodal freight transportation, comparing the two types of analysis approaches, and identifying future trends. This gap is addressed by answering the RQ:

What is the current state-of-the-art of synchromodal transportation?

To answer this RQ conclusively, three sub-questions arise:

1.1 What is the most relevant literature in the context of synchromodal transportation?
1.2 How can research on SMT be systematically classified, what trends can be observed, what primary research methods are used, and how do they relate and compare to each other?
1.3 Which fields for future research can be derived?

After introducing the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines and the methodology in Section 8.2, the literature is analyzed by a two-step process (Page et al., 2021). First, descriptive characteristics of the research corpus are summarized in Section 8.3.1. Thereafter, based on the division of the literature into qualitative, Section 8.3.2, and quantitative papers, Section 8.3.3, the development of a taxonomy follows, consisting of distinguishing features on novel SMT characteristics and assessment criteria, which are then clustered into dimensions and categories. The following discussion in Section 8.4 compares qualitative and quantitative research results, and fields for future research are derived. Finally, we conclude in Section 0.

8.2 Methodology

Systematic literature reviews aim to better understand a real-life phenomenon and identify and critically evaluate an existing body of knowledge in a precise, rigorous, and replicable method (Denyer and Tranfield, 2009). According to Denyer and Tranfield (2009) the four basic principles of an SLR consist of transparency, inclusivity, explanation, and heuristic. Transparency is enabled by three factors: 1. disclosing the processes and methodologies used, 2. presenting the conclusions that are derived, which have clear dependencies on the found evidence in the literature, and 3. by a reflection of the author's values towards the scientific topic to further prevent bias. Furthermore, the articles included in the review play a central but complex role. The quality of the used information sources needs to be appraised to uphold a high standard. The third principle, explanation, covers synthesizing the information into one piece of work, which goes far beyond merely combining the individual articles. Lastly, SLRs present a heuristic consisting of "rules, suggestions, guides, or prototype protocols" instead of fixed solutions to a specific problem (Denyer and Tranfield, 2009). As a result of the four principles that were formerly introduced, five straightforward steps are derived by Denyer and Tranfield (2009), guiding this SLR:

First, the research question(s) must be formulated to define the scope of the SLR.

Subsequently, the literature has to be identified in a transparent and documented manner. Based on the research questions, we aim for a holistic view of SMT and have chosen a search string that is as broad as possible. We searched the database Web of Science with the string synchromodal* OR synchro-modal* starting in 2010, the first time synchromodality was mentioned. The broad search led to 83 articles.

To assess the importance of each article, we set up distinct selection criteria:

- The article is written in English
- Articles have to be peer-reviewed, and if published in a journal, the journal has to be ranked Q2 or higher by the Scimago Journal & Country Rank
- Non-related papers or papers that only scarcely deal with SMT are excluded. Those papers were identified after reading the title and abstract
- Conference papers were excluded if they were adopted into journal publications or had no documented methodological approach

After applying the selection criteria, 56 papers remained. An upstream and downstream search of the citations yielded another six papers. The procedure is summarized in the PRISMA flowchart (Figure 40). Qualitative content analysis sets the framework for analyzing the corpus on synchromodal transportation (Mayring, 2015). Thereby two different techniques can be considered: the deductive and the inductive approach. A deductive approach determines the assessment categories before reviewing each paper. In contrast to the deductive approach, categories are flexibly added during the data evaluating procedure in an inductive approach (Seuring and Gold, 2012). Although this procedure yields the need for iterative readings, the inductive approach is chosen due to the novel concept of synchromodal transportation and the lack of knowledge of well-fitting dimensions and categories. Based on the ontological and epistemological idiosyncrasies of SCM and logistics management research and the six idiosyncrasies (theoretical boundaries, unit of analysis, sources of data, study context, definitions and the operationalization of constructs, research methods), as identified by Durach et al. (2017), we code and synthesize the literature and develop a taxonomy.

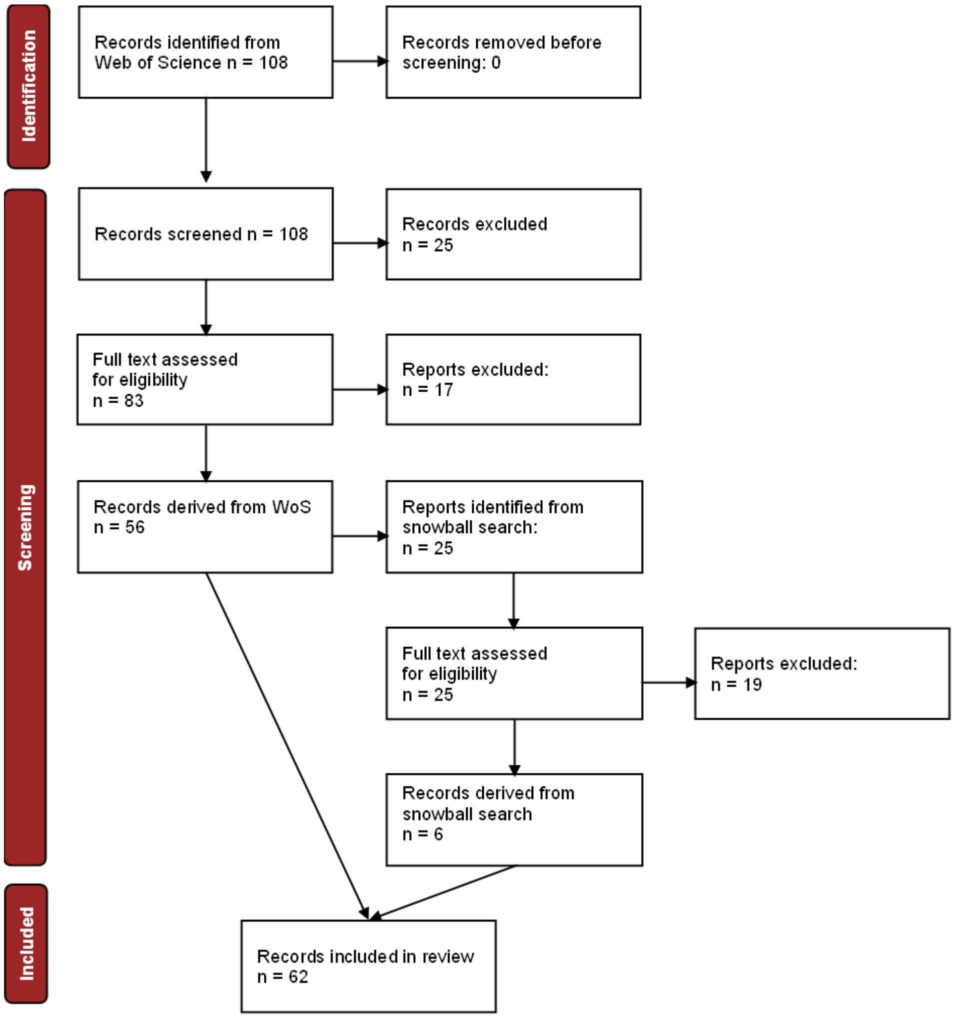


Figure 40: Procedure of SLR according to the PRISMA flowchart

8.3 Results

To evaluate the corpus of 62 papers, we cluster the content and conduct extensive analysis, resulting in a sequential process. At first, a distinction is drawn between descriptive and content-based analysis. Henceforth, the content-based analysis is performed by distinguishing between qualitative and quantitative papers.

8.3.1 Descriptive results

Although already introduced in 2010, the first papers on SMT were published in 2014 (Figure 41). It becomes apparent that the research on SMT started with a qualitative approach, and in subsequent years, papers with a quantitative focus picked up. As synchromodality is a concept coming from the Netherlands, it is no surprise that most research, totaling 35 publications, is located there. The remaining publications are spread worldwide in 15 countries, focusing on Europe.

Figure 41: Publications on synchromodality per year

As displayed in Figure 42, 20% of the authors were involved in around 50% of the publications on synchromodality. Therefore, although a linear relationship between authors and published papers is not observed, there is no Pareto distribution between authors and published papers. This is a good condition to counter mind bias (Kitchenham and Charters, 2007). Nevertheless, two authors (R. Tadei and B. Atasoy) contributed to more than five papers, and R. R. Negenborn to 16 papers, all focusing on quantitative research. Hence, 28 authors (21%) are engaged in publishing more than one paper. This does not necessarily speak for inconsistency in research, as the research is mainly driven by three universities (Research Group Logistics at Hasselt University, Belgium; Department of Maritime and Transport Technology & Center for Systems and Control both Delft University of Technology, Netherlands; Politecnico di Turino, Italy). We suspect that many Ph.D. students are involved in the research, which increases the number of authors with only one publication on SMT.

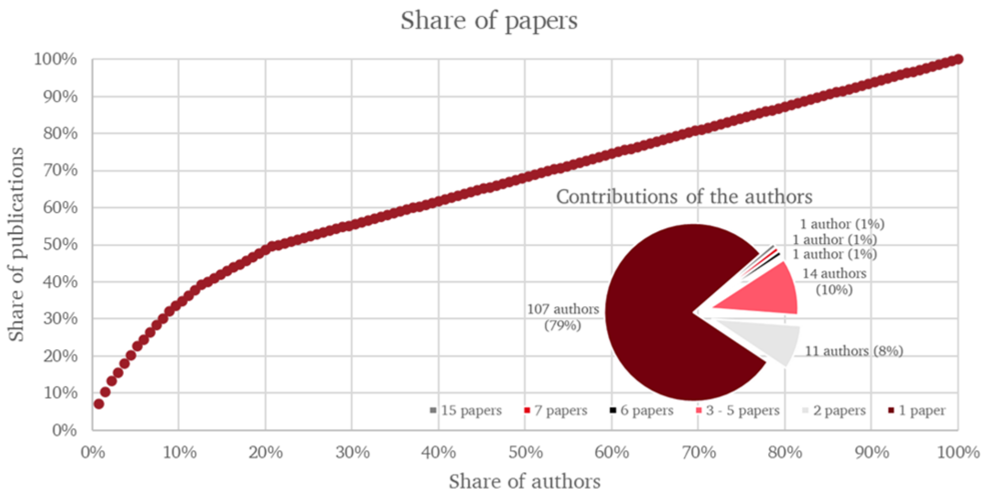


Figure 42: Paper to author and author to paper ratio

8.3.2 Results of the qualitative papers

In the following, we analyze qualitative papers in a twofold way. Firstly, Six distinguishing features, based on the six idiosyncrasies as identified by Durach et al. (2017), are introduced, comparing reoccurring topics within the qualitative literature corpus. After that, the qualitative literature is divided into two dimensions and four categories based on the distinguishing features (Table 31). Hence, a taxonomy of the synchromodal transportation literature is accomplished.

Table 31: Distinguishing features and taxonomy of qualitative papers

Distinguishing features	Dimension	Category
▪ Topic and methodology ▪ Stakeholder focus ▪ Development of synchromodality ▪ SMT application fields ▪ Network organization ▪ Comparative benefits of synchromodality	1. Explanatory research on synchromodality	1. Synchromodality theory refinement 2. Literature reviews on SMT problem modeling
	2. Contextualizing research on synchromodality	3. Case study on SMT implementation 4. SMT implementation linked to further research topics

8.3.2.1 Distinguishing features

Six distinguishing features of synchromodality were identified. Each paper's main topic and methodology are broken down into the feature topic and methodology, giving the reader a chance to gain an overview of the paper's findings. As SMT causes disruptive changes in the overall transportation organization and execution, the topics of the studied papers are equally broad. The main methodology used is a literature review (Ambra et al., 2019b; Tavasszy et al., 2017), often conducted systematically (Ambra et al., 2019b; Delbart et al., 2021). The second most used methodology is case studies, applied to the analysis of existing SMT implementation projects (Alons-Hoen et al., 2019; Brümmerstedt et al., 2017), on potential fields of SMT implementation (Agbo et al., 2017; Tsertou et al., 2016), or demonstrators and simulation games (Buiel et al., 2015; Kurapati et al., 2018).

The second feature, Stakeholder focus, assesses which stakeholders are most emphasized. Although authors agree that SMT impacts all existing stakeholders along the transportation chain (Giusti et al., 2019b), some papers highlight certain operators more than others or dedicate their research to one specific stakeholder.

The feature Development of synchromodality analyses aspects in need of expansion, such as technical, operational, or business. Mostly, authors use conceptual approaches to distinguish synchromodality from previous transportation concepts (Reis, 2015; Tavasszy et al., 2017) and extract their key elements (Acero et al., 2022; Pfoser et al., 2021). One of the few papers focusing on the business perspective of synchromodality is Perboli et al. (2017), which highlights the need for a commercially sustainable solution for all stakeholders involved.

The application of synchromodal theory to case studies, real-world implementations, and research projects is captured by SMT application fields. Due to the conceptual-descriptive or mathematical nature of many papers and the small number of SMT projects in the real world, more than 50% of the reviewed papers lack an application of their research to a practical study (Pfoser et al., 2021).

How the transportation corridors can be organized so that the concept of synchromodality and its benefits are realized, and the requirements of all involved stakeholders are taken care of is considered by the feature Network organization. While analyzing SMT, Tavasszy et al. (2017) suppose that SMT is not the sum of a single origin-to-destination transportation but rather an integrated way of transportation and, therefore, needs to be organized from a network perspective. Furthermore, a prerequisite for a functioning SMT network is the intensive exchange and cross-company integration of sensitive data to create a seamless flow of information along the entire transportation chain (Acero et al., 2022; Pfoser et al., 2021). Therefore, collaboration and trust are crucial in vertical relationships and significantly more important in horizontal cooperation (Agbo et al., 2017; Alons-Hoen et al., 2019; Kurapati et al., 2018).

The last feature, Comparative benefits of synchromodality, summarizes the various envisioned advantages of SMT and clusters these into the four facets: planning and execution flexibility, cost- and resource efficiency, sustainability, and transparency.

8.3.2.2 Taxonomy of qualitative papers

A taxonomy comprising two dimensions and five categories is developed to structure the qualitative papers. The first dimension of Explanatory research on synchromodality tends to be more conceptual and introductory and shows a higher illustrative character. This dimension is split into two categories: Synchromodality theory refinement and Literature reviews on synchromodal transportation problem modeling.

With a higher practical reference, the second dimension, Contextualizing research on synchromodality, covers papers that frame SMT in a more implementation-oriented way. Three further categories that differ in their focus were disclosed. Case studies on synchromodal transportation implementation comprise companies involved in the logistics context and the resources and tools that are already in place or needed for SMT implementation. Synchromodal transportation is linked to further research topics that examine the interconnection of the development of synchromodality in literature. Experimental learning about SMT explores the opportunities of serious simulation gaming.

Table 32: Taxonomy of 1. qualitative dimension: Explanatory research on SMT

1. Dimension: Explanatory research on synchromodality

Author	Topic Focus	Method-ology *	Stakeholder Focus *	Development of SMT	Application	Network Organization	Comparative Benefits of SMT
Category 1: Synchromodality theory refinement							
(Acero et al., 2022)	Conceptual SMT definition and empirical validation	SLR, I, FG, S	D2D	Conceptual, Verification & Validation	N/A	Using tools from SYNCHRO-NET or IDS company	Flexibility, Efficiency, Sustainability, Transparency
(Pfoser et al., 2021)	Prerequisites and distinguishing factors of SMT	SLR	Shipper, D2D, legal entity	Conceptual	N/A	Neutral network orchestrator	Flexibility, Efficiency, Sustainability, Transparency
(Giusti et al., 2019b)	SMT network organizer and technology to enable SMT	LR	Shipper, TSP, D2D, IM	Conceptual	Rotterdam, CS:SYNCHRONET	5 party logistics provider	Flexibility, Efficiency, Sustainability, Transparency
(Pfoser et al., 2016)	Critical success factors of SMT	LR, CSF, I	Shipper, TSP, D2D, IM, legal entity	Conceptual, Verification & Validation	N/A	Not explicitly mentioned	Flexibility, Efficiency, Sustainability, Transparency
(Tavasszy et al., 2017)	Enablers/barriers of SMT	LR	Shipper, TSP, D2D, IM, legal entity	Conceptual	N/A	Existing actors along the transportation chain or ICT platform	Flexibility, Efficiency
(Reis, 2015)	Ontology to create definitions of transportation concepts	LR	N/A	Conceptual	N/A	N/A	Flexibility, Efficiency
Category 2: Literature reviews on synchromodal transportation problem modeling							
(Delbart et al., 2021)	SMT problems dealing with uncertainty	SLR	TSP, D2D, IM	Mathematical	N/A	N/A	N/A
(Juncker et al., 2017)	SMT problem classification	LR	N/A	Mathematical	N/A	Global controller	Flexibility, Efficiency, Sustainability
(van Riessen et al., 2015a)	Methods for SMT planning in inland container networks	LR, CS	Shipper, TSP, D2D, IM	Mathematical, Conceptual	European Gateway Services, Rotterdam	Network operator	Flexibility, Efficiency, Sustainability
(SteadieSeifi et al., 2014)	Problem modeling and solution techniques	LR	Shipper, TSP, D2D, IM	Mathematical	N/A	N/A	Flexibility, Efficiency

Methodology**: LR = Literature review|I = Interview with experts|FG = Focus groups with transport logistics experts|S = Survey amongst transport logistics experts|CS = Case study|Stakeholder focus**: D2D = Door-to-door service provider|TSP = Transportation service provider|IM = Inframanager| CSF = Critical Success Factors.

Dimension 1: Explanatory research on synchromodality

Dimension 1 encompasses ten papers, of which six belong to the first category (see Table 32). Both categories include papers that, on the one side, belong to the earliest research on synchromodality (Reis, 2015; Tavasszy et al., 2017) and, on the other side, to the most recent (Acero et al., 2022; Delbart et al., 2021). In general, comparing the papers in dimension one over time, their character becomes increasingly summarizing and unifying as the literature research body they build upon extends as well.

The category Synchromodality theory refinement extracts the innovative features and their distinction from existing transportation concepts while also elaborating on characteristics, critical success factors, or barriers (Acero et al., 2022; Pfoser et al., 2021). Although literature reviews on mathematical SMT problems in the second category exhibit the analysis of quantitative papers, they are summarizing and qualitative in their nature. In addition to these methodologies, surveys and interviews can be conducted to collect data (Talpur et al., 2012) . Each of the four examined reviews focuses on different areas of mathematical transportation planning problems and covers different periods in their analysis. Analyzing mathematical SMT problems, distinguishing them from existing multimodal transportation problems, and striving to set up a framework to group different characteristics of SMT modeling problems are core topics of the latter category.

Dimension 2: Contextualizing research on SMT

Dimension 2 comprises 13 papers, of which Case studies on synchromodal transportation implementation represent the most prominent category with seven papers, followed by Synchromodal transportation linked to further research topics and Experimental learning about synchromodal transportation (see Table 33).

Moving from theory to practice, the papers in Category 3 elaborate on the possibility of implementing synchromodality and assess its degree of implementation and the necessary prerequisites. Tsertou et al. (2016) and Bol Raap et al. (2016) are similar in that they present the development of a technological tool to introduce synchromodality. The second set of papers examines how a-modal booking of shippers can be realized (Khakdaman et al., 2020) and how to establish synchromodality as a whole to a country (Agbo et al., 2017). The remaining papers cover case studies on how far SMT implementation has advanced.

The papers in category 4 connect synchromodality with two further research directions: slow steaming and physical internet. Fostering sufficient technological and managerial conditions to establish the former and accounting for the success of the latter is assumed by the implementation of SMT. A different yet promising approach to transferring the theoretical concept of synchromodality to newcomers in a tangible way is serious simulation gaming. Used by Buiel et al. (2015) and Kurapati et al. (2018), they strive to reveal the benefits of comprehensive planning freedom to Dutch logistics and transportation experts through simulation games.

Table 33: Taxonomy of 2. qualitative dimension: Contextualizing research on SMT

2. Dimension: Contextualizing research on synchromodality

Author	Topic Focus	Method-ology *	Stakeholder Focus	Development of SMT	Application	Network Organization	Comparative Benefits of SMT
Category 3: A case study on synchromodal transportation implementation							
(Khakdaman et al., 2020)	Control over transportation mode	S	Shipper, TSP, D2D	Operational, Business	N/A	LSP as orchestrator	Efficiency, Flexibility
(Alons-Hoen et al., 2019)	Degree of SMT within companies	Q, I, CS	Shipper, TSP, D2D, IM	Operational, Verification & Validation	Continental & intercontinental companies	Logistics orchestrator via control tower	Flexibility, Efficiency
(Brümmerstedt et al., 2017)	Degree of SMT at European ports	LR, FG, CS	TSP, D2D, IM	Conceptual, Operational, Technical	Rotterdam, Antwerp, Hamburg	Central institution including a central platform	Flexibility, Efficiency, Sustainability
(Agbo et al., 2017)	SMT implementation in Ghana	LR, CSF, RA, Q SWOT	Shipper, TSP, D2D, legal entity, IM	Conceptual, Operational	CS: Ghana	LSP as orchestrator + common platform as a control tower	Flexibility, Efficiency, Sustainability, Transparency
(Bol Raap et al., 2016)	Automated retrieval of real-time data	I, FG	Shipper, TSP, D2D	Operational, Technical	CS: 4PL at the Schiphol Airport	4PL using a common data platform	Flexibility, Efficiency, Transparency
(Tsertou et al., 2016)	Container consolidation	LR, CS	Shipper, TSP, D2D	Technical	CS: Piraeus, Greece	Cloud-based cooperation portal	Flexibility, Efficiency, Transparency
(Hofman, 2014)	Architecture for real time data	CS	Shipper, TSP	Operational, Technical	N/A	Control tower	N/A
Category 4: Synchromodal transportation linked to further research topics							
(Giusti et al., 2021b)	Introduction of smart steaming	LR, SWOT	TSP, D2D, IM, legal entity	Operational, Technical	N/A	LSP as orchestrator + common information platform	Flexibility, Efficiency, Sustainability
(Ambra et al., 2019b)	Correlation of SMT and PI	SLR	TSP, D2D	Operational, Technical	N/A	Multi-stakeholder platform	Flexibility, Efficiency, Sustainability
(Giusti et al., 2019a)	SYNCHRO-NET project	LR, CS: gaming	Shipper, TSP, D2D, IM	Operational, Technical, Business	SYNCHRO-NET	SYNCHRO-modal supply chain eco-NET	Flexibility. Efficiency, Sustainability, Transparency
(Perboli et al., 2017)	Business models in the field of slow steaming	LR, S, BMC, VPC	Shipper, TSP, D2D, IM	Operational, Technical Business	SYNCHRO-NET	One single platform	Flexibility, Efficiency, Sustainability, Transparency
(Kurapati et al., 2018)	Test information strategies	S, FG, CS: gaming	IM, legal entity	Operational	Gaming CS: Modal manager	IM as SMT network orchestrator	Flexibility, Efficiency, Sustainability, Transparency
(Buiel et al., 2015)	Teach SMT concept	Q, CS: gaming	Shipper, TSP, D2D	Operational	Gaming CS: Synchro-mania	Forwarder as a network orchestrator	Flexibility, Efficiency, Sustainability

***Methodology**: Q = Structured questionnaire | SWOT = Strengths, weaknesses, opportunities, threats analysis | RA = Regression analysis | BMV = Business Model Canvas | VPC = Value Proposition Canvas | CSF = Critical Success Factors | PI = Physical Internet.

8.3.3 Results of the quantitative papers

Similar to the qualitative analysis, an initial explanation and overview of the applied evaluation criteria are provided. Instead of distinguishing factors that examined whether and how certain areas of synchromodality are covered in the qualitative papers, 13 assessment criteria are applied to the quantitative papers. The reason for this slightly different approach is that the analyzed quantitative papers are mostly very distinct about certain factors and thus can be clearly assessed. Based on the detailed assessment criteria, a taxonomy comprising three dimensions and nine categories is accomplished (Table 34).

Table 34: Assessment criteria and taxonomy of quantitative papers

Assessment criteria	Dimension	Category
General criteria ▪ Overarching problem ▪ Mathematical model ▪ Solution method ▪ Planning horizon ▪ Optimization objective ▪ Information evolution and quality **Synchromodal transportation-specific criteria** ▪ System characteristics ▪ Scope of horizontal collaboration ▪ Transport service characteristics o A-modal booking of shippers o En-route mode and tour recalculation o Predefined truck routes o Predefined departure/arrival schedule	1. Shipment matching problems in synchromodal transportation	1. Deterministic problems 2. Online and stochastic problems 3. Synchromodality and intermodality comparison
	2. Synchromodal network mapping	4. Synchromodal transshipment location planning 5. Synchromodal transportation revenue management 6. Transport mode schedule and tour determination 7. Decentralized decision-making
	3. Synchromodal transportation application	8. Digital planning tools for synchromodal transportation 9. Synchromodal transportation in supply chain context

8.3.3.1 Assessment criteria

Although the SMT problems are based on classic transportation problems (Koop and Moock, 2018), their complexity far exceeds the usual problem. This is primarily due to the a-modal booking of shippers and real-time switching until shortly before, but also during, transportation execution. In two-thirds of cases, the underlying mathematical formulations are recognized as mixed integer (MIP) or integer problems (IP). Furthermore, simulation and Markov Chains are applied. Most papers deal with operational issues, thereby integrating real-time information evolution and stochastic information.

Nearly 80% of the papers apply their models to intra-continental transportation. Moreover, 29 papers refer to port hinterland transportation in their studies. The Port of Rotterdam as the source or sink for an SMT network appears especially suitable, as it opens the door for the tri-modal Rhine corridor. Besides, also the hinterland corridors from the Greece port in Piraeus to Prague (Kapetanis et al., 2016), the Shanghai container hinterland (Xu et al., 2015), and the Klaipeda seaport hinterland in Lithuania (Batarlienė and Šakalys, 2021) are subject of SMT network analysis.

The majority of 25 papers test their proposed model in a case study. However, the case studies differ significantly in size. As presented by Kapetanis et al. (2016) or Koop and Moock (2018), smaller networks more often relate to synthetic data and comprise less than ten terminals. In general, case studies on SMT with small scope must be viewed with caution since important features such as en-route real-time switching, integrated network planning, and infrastructure interconnection only develop their potential with increasing network size. On the contrary, more extensive networks cover hundreds of shipment requests, links and nodes, hundreds of services, and several dozen terminals (Guo et al., 2021b; Zhang and Pel, 2016).

Adapted from Juncker et al. (2017), the System characteristics distinguish between four model cases that differ in the SMT actors' knowledge level and the optimization perspective. In limited models, information availability and optimization are local, unlike cooperative models, where information is still only available locally, but optimization is global. A model is called selfish if, on the one hand, global information is available for each stakeholder, but on the other hand, optimization is still local. Lastly, social models assume global information and optimization. In addition, an extension of the classification is provided by further separating social models by their organizing scope.

Although global optimization requires the highest level of mutual trust among transportation operators, it was chosen by more than 69% of all papers (see Figure 43). Nineteen papers based their assumptions on a social orchestrator that, when equipped with global information, optimally organizes an entire synchromodal network, testifying to the authors' great interest in optimization approaches for entire transportation networks. Nonetheless, representing the second largest identified group, papers identified with selfish system characteristics reveal a wide range of coordination forms within synchromodal networks.

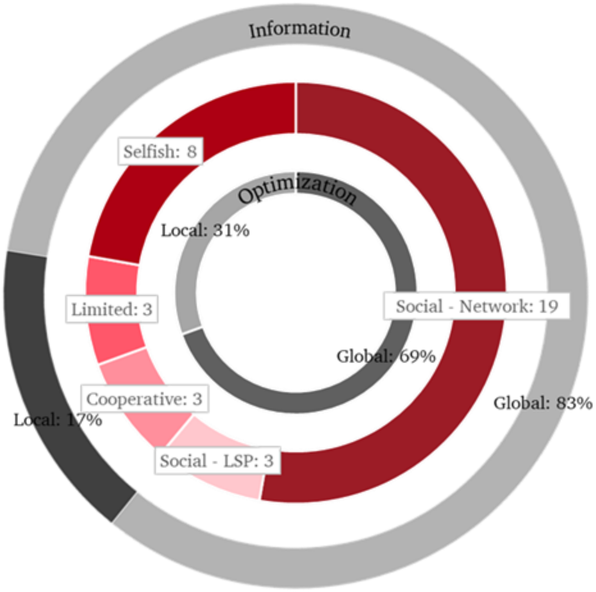


Figure 43: System characteristics analysis results

The evaluation of the Cooperation mechanisms shows that, with almost 70% of all papers, a full horizontal collaboration between the transportation actors is modeled most frequently.

The Transportation service characteristics differ substantially from those of previous multimodal transportation concepts. Four underlying criteria were determined to assess how the authors understand real-time switching and integrated network planning as a crucial part of synchromodality and to what extent these are integrated into the model formulations. As a prerequisite to other service criteria, the models were reviewed for shippers' a-modal booking. Whereas this is a prerequisite for real-time switching before transportation execution, it was also examined if the model promoted en-route mode or tour re-scheduling for the shipped cargo in case of unforeseen disturbances or new transportation orders. Closely related, truck tours were analyzed to determine whether or not they are predefined or flexible.

8.3.3.2 Taxonomy of quantitative papers

Based on three dimensions and ten subcategories, papers with similar content are compared and clustered. Dimension 1, Shipment matching problems in SMT, covers operational decision processes under varying scenario conditions. Dimension 2 addresses the Transportation network mapping under the influence of synchromodality features. This comprises strategic terminal planning, transportation service pricing, transportation mode schedule planning, and decentralized cooperation mechanisms. Lastly, dimension 3 focuses on Adapting synchromodality in a supply chain context and developing digital tools for SMT applications.

Dimension 1: Shipment matching problems in SMT

The first and largest dimension comprises 16 papers concentrated on synchromodal shipment matching. These are clustered according to their information quality, and their results are compared to intermodal solutions in category 3 (Table 35).

Deterministic shipment matching problems focus mainly on transportation mode and route real-time switching, implying integrated network planning and a centralized network organization. Whereas Lin et al. (2016) highlight a-modal booking, Nabais et al. (2015) and Guo et al. (2020) concentrate on real-time switching as the central aspect of synchromodality.

The second category consists of Online and stochastic problems. Like Guo et al. (2020), all three papers by Guo et al. (Guo et al., 2021a, 2021b; Guo et al., 2022) consider a digital matching platform, yet with different dynamic and stochastic variables. In contrast, the models presented by Rivera and Mes (Rivera and Mes, 2016; Rivera and Mes, 2019; Rivera and Mes, 2022) are not placed in an application-based context but rather stand for themselves. While Rivera and Mes (2016) and Rivera and Mes (2019) seek overall transportation cost minimization, profit maximization is the objective of Rivera and Mes (2022).

The third category includes three papers that specialize in Comparing synchromodal and intermodal transportation, i.e., in the Rotterdam transportation hinterland. Whereas in SMT, a-modal booking allows for flexible re-scheduling in case of delays, shipments in intermodal transportation remain with their initial transportation plan. This fact is considered a distinct advantage in the current literature on SMT, but the findings of (Ambra et al., 2019a; Yee et al., 2021; Zhang and Pel, 2016) do not provide unconditional evidence for this.

Table 35: Taxonomy of 1. quantitative dimension: Shipment matching problems in SMT

1. Dimension: Shipment matching problems in synchromodal transportation

Author	Overarching problem*	Mathematical model*	Solution method*	Planning horizon	Optimization objective*	Information evolution	Information quality	System characteristics	Scope of horizontal collaboration	A-modal booking	En-route re-scheduling	Truck tours	Departure / arrival schedule
Category 1: Deterministic problems													
(Guo et al., 2020)	DSM	MIP, BIP	A: HA	O	Ec: C, E, Delay	Online. SR	Det.	Social: network	DTM, STM, TTM	✓	X	Fixed	Road: flexible
(Resat and Turkay, 2019)	Network design	MOMIP	E: Solver	O	Ec: C; En: CO_2; P: TT	Online: D, TT, truck speed	Det.	Social: network	DTM, STM, TTM	✓	✓	Flex	Road: flexible
(Lin et al., 2016)	Perishables goods	IP	E: Solver	O	En: quality loss	Offline	Det.	Social: network	DTM; STM	✓	X	Fixed	All: Fixed
(Nabais et al., 2015)	Cargo allocation	State-space model	A: HA	O	Ec: C; En: E	Online: D	Det.	Cooperative	TTM	✓	X	Fixed	Road: flexible
Category 2: Online and stochastic problems													
(Guo et al., 2022)	DSGSM	MIP	A: RLA	O	Ec:P	Online: TT	S: TT	Social: network	DTM, STM, TTM	✓	✓	Fixed	Road: flexible
(Rivera and Mes, 2022)	Container scheduling	MDP	A: ADP-VPI	O	Ec: P	Online: D, Resource capacity,	S: D	Social: LSP	Full: DTM, TTM	✓	✓	Fixed	Road: flexible
(Guo et al., 2021b)	DSGSM	MIP	A: HSA	O	Ec: P	Online: SR, TT	S: SR, TT	Social: network	DTM, STM, TTM	✓	✓	Fixed	All: Flexible
(Guo et al., 2021a)	DSSM	MIP, BIP	A: SAA, PHA	O	Ec: C, E, Delay	Online: SR	S: SR	Social: network	DTM, STM, TTM	✓	✓	Fixed	Road: flexible
(Batarlienė and Šakalys, 2021)	SITM	IP	E: Solver	O	P: TT,	Online: TT	S: TT	Social: network	STM	✓	X	-	All: Flexible
(Rivera and Mes, 2019)	STSSN	MIP, MDP	A: MH, ADP	O	Ec: C	Online: D	S: D	Social: network	DTM, STM, TTM	✓	X	Flex	All: Flexible
(van Riessen et al., 2016)	DSSM	IP	A: Solver	O	Ec: C	Online: D	S: D	Social: network	-	✓	X	Fixed	Road: flexible
(Rivera and Mes, 2016)	Service selection	MDP	A: ADP	O	Ec: C	Online: D, TT	S: D	Social: network	DTM, STM, TTM	✓	✓	Fixed	Road: flexible

Author	Overarching problem*	Mathematical model*	Solution method*	Planning horizon	Optimization objective*	Information evolution	Information quality	System characteristics	Scope of horizontal collaboration	A-modal booking	En-route re-scheduling	Truck tours	Departure / arrival schedule
(Xu et al., 2015)	DSSM	Two-stage	A: GA	O	Ec: P	Online: D	S: D	Social: network	DTM	✓	X	Flex	All: Fixed
Category 3: Synchromodality and intermodality comparison													
(Yee et al., 2021)	SMT planning	MDP	E: Back-tracking	O	Ec: C	Online: TT, resource capacity	S: TT, capacities	Selfish	DTM, STM, TTM	X	✓	Fixed	Road: flexible
(Ambra et al., 2019a)	Long-distance digital twin	Simulation	A: Simulation optimization	O	Ec: C, TT; En: E P: reliability,	Online: order costs, lead-time	S: order costs, lead-times, TT	Selfish	Limited: DTM, STM	X	✓	Flex	Road: flexible
(Zhang and Pel, 2016)	RS-BCR	MIP	E: CS-BFAA	O	Ec: C	Online: D	S: D	Social: network	DTM, STM, TTM	✓	X	Flex	Road: flexible

Overarching problem: DSM = Dynamic and stochastic matching|DSSM = Dynamic and stochastic matching|DSGSM = Dynamic and stochastic global shipment matching|SITM = Synchronized intermodal traffic management|STSSN = Service and transfer selection problem in a synchromodal network|RS-BCR = Repeated schedule-based cheapest route|***Mathematical model**: BIP = Binary integer programming|MOMIP = Multi-objective mixed-integer programming|***Solution method**: E = Exact|A = Approximate|HA = Heuristic algorithm|RLA = Reinforcement learning approach| ADP-VPI = Approximate dynamic programming-Value of Perfect Information|SAA = Sample average approximation|PHA = Progressive Hedging Algorithm|GA = Genetic algorithm|CS-BFAA = Capacitated schedule-based flow assignment algorithm|***Optimization Objective:** Ec = Economic|En = Environmental|P = Performance|C = Cost|TT = Travel Time|P = Profit|E = Emission|***Information evolution and quality:** D = Demand|SR = Spot Request|S = Stochastic.

Dimension 2: Synchromodal network mapping

Fifteen papers in four categories deal with the framework of a synchromodal network, differentiating between strategic, tactical, and operational levels as well as decentralized cooperation mechanisms (Table 36). On a strategic level, this includes the consideration of SMT characteristics in the positioning of transshipment terminals. At the tactical level, the papers in Category 5 describe how transportation pricing policies need to be adjusted to support SMT. Category 6 is characterized by the effort to determine the schedules and route and tour planning of the vehicles within a synchromodal network. In contrast to an often assumed centralized network organization, several decentralized cooperation mechanisms are introduced by the papers in category 7.

Category 4 includes two papers addressing the strategic issue of how Transhipment locations can be optimally placed in an SMT network. Next to the already immensely complex challenge of ideally locating facilities within a transportation network, Crainic et al. (2021) also consider the operational processes of a multi-period Synchronized Location-Transshipment Problem already at the strategic planning horizon.

Two papers cover the Tactical planning problem of defining the transportation product conditions. In general, products in the transportation context are defined by their price, lead time, and resulting service level. In contrast to traditional pricing mechanisms, van Riessen et al. (2017) and van Riessen et al. (2021) design new pricing strategies that consider the synchromodal characteristics of a-modal booking and real-time switching.

Truck or barge routing, as well as schedule determination, is the focus of category 6. Operational transportation means and container movements are represented by various cargo allocations and VRPs (Koning et al., 2020; Larsen et al., 2021a; Zhang et al., 2021). Moving from tour optimization to transportation network resource scheduling, Behdani et al. (2016) focus on rail and barge schedules.

Cooperation mechanisms that are significantly different from previously mentioned cooperation mechanisms are considered in the category of Decentralized decision-making. Instead of a central unit controlling the entire network, the coordination of routes and schedules is based on a decentrally organized process. Instead of assuming complete horizontal cooperation among actors within a synchromodal network, Larsen et al. (2021b) and Li et al. (2017a) present various coordination strategies to achieve intensified cooperation among transportation operators, and Juncker et al. (2018) model an agent-centric synchromodal network.

Table 36: Taxonomy of 2. quantitative dimension: SMT network mapping

	Overarching problem*	Mathematical model	Solution method*	Planning horizon	Optimization objective	Information evolution*	Information quality	System characteristics	Scope of horizontal collaboration	A-modal booking	En-route re-scheduling	Truck tours	Departure/arrival schedule	Departure/arrival schedule
	Category 4: Synchromodal transshipment location planning													
	(Crainic et al., 2021)	SLTP	MIP	E: Solver	S	Ec: C	Offline	Det.	Social: LSP	TTM	N/A	N/A	N/A	N/A
	(Giusti et al., 2021a)	TLAP	Two stage	A: PHA	S-T	P: max. transportation utility	Offline	S: Trans-shipment cap.	Social: network	TTM	N/A	N/A	N/A	N/A
	Category 5: Synchromodal transportation revenue management													
	(van Riessen et al., 2021)	Cargo fare class mix	Markov Chain	A: Greedy	T	Ec: P	Offline	S: D	Social: network	Limited: DTM, STM	✓	X	Fixed	Fixed
	(van Riessen et al., 2017)	Cargo fare class mix	MIP	E: Solver	T	Ec: revenue	Offline	S: D	Selfish	None	✓	X	Fixed	Fixed
	Category 6: Transportation mode schedule und tour determination													
	(Zweers et al., 2021)	DSSM & Resource schedul	Two stage & IP	A: SAA	O	Ec: C	Online: D, capacity	S: D, capacity	Limited	Limited: DTM, STM	✓	X	Fixed	Flexible
	(Larsen et al., 2021a)	Cargo allocation and vehicle routing	State-space commodity flow	E: Solver	O	Ec: C	Online: TT, resource capacity	S: TT	Social: network	DTM, STM, TTM	✓	✓	Flex	Road: flexible
	(Zhang et al., 2021)	PDPT	MIP	A: ALNS	O	Ec: C; En: CO_2	Online: TT	S: D	Social: network	DTM, STM, TTM	✓	✓	Flex	Flexible
	(Koning et al., 2020)	Online order assignment	IP	E: Solver	O	Ec: C	Online: D, AA	S: D, AA	Selfish	DTM, STM	✓	✓	Flex	Flexible
	(Kalicharan et al., 2020)	Network design	IP	E: Solver	O-T	Ec: C	Offline	Det.	Selfish	None	✓	X	Flex	Road: flexible
	(Qu et al., 2019)	SMT replanning	MIP	E: Solver	O	Ec: C	Online: D, TT shipment release time	Det.	Social: network	DTM, STM, TTM	✓	✓	Fixed	Flexible
	(Behdani et al., 2016)	Network resource schedule	IP	E: Solver	O	Ec: C	Offline	Det.	Social: LSP	DTM	✓	X	Fixed	Flexible

Author	Overarching problem*	Mathematical model	Solution method*	Planning horizon	Optimization objective	Information evolution*	Information quality	System characteristics	Scope of horizontal collaboration	A-modal booking	En-route re-scheduling	Truck tours	Depa s
Category 7: Decentralized decision-making													
(Larsen et al., 2021b)	Resource schedule	MIP	E: Solver	O	Ec: C	Online: D, cost	Det.	Limited	Limited: DTM, STM	✓	X	Fixed	Flexible
(Li et al., 2018)	Inland vessel coordination	CP, MIP	E: Solver A: LNS	O	P: Efficiency	Offline	Det.	All	Limited to full: STM, TTM	N/A	X	-	Flexible
(Juncker et al., 2018)	Dynamic traffic assignment	Simulation	A: Greedy	O	Ec: C	Online: TT	S: TT	Limited, selfish	DTM, STM, TTM	X	✓ / X	Flex	Road: flexible
(Li et al., 2017a)	Cooperative model predictive container flow control	Simulation	A: ALR, ADMM	O-T	Ec: C	Online: D, resource capacity	Det.	Cooperative	Limited: DTM, STM, TTM	✓	X	-	Road: flexible

Overarching problem: SLTP = Single-commodity multi-period synchronized Location Transshipment Problem | TLA = Stochastic multi-period Transshipment Location-Allocation Problem | CP = Constraint Programming | **Solution method**: (A)LNS = (Adaptive) Large Neighborhood Search | ALR = Augmented Lagrange Relaxation | ADMM = Alternating Direction Method of Multipliers | **Information evolution:** AA = Appointment approval.

Dimension 3: SMT application

Papers in the third dimension are characterized by their high application relevance (Table 37). Category 8 represents digital planning tools. Category 9 broadens the focus beyond a purely transportation-based synchromodality view to a synchromodal supply chain. Del Vecchyo et al. (2018) and Dobrkovic et al. (2018) research prerequisites to enable digital tools for SMT. The former observes that in operational SMT planning, costs and transportation times are the most important KPIs. Dobrkovic et al. (2018) focus on IT platforms in the context of SMT that require reliable ship arrival and delay data. This information is a prerequisite for barge planning of LSPs, which are given the freedom by synchromodality to replan hinterland transports flexibly. The overall goal of the papers concerning digital planning tools for synchromodal transportation is to provide an SMT planner with a support tool. Focusing on the transportation route from Piraeus to Prague, Kapetanis et al. (2016) introduce a support tool for LSPs, which enables transparent tour planning. Offering various multimodal alternatives, the tool entirely relies on a-modal booking, the horizontal collaboration of transportation operators, and integrated network planning. The last category is characterized by the combination of SMT and supply chain optimization. Economic, environmental, and performance-oriented synchromodal decisions are considered part of a corporate supply chain. Hence, material and information synchronization is not limited to SMT processes but applies to the entire supply chain. Synchromodality no longer only represents a transportation concept but rather a supply chain principle. (Dong et al., 2018) shape the term Synchromodality from a Supply Chain Perspective (SSCP) and model the optimal freight allocation within an SMT network while simultaneously considering inventory costs. The authors argue that although synchromodal rail-road transportation causes higher travel times than road-only transportation, SSCP reduces the total logistics costs by 6% through the cost advantage of SMT. However, the limited transportation corridor of the presented case study neglects flexible replanning during the transportation execution. On the contrary, Lemmens et al. (2019) includes real-time switching of transportation modes into their synchromodality decision rule.

Table 37: Taxonomy of 3. quantitative dimension: SMT application

	Author	Overarching problem*	Mathematical model	Solution method	Planning horizon	Optimization objective	Information evolution	Information quality	System characteristics	Scope of horizontal collaboration	A-modal booking	En-route re-scheduling	Truck tours	Departure / arrival schedule
3. Dimension: Synchromodal transportation application	**Category 8: Digital planning tools for synchromodal transportation**													
	(Del Vecchyo et al., 2018)	MCMCF	MIP	E: Solver	O	P: flexibility, robustness, customer satisfaction	Offline	S: TT, handling times	N/A	Full: DTM, STM, TTM	✓	✓	Flexible	Road: flexible
	(Dobrkovic et al., 2018)	Maritime pattern extraction	Simulation	A: GA	O	Ec: C, TT; En: E	Online: vessel position data	S: Ship waypoints	Cooperative	N/A	N/A	N/A	N/A	N/A
	(Zahid et al., 2022)	SMT cargo allocation	MIP	E: Solver	O	Ec: C, TT	Offline	Det.	Social: network	None	✓	X	Flexible	Fixed
	(Kapetanis et al., 2016)	Exceptional Handling & Real-time switching	N/A*	N/A*	O	Ec: C, TT, fuel consumption	Online: TT, C	Det.	Selfish	N/A	X	✓	N/A	N/A
	(Mes and Iacob, 2016)	Multi-objective k-shortest path	Simulation	A: Sequential heuristic	O	Ec: C; En: CO_2; P: reliability	Online: SR	S: TT	Social: network	Full: DTM, STM, TTM	✓	✓	Fixed	Road: flexible
	Category 9: Synchromodal transportation with Supply Chain focus													
	(Lemmens et al., 2019)	Multimodal dual sourcing	MIP	E: Solver	O	Ec: C	Online: D, lead-times	S: D, lead-times	Selfish	Full: DTM, STM, TTM	X	✓	Fixed	Fixed
	(Dong et al., 2018)	Dynamic inventory replenishment	IP	E: simulation-optimization	O	Ec: C	Online: D	S: D	Selfish	None	X	X	Fixed	Road: flexible
	(Farahani et al., 2018)	SMT network design	MIP	E: Solver	S	En: E, C, energy consumption	Offline	Det.	Limited	N/A	X	X	N/A	N/A

***Overarching problem**: MCMCF = Minimum Cost Multi-Commodity Flow problem.

8.4 Discussion and fields of future research

This paper compared qualitative and quantitative papers, providing insights into commonalities and differences of SMT characteristics. While the assumptions and results of the papers have been analyzed and compared in detail so far, this discussion offers a meta-level comparison and identifies open research fields in the context of SMT. As identified in the descriptive analysis, research on SMT started with qualitative approaches, and it was only afterward that quantitative papers were published. Therefore, the extent to which the quantitative papers' models reflect the theoretical findings of the qualitative papers on SMT is examined, and further, it is analyzed to what degree the quantitative papers' modeling results support the qualitative papers' conclusions regarding the positive effects of SMT.

An analysis of the planning horizons of the quantitative models has shown that SMT problems can indeed be divided into the conventional categories of operational, tactical, and strategic, as assumed by Delbart et al. (2021). However, planning horizons increasingly merge in SMT. Due to the real-time synchronization and a global network orchestrator, the analysis of the quantitative papers dealing with strategic hub-location problems revealed that the operational level needs to be taken into account even more than in previous multimodal transportation problems. An operational-tactical hybrid of planning problems in SMT arises. Contrary to fixed transportation resources with fixed schedules, the short-term operational demand determines which means of transportation are used and when (Qu et al., 2019).

The quantitative papers provide a realistic representation of operational uncertainties in SMT, as identified by qualitative papers. More than 50% of the papers model the SMT problems using stochastic and dynamic parameters. In addition, the geographical references of the case studies in the quantitative papers are well aligned with actual SMT application areas. Nearly 75% of the models refer to port hinterland transportation. Moreover, the claim of (van Riessen et al., 2015a) that existing models describing multimodal transportation problems are unsuitable for representing SMT, is confirmed. Due to real-time switching and horizontal collaboration within SMT, quantitative papers are developing new models precisely tailored to these characteristics (Mes and Iacob, 2016).

At the same time, many inconsistencies exist between the results of the qualitative papers and the representation of SMT in the quantitative models. For example, the form of cooperation between the actors and the acceptance of a central network organizer. Several qualitative papers conclude that horizontal cooperation, a-modal booking, real-time switching, and the preceding mind-shift to transfer competencies and responsibilities represent the greatest challenges for the introduction of SMT (Tavasszy et al., 2017). Since today's market positions are based on a business model of data evaluation, logistics companies tend to avoid these characteristics of SMT (Alons-Hoen et al., 2019). Furthermore, qualitative papers emphasize that legal barriers must first be overcome before such sensitive data can be exchanged. On the other hand, more than 70% of the quantitative papers build their models on full horizontal cooperation.

Another issue concerns the optimization objectives of the quantitative papers. While SMT is to be introduced especially because of its environmental friendliness and promise outstanding potential for sustainable cargo transportation, 70% of all quantitative papers optimize economic objectives exclusively.

While qualitative conceptual-oriented papers exclusively expect cost benefits from the application of SMT (Acero et al., 2022; Agbo et al., 2017), it turns out that handling costs and pro-active route and mode switching lead to higher costs compared to static intermodal transportation (Ambra et al., 2019b). Furthermore, the conclusion of the qualitative papers that SMT leads to a reduction in road freight transportation has to be considered in a differentiated way. However, quantitative papers agree that SMT increases the share of rail transportation, and Zhang and Pel (2016) document a drastic increase in road transportation in the vicinity of transshipment terminals.

Synchronizing the papers' results and comparison to current drivers impacting the European transportation sector opens the door for future research fields on SMT. Five distinct research areas are disclosed and summarized in Table 38.

Considering future research on business aspects of synchromodality, business models, a two-sided platform, and trust are the key subjects. While various quantitative papers represent an orchestrator and its tasks, necessary business models, including profit and loss sharing mechanisms for all engaged actors within a centralized network organization, are entirely missing. The necessity to establish profit and loss compensation mechanisms that treat all involved parties fairly and are accepted by all involved stakeholders becomes even more critical when realizing that SMT causes very different cost changes.

Several papers (Agbo et al., 2017; Giusti et al., 2019a) highlight legal barriers, liability, and insurance issues to the proposed horizontal collaboration. However, no paper deals with the legal controversy of what laws at national and European levels are involved and which specific changes are required to allow for intensive data sharing, real-time switching, and horizontal collaboration in SMT.

Although identified as one of the requirements for SMT by qualitative research and presumed in quantitative papers, loading units and interconnections of infrastructure remain uncovered prerequisites of SMT in scientific literature. No paper deals with physical interoperability problems of SMT that exist between neighboring countries and impede real-time switching. Furthermore, the characteristics of loading units are not mentioned, or containers are assumed to be most suitable for real-time switching. While the technologies of Blockchain and IoT are emerging, their application to data security in horizontal collaboration and connectivity of loading units, respectively, have yet to be explored.

The remarkable share of quantitative papers in the overall literature corpus could not lead to the clarification of all modeling issues concerning SMT but rather represents the beginning of the transportation problems to be investigated. In general, all mathematical models should include data from real-life SMT projects. To better reflect ongoing trends affecting the European transportation industry, truck driver shortages, alternative fuels and engines (e.g., electric trucks, Methanol powered barges), as well as short-duration disruptions, need to be considered in modeling SMT problems.

As the concept of synchromodality still occupies a niche position in the discussion on sustainable transportation logistics, awareness needs to be strengthened. Studies on increasing shippers' willingness regarding a-modal booking (Khakdaman et al., 2020) and the methods of serious gaming (Buiel et al., 2015; Kurapati et al., 2018) can help foster this development. The combination of qualitative, which forms the basis for modeling assumptions, and quantitative literature is an essential approach to cover the presented areas of future scientific research on synchromodality.

Table 38: Fields of future research on SMT

Field of development	Open research fields
Business	▪ Differentiated investigation of the effects of SMT on the cost development of individual cost units and transportation actors in comparison to currently used multimodal concepts. ▪ Conceptual design and modeling of a centralized entity with a focus on profit and loss sharing mechanisms as well as more realistic SMT pricing strategies, considering spot requests, demand variations, and cannibalization effects between fare classes. ▪ Further investigation is needed to determine the tasks of a platform organizing SMT and whether an existing actor or an additional player will manage it. ▪ Determination of which overall goals a platform for organizing an SMT network pursues.
Legal	▪ Determination of which legal barriers impede the requested horizontal collaboration and how these can be overcome. ▪ Clarification of liability, data security, and insurance issues of a-modal booking and real-time switching.
Technological / Physical	▪ Investigation on how the connectivity of loading units can be established through IoT technology. ▪ Impact of infrastructure interoperability issues on anticipated en-route real-time switching. ▪ Investigation of which loading units are best suited to be used in SMT.
Mathematical Modeling	▪ Consideration of larger SMT networks in numerical experiments, consisting of multiple transshipment points and transportation corridors offering several transportation modality alternatives. ▪ Elaboration of a model incorporating transportation modalities using alternative fuels or engines (e.g., electric trucks, Methanol powered barges). ▪ Consideration of truck driver shortages. ▪ Modeling based on data from SMT real-life applications. ▪ Analysis and quantification of cost and travel time effects of SMT shipments facing short-duration disruptions.
Awareness and implementation	▪ The expansion of existing serious gaming methods and their application among employees are directly affected by process changes induced by SMT. ▪ Further investigation and verification of existing results regarding conditions and compensations under which shippers agree to a-modal booking. ▪ Further investigation and verification of existing results regarding the implementation challenges of individual SMT characteristics differentiated by cultural and legal conditions.

8.5 Conclusion

The purpose of this paper is to provide a systematic review of the scientific literature that addresses SMT from a logistics and management perspective. A comprehensive summary was achieved by employing broad search terms, and an in-depth analysis was performed to provide an overview of the current state-of-the-art SMT research. Concerning the limitations of the work, two points should be mentioned: The database search was conducted exclusively in Web of Science. The papers identified in this way were subjected to a forward and backward search, through which six further papers were identified. However, the possibility that further literature on SMT exists cannot be excluded entirely. Furthermore, we limited the review's scope to references that explicitly focus on synchromodal transportation. Therefore, the possibilities of transforming approaches from other related research fields, such as the physical internet or digitalization of the transportation sector, are not investigated.

The review's main findings can be concluded according to the RQs.

Regarding RQ 1.1, SMT can be seen as an active topic that has attracted the interest of researchers worldwide, but especially in Europe, in the past years. Starting with mainly qualitative research, the focus shifted to mathematical planning problems over the years. To organize the literature and answer RQ 1.2, a comprehensive taxonomy of five dimensions and 13 categories for qualitative and quantitative papers is developed. Consequently, an extensive evaluation of the papers' content is achieved, connections between the papers are established, and research results are consolidated. Furthermore, the two research approaches are compared, and commonalities and differences are identified. The results reveal a mixed picture, with high consistency in geographical areas of SMT implementation and suitable modeling of operational disruptions and uncertainties but little alignment in the forms of collaboration and synchromodal transportation network organization. Finally, future research fields, namely business, legal, technological, modeling, and awareness of synchromodal transportation (RQ 1.3), are disclosed to foster the successful long-term implementation of synchromodal transportation.

9 Conclusions

The box that changed the world has come a long way. From its humble beginnings as a practical solution for transporting whisky, containerization has revolutionized shipping, transforming it into a digitally connected worldwide network (Mirsky, 2007). By seamlessly integrating multiple modes of transportation—such as rail, road, and maritime—and leveraging standardized containers or trailers, intermodal transportation capitalizes on the strengths of each transportation mode, optimizing efficiency, cost-effectiveness, and environmental sustainability.

This dissertation has systematically addressed the complexities and transformative potential of intermodal transportation by investigating the structural configuration of transportation networks and the impact of digitalization and real-time data through a multi-method approach. Besides an overall summary of the results, the following sections describe the managerial insights, the limitations that have to be considered, and further research topics.

9.1 Results and implications

This dissertation investigated intermodal transportation, utilizing a multi-method approach. It focused on network configuration and the impact of digitalization from various perspectives. Two overarching RQs have been considered, which were split into four relevant subquestions. The theoretically guided propositions were addressed within the scope of each respective study. In this section, the focus will be on synthesizing these findings to answer the overarching research questions. The two overarching RQs are repeated along with their research propositions in the following for individual reflection.

Connecting Networks

RQ 1 Connecting Networks – How does the structural configuration of intermodal transportation networks contribute to addressing fundamental challenges and improving overall system performance?

> **RP 1.1:** *Integrating strategic hub location and tactical service network design models provides deeper insights into the network structure, leading to optimized configurations that enhance efficiency and reduce costs.*
>
> **RP 1.2:** *Continental intermodal transportation offers a viable solution for connecting Asia and Europe, leveraging the strengths of various transportation modes. It can be a feasible alternative to sea freight transportation, offering an opportunity to diversify networks and increase resilience.*

The first research question explored the structural configuration of intermodal transportation networks and corridors and their contribution to addressing fundamental challenges and improving overall system performance. Overall, RQ1 spans the Chapters 4 to 6.

The investigation started by assessing the state of the research on HLPs and SNDPs. The SLR of SNDPs in Chapter 4 evaluated the identified 74 references in terms of problem characteristics, model formulations, and solution approaches. Moreover, the research streams on deterministic (46 references) and stochastic (28 references) models (including uncertain demand, transportation times, costs, and capacities) were compared. The predominance of mixed integer programming for deterministic models and two-stage stochastic programming for stochastic models was identified. These quantitative models helped in understanding the impact of different network configurations and stochastic parameters on system performance. Another contribution of the SLR is the identification of existing research gaps. Five areas for future investigation were highlighted: expanding approaches for green SNDP by incorporating environmental considerations alongside economic evaluations, exploring multi-actor planning, integrating profit maximization more frequently, developing efficient heuristics for stochastic models, and further examining additional decision-making options. Specifically, the last area of future research is taken up by the following study on integrating HLP and SNPD.

The study in Chapter 5 examined the structural differences between classical sequential HLP and integrated HLP and SNDP models. As part of the study, the most important developments and current research trends in recent years were summarized. Although solutions to the SNDP can act as detailed assessments for the HLP and consideration of a combined strategic and tactical problem seems to be promising, most research focuses only on either the HLP or the SNDP. Through the sequential analysis of the strategic and tactical planning levels, a variety of constraints are placed on the tactical level. Through integrated planning, more comprehensive results can be achieved, although, at the same time, it can lead to a significant increase in complexity. Therefore, an integrated HLP and SNDP model was developed and tested in a case study involving a German intermodal operator. The case study highlighted that integrating these problems leads to more realistic and efficient network configurations. Specifically, strategic decisions on hub locations significantly impact the network's overall efficiency and cost-effectiveness. The case study has shown a possible cost reduction of up to 3.3% of the integrated model compared to the sequential modeling approach. A closer analysis of solution characteristics between the sequential approach and the integrated C-HL-SNDP (integrated model) model provided valuable insights. A structural difference in the assignment of non-hub to hub nodes was discovered. A further discovery was made regarding the flow of commodities. In the classical p-hub median model, two-thirds of all transports were carried over two hubs to benefit from discounts on interhub connections. This model favored economies of scale, resulting in evenly distributed hubs across the network to maximize the length and cost reduction of interhub transportation. On the other hand, the C-HL-SNDP preferred economies of density, leading to the majority of transports occurring via one hub or directly. Direct shipments were favored where demand ensured high utilization of transportation capacity, while transports via one hub were used to bundle flows, ensure high utilization, and reduce connections. Interviews with the intermodal operator confirmed the practical application of these findings. The operator relies heavily on fully utilizing contracted block trains, aligning with the C-HL-SNDP model's emphasis on high capacity utilization. The integrated approach of combining HLP and SNDP models leads to optimized network configurations that enhance operational efficiency and reduce costs.

The feasibility and benefits of continental intermodal transportation as a possible solution for connecting Asia and Europe were investigated in Chapter 6. An exploratory qualitative analysis of the Trans-Caspian Corridor through 14 expert interviews with logistics companies and political authorities was conducted on the methodological basis of grounded theory. The grounded theory approach allowed for the identification of emergent themes and patterns that were not initially anticipated. It revealed the intricate geopolitical and strategic challenges influencing the corridor's development. Based on this analysis, we identified five groups of stakeholders and distilled their ambitions and motivations for shaping the corridor in light of current geopolitical tensions. Five areas of strategic interest were identified: infrastructure and equipment, standardization and digitization, cooperation and coordination, current and lasting interest, and spillover effect. These areas are critical for the successful development and operation of the corridor. For each of these five areas, research propositions were developed. Based on the RPs, five fields for further research were developed to provide a structured framework for future investigations.
The study also placed the research and development of the TCC into the established transportation corridor theory. Tracing the corridor's evolution from basic transportation infrastructure towards a holistic growth corridor that integrates logistics, trade facilitation, and economic diversification in light of the corridor development model. It was further highlighted that the geopolitical discourse on the TCC serves as a pertinent example of how modern geopolitics plays a crucial role in shaping transportation corridors. It thereby resonates with the aspects of transportation visions and imaginations, rule-making in transportation, and militarism in transportation.
The findings highlight that continental intermodal transportation could significantly enhance connectivity between Asia and Europe. The TCC can reduce transit times compared to traditional sea freight and offer a reliable alternative that diversifies transportation options and increases resilience, especially in the face of disruptions or geopolitical tensions. Still, several challenges, such as standardized transportation operations, securing long-term demand, and digitalization, must be overcome.

Connecting Digitalization

RQ 2 Connecting Digitalization – How do digitalization and the availability of real-time data impact intermodal transportation?

> **RP 2.1:** *Real-time data availability significantly improves operational processes in the pre-and post-haulage phase of intermodal transportation by enhancing visibility and enabling dynamic adjustments to the pickup and delivery process.*

> **RP 2.2:** *Digitalization and real-time data integration evolve the intermodal transportation concept toward synchromodal transportation, enhancing overall system performance and enabling more responsive and adaptive transportation solutions.*

The second research question explored the impact of digitalization and real-time data on intermodal transportation and its transformative potential. Overall, RQ2 spans the Chapters 7 and 8.

The study in Chapter 7 examined the impact of clustered, dynamic, and ETA forecasts on the PPH of intermodal transportation in a simulation-optimization study. It demonstrated that real-time data significantly enhances visibility across the transportation chain. By providing precise and up-to-date information about the expected arrival times of trains, ETA forecasts allow for better tracking and planning throughout the transportation process. This visibility enables operators to make informed decisions and promptly address any issues that arise, thereby reducing delays and reacting to potential disruptions more effectively.

Methodologically, this scenario gives rise to a dynamic and stochastic Pickup and Delivery Problem with Time Windows and clustered ETA forecasts (PDPTW-crd), a complex optimization problem that has not been addressed in the context of intermodal transportation. Commodities must be transported to the intermodal terminal from the surrounding area or arrive by train. A dynamic and stochastic ETA forecast announces the arrival of a train at the terminal. However, these forecasts are inherently inaccurate and have varying degrees of accuracy at different times. In principle, the quality of this forecast increases the closer the train is to the depot. To tackle this dynamic and stochastic optimization problem, a simheuristic solution procedure that combines simulation and heuristic-based components is proposed. A biased randomized savings algorithm has been developed to generate solutions for the PDPTW-crd. These solutions are then evaluated in a Monte Carlo sampling to account for the stochastic nature of the problem. This solution procedure is then extended with a rolling horizon framework to cope with the real-time aspect and introduce five different solution strategies.

In a real-world case study in Central Europe involving one intermodal terminal, one road hauler, and three major intermodal relations, it is demonstrated that real-time data integration leads to substantial cost savings. It is found that even basic quality ETA forecasts lead to an average cost reduction of 7% compared to situations where no ETA forecasts are used. Therefore, even basic quality forecasts prove beneficial, but higher-quality predictions yield superior planning outcomes, reduce the number of tours that have to be driven, lower the need for frequent adjustments of the tours, and generally decrease wait and delay time. Detailed cost structure analysis revealed that while waiting costs at terminals constituted only a minor fraction of total expenses, they significantly influenced solution structures.

Several practical policy recommendations were suggested to enhance the integration of ETA forecasts within intermodal transportation systems. These included the development of industry-wide standards for dynamic ETA forecasting systems, infrastructure improvements such as integrating IoT devices along transportation routes, training and education of professionals, and policy support for research and development.

Digitalization drives the evolution of intermodal transportation towards synchromodal transportation, where different transportation modes are seamlessly integrated to provide flexible and adaptive real-time solutions. SMT leverages the strengths of various modes, such as rail, road, and maritime, to provide the best possible transportation solution based on real-time conditions. The SLR of SMT research in Chapter 8 analyzed 62 references and developed a comprehensive taxonomy consisting of five dimensions and 13 categories for both qualitative and quantitative papers. The research emphasized that digitalization is a critical enabler of this seamless integration, providing the necessary tools for real-time monitoring, data analytics, and decision-making. The availability of real-time data significantly improves operational efficiency by enhancing visibility and enabling dynamic adjustments to routing and scheduling. The integration of digital technologies such as IoT, blockchain, and AI further supports this transition.

The results of the review further reveal a mixed picture, with high consistency in geographical areas of synchromodal transportation implementation and suitable modeling of operational disruptions and uncertainties. However, compared to multimodal or road transportation, there is little alignment in the forms of collaboration, network organization, or the advantages of synchromodal transportation. Finally, five main fields for future research are identified, namely business concepts, legal framework, technological challenges, mathematical modeling, and awareness and implementation.

Synchromodal transportation can be regarded as the natural evolution of intermodal transportation. However, planning horizons increasingly merge in SMT. Due to real-time synchronization and a global network orchestrator, operational-tactical hybrids become more common. The analysis of strategic hub-location problems further revealed that the tactical and operational level needs to be taken into account even more than in previous intermodal transportation problems.

The research in this dissertation confirmed that connecting multiple research methodologies enriches the understanding and analysis of intermodal transportation, leading to more comprehensive insights. By combining qualitative and quantitative approaches and integrating the different planning levels, this dissertation demonstrated the value of diverse perspectives in capturing the complexities and dynamics of intermodal transportation systems.

The findings highlight that qualitative methods, such as case studies and expert interviews, complement quantitative models by providing contextual and experiential insights and practical knowledge from industry professionals and stakeholders.

9.2 Managerial insights

The research conducted in this dissertation provides valuable managerial insights for stakeholders in the European intermodal transportation market, including LSPs, policymakers, and intermodal transportation operators. The insights include both holistic, cross-actor aspects as well as actor-specific considerations.

Strategic network configuration and planning

The structural configuration of intermodal transportation networks plays a central role in addressing fundamental challenges and improving overall system performance. The integration of strategic hub location and tactical service network design models, as demonstrated in Chapter 4 and Chapter 5, leads to more realistic and efficient network configurations. This integrated approach considers economies of scale and density, optimizing the placement of hubs and the design of service networks. For managers, this means that by aligning long-term goals with short-term actions, they can develop connected and effective solutions. To operationalize this, they should invest in integrated planning tools and models and conduct decisions informed by a detailed analysis of demand patterns and transportation flows.

Operational efficiency through ETA forecasts

Exploring the integration of dynamic and stochastic ETA forecasts into the PPH phases of intermodal transportation unveiled promising opportunities for operational efficiency. The simulation study conducted in Chapter 7 indicates that incorporating ETA forecasts into routing decisions can lead to an average cost reduction of around 7% by reducing the need for frequent adjustments and minimizing waiting and delay times. For logistics managers, this underscores the importance of investing in advanced ETA forecasting technologies and integrating them into operational planning processes. By leveraging real-time data, LSPs can enhance visibility across the transportation chain.

Digitalization and real-time data integration

Digitalization drives the evolution of intermodal transportation towards SMT, where different transportation modes are seamlessly integrated to provide flexible and adaptive real-time solutions. The findings from Chapter 8 highlight the potential of digital technologies such as IoT, Blockchain, and AI in enhancing real-time monitoring, data analytics, and decision-making. For managers and policymakers, this suggests that fostering digital infrastructure and adopting advanced digital tools can significantly enhance the responsiveness and efficiency of intermodal transportation operations. Investments in smart transportation networks and the integration of IoT devices along transportation routes can facilitate the collection and dissemination of real-time data, improving the accuracy of ETA forecasts.

Policy and regulatory support

The research in this dissertation also provides insights for policymakers on how regulations can incentivize the use of intermodal transportation and enhance its cost attractiveness. For example, the findings from Chapter 6 on the Trans-Caspian Corridor suggest that achieving interoperability through technical harmonization and operational standardization requires collaboration among diverse stakeholders. Policymakers are crucial in facilitating this collaboration and supporting investments in infrastructure projects along key transportation corridors. Additionally, policies that encourage the adoption of advanced digital technologies and provide subsidies or grants for their implementation can further enhance the efficiency of intermodal transportation systems.

Holistic and collaborative approaches

Overall, the research underscores the importance of adopting holistic and collaborative approaches to address the complexities of intermodal transportation. Integrating multiple planning horizons and methodologies, as demonstrated in this dissertation, leads to more comprehensive and actionable insights. For managers, this means that cross-functional collaborations are essential. Policymakers can support these efforts by creating a conducive regulatory environment and providing incentives for innovation and collaboration in the intermodal transportation sector.

In conclusion, the managerial insights derived from this dissertation emphasize the need for integrated planning, advanced digitalization, and collaborative efforts to enhance the efficiency, resilience, and adaptability of intermodal transportation systems in Europe.

9.3 Limitations

The research presented in this dissertation is subject to several limitations. These limitations arise from the specific focus of the study, the methodologies employed, and the generalizability of the findings.

Focus on specific aspects of intermodal transportation

One limitation of this dissertation is the focus on certain aspects of intermodal transportation while excluding others. The research primarily addresses the structural configuration of intermodal transportation networks and the impact of digitalization and real-time data. Although these areas are crucial for understanding intermodal transportation, other important aspects, such as environmental impacts, regulatory frameworks, and economic factors, have not been deeply explored. Consequently, the findings may not comprehensively capture all dimensions of intermodal transportation.

Generalizability of findings

Another limitation concerns the ability to generalize the research findings. The studies conducted in this dissertation, while incorporating real-world data and stakeholder interviews, are primarily based on specific case studies and simulations within a defined geographic and operational context. While the research provides valuable insights into the structural configuration and digitalization of intermodal transportation networks within Europe, it may not fully capture the nuances and challenges unique to other regions, such as North America or Asia. These regions have different geographical layouts, infrastructure capacities, and regulatory environments, which can influence the applicability of the findings.

Methodological constraints and assumptions in modeling and simulations

The dissertation employs a combination of qualitative and quantitative research methods, including simulation modeling, interviews, and SLRs. While these methods provide a comprehensive understanding of intermodal transportation, they also come with inherent limitations. Qualitative methods, such as expert interviews and case studies, may introduce subjective biases, and the findings may not be easily replicable.

The research methodologies employed, particularly in the modeling, optimization, and simulation studies, involve certain assumptions that may limit the applicability of the results. The reliance on simulation models, while useful for exploring complex scenarios, may oversimplify real-world conditions and fail to capture all possible variables and uncertainties.

For instance, the simulation models used to analyze the impact of ETA forecasts on the PPH of intermodal transportation assume specific conditions of data availability and accuracy. In practice, real-time data may be incomplete or subject to delayed transfer and inaccuracies, which could affect the outcomes. Similarly, the use of specific modeling techniques, such as the HLP and SNDP, may not encompass all aspects of intermodal transportation network design. These models often rely on assumptions regarding cost structures, demand patterns, and service reliability, which may not hold true in all contexts.

Assumptions and simplifications

Several assumptions and simplifications were necessary to conduct the research. For instance, the models often assume rational decision-making by LSPs and optimal conditions for implementing digital technologies. However, in reality, decision-making processes may be influenced by a range of factors, including organizational culture, regulatory constraints, and market competition, which are not fully captured in the models. Additionally, the impact of digitalization and real-time data availability is assumed to be uniformly beneficial, whereas the actual implementation may face challenges such as data privacy concerns, technological disparities, and resistance to change.

Another limitation is the exclusion of certain stakeholder perspectives. The research primarily focuses on the perspectives of LSPs and intermodal transportation operators. However, the perspectives of other stakeholders, such as policymakers, shippers, and end consumers, are not extensively considered. These stakeholders are also part of the intermodal transportation ecosystem, and their inclusion could provide a more holistic understanding of the challenges and opportunities in intermodal transportation.

Despite these limitations, the research in this dissertation provides valuable insights into the structural configuration of intermodal transportation networks and the impact of digitalization, particularly within the European context. The findings contribute to a better understanding of how to enhance efficiency and sustainability in intermodal transportation.

9.4 Future research

Building on the limitations identified in this dissertation, several avenues for future research emerge that could further enhance the understanding and application of intermodal transportation systems. These suggestions aim to address the gaps identified and expand the scope of current research to include a wider variety of contexts, methodologies, and practical applications.

Diverse contexts and broader applications

One potential area for future research involves exploring different types of intermodal transportation systems beyond the European context. While this dissertation focuses primarily on European continental intermodal transportation, future studies could investigate intermodal transportation systems in North America, Asia, and emerging economies. These regions present unique logistical challenges and opportunities due to their distinct geographical, economic, and regulatory environments. For example, research could examine how the vast distances in North America impact the efficiency and feasibility of intermodal transportation or how rapidly developing economies in Asia integrate new technologies into their transportation infrastructure.

Multi-Criteria evaluation approaches

The evaluation of intermodal transportation systems in this dissertation primarily focuses on cost and efficiency. However, future research could incorporate multi-criteria evaluation approaches that include non-monetary factors such as environmental impact, social benefits, and psychological barriers to adoption. For instance, the inclusion of environmental metrics could provide a more holistic view of the sustainability of intermodal transportation solutions, aligning with broader climate goals and regulatory frameworks. Multi-criteria decision models could be employed to balance these diverse factors and provide more comprehensive evaluations of intermodal transportation projects.

Dynamic optimization and integration of stochastic elements

Another promising area for future research is the increased use of dynamic and real-time optimization models for intermodal transportation networks. Current models often rely on static data and assumptions, which may not fully capture the complexities and uncertainties of real-world logistics operations. This could involve the use of advanced technologies such as AI, machine learning, and IoT to enhance the responsiveness and adaptability of intermodal transportation systems. Incorporating stochastic elements into intermodal transportation models could also enhance their robustness and resilience. While this dissertation addresses some uncertainties, such as ETA forecasts, future research could delve deeper into the impact of stochastic variables on network performance. This could include modeling the effects of unexpected disruptions, such as natural disasters, strikes, or geopolitical events, and developing recourse actions to mitigate these risks.

Technological advancements and digitalization

The rapid advancement of digital technologies offers numerous opportunities for enhancing intermodal transportation systems. Future research could explore the integration of blockchain technology for improving transparency and traceability in logistics chains, as well as the use of big data analytics for optimizing routing and scheduling decisions. Additionally, investigating the potential of emerging technologies, such as autonomous vehicles and drones for intermodal transportation, could provide valuable insights into the future of logistics.

Cross-disciplinary collaboration

Finally, fostering cross-disciplinary collaboration between researchers from different fields, such as engineering, computer science, behavioral economics, and environmental studies, could lead to more innovative and comprehensive solutions for intermodal transportation. By combining expertise from various disciplines, future research can address the multifaceted challenges of intermodal transportation and develop integrated approaches that consider technical, economic, social, and environmental aspects. Collaborative efforts could also facilitate the translation of research findings into practical applications, bridging the gap between theory and practice.

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