Combined Rail-Road Transport in Europe - Improvement Potential and Impact of Environmental Policy on Competitiveness

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M. Gleser

Vorwort

Das Verfassen einer Dissertation ist nicht nur akademisch eine Herausforderung, sondern gleichermaßen eine persönliche Reise. Stärker, als ich zu Beginn erwartet hatte, war der gesamte Prozess von Ereignissen in der Welt beeinflusst. Als ich mit der Dissertation begann, gab es noch keine Spur von COVID-19 und keinen Krieg in Europa. China hatte zweifellos einen phänomenalen wirtschaftlichen Aufstieg hingelegt, sein Machtbewusstsein tritt jedoch erst seit Kurzem offensiv hervor. Leider haben diese Entwicklungen auch erhebliche Auswirkungen auf die Forschung im Bereich des Transports, insbesondere wenn man bedenkt, dass dieser Bereich immer mehr mit geopolitischen Aspekten in Berührung kommt. Diese Ereignisse haben mir bewusst gemacht, dass wissenschaftliche Forschung, insbesondere in den Wirtschaftswissenschaften, immer auch ein Spiegelbild ihrer Umgebung und ihres Umfelds ist. Konzepte und Prozesse, die in vorherigen Zeiten entstanden sind, können in unserer sich rasch verändernden Welt auf den Kopf gestellt werden. Die Pandemie, die im Jahr 2020 begann, hat unter anderem Arbeitskonzepte, vornehmlich hinsichtlich der Präsenzarbeit und der Notwendigkeit zum digitalen Austausch, einer disruptiven Änderung unterzogen. Und diese Änderungen waren nicht begrenzt auf einzelne Regionen, sondern hatten weltweit Auswirkungen. Es wäre nicht übertrieben zu behaupten, dass wir in vielerlei Hinsicht digitaler geworden sind, nicht nur im geschäftlichen Austausch, sondern auch im Privaten. Auch vermeintlich sicher geglaubte Machtverhältnisse hat die Pandemie erschüttert. Die russische Aggression gegenüber der Ukraine und auch das Gebaren des (ehemaligen) US-Präsidenten Trump haben Europa in Teilen seinen Machtverlust bewusst gemacht. Am Ende bleibt den Ländern Europas, welche im Allgemeinen ohne bedeutende Bodenschätze gesegnet sind, nur die interne Verbesserung, um trotz solcher Krisen ihre Bedeutung in der Welt zu wahren. Die vorliegende Dissertation widmet sich dem intermodalen Transport, dessen Verbesserung neben wirtschaftlichen Auswirkungen auch volkswirtschaftliche Vorteile mit sich bringt. Neben der Verantwortung der Akteure in den Transportketten zur Verbesserung dieses Transportsystems ist hierbei auch die Politik gefordert. Sie muss geeignete Rahmenbedingungen schaffen, um absehbar steigende Transportmengen mit minimalem Ressourcenaufwand zu bewältigen. Für Europa als relativ rohstoffarmen Kontinent ist dies meines Erachtens auch eine Frage der Sicherung des eigenen Wohlstands, der Stabilität seiner Gesellschaften und der Wahrung der eigenen Unabhängigkeit. Trotz des Wettbewerbs müssen wir uns jedoch auch globalen Problemen stellen, die nicht allein durch wirtschaftliches Wachstum gelöst werden können. Die Reduzierung von CO2-Emissionen, einem Treibhausgas, das das globale Klima beeinflusst, sollte ein weltweites Ziel sein. Leider zeigen sich vorübergehende Wettbewerbsnachteile für Länder, die sich um eine Beschränkung dieser Emissionen bemühen. Daher gestalten sich Verhandlungen zur globalen Begrenzung von CO2-Emissionen auch so schwierig. Für Regionen ohne eigene fossile Rohstoffe bringt ein möglichst vollständiger Verzicht auf jene fossilen Energieträger jedoch langfristig die Sicherheit der eigenen Energieversorgung, falls diese durch erneuerbare Energieerzeugung gesichert ist. Eine Warnung sind derzeit einsetzende Entkopplungsprozesse nach Jahrzehnten der ungebremsten Globalisierung, die insbesondere auch im Hinblick auf Energie die Versorgungssicherheit infrage stellen. Eine CO2-Steuer halte ich persönlich für einen äußerst effektiven Weg, nicht nur um die eigenen Emissionen zu senken, sondern auch um die Gesamteffizienz einer Gesellschaft hinsichtlich ihres Energieverbrauchs zu optimieren. Dies muss jedoch immer unter Berücksichtigung der globalen Wettbewerbssituationen geschehen. Es handelt sich zweifellos um ein komplexes Problem.

Auch persönlich ist während des Verfassens dieser Dissertation viel passiert. Meine beiden Brüder haben ihre Lebenspartnerin gefunden und geheiratet. Darüber hinaus bin ich Onkel eines bezaubernden Neffen und einer entzückenden Nichte geworden, die mir jedes Mal, wenn ich sie sehe, ein Lächeln ins Gesicht zaubern. Es ist ermutigend zu sehen, dass trotz weltweiter Krisen das Leben weiter seinen Lauf nimmt. Ein wichtiger Ausgleich zum wissenschaftlichen Arbeiten war mir auch immer mein Herzensverein, dem ich hautnah direkt an der Mittelfeldlinie in Sevilla beim historischen Gewinn der Europa League 2022 beiwohnen durfte. Meine Familie und meine Freunde waren und sind stets ein Anker für mich. Mit dem Abschluss dieser Arbeit fällt sicherlich auch ihnen ein großer Stein vom Herzen. Ein langer akademischer Weg findet somit zumindest seinen temporären Abschluss. Ich möchte mich herzlich bei Prof. Elbert für die Begleitung auf diesem Weg bedanken und auch bei all meinen Kollegen, mit denen ich einige Herausforderungen und die Freude nach Erfolgen teilen durfte. Insbesondere geht ein Dank an Hongjun Wu für die inhaltlichen Diskussionen zu meinem Journalbeitrag, auf dem ich sie gerne als Mitautorin aufführe. Ich habe vieles über mich, die deutsche Gesellschaft und wie Wissenschaft hier gelebt und gestaltet wird, gelernt. Am Ende machen uns unsere Erfahrungen aus und ich bin froh, diese gemacht zu haben.

Michael Gleser

Zusammenfassung

Die vorliegende Dissertation beschäftigt sich mit dem Themenbereich des kombinierten Straßen-/Schienengüterverkehrs mit einem Fokus auf den europäischen Raum. Sie besteht, neben einer Einführung in das Themengebiet und der Beschreibung des Forschungsdesigns, aus drei Studien, deren Ergebnisse inhaltlich aufeinander aufbauen. In der ersten Studie, einer Delphi-Befragung kombiniert mit einer systematischen Literaturrecherche, wurden Maßnahmen ermittelt, wie es aus einer Praxissicht zu einer Stärkung des kombinierten Verkehrs kommen kann und mit welchen Themengebieten sich die angrenzende Forschung beschäftigt. Durch die Synthese der Ergebnisse beider Methoden ist ein praxisorientierter Forschungsleitfaden entstanden, der sich als Dokument der aktuellen Herausforderungen des kombinierten Verkehrs und einer effektiven Lösung dieser versteht. Die zweite Studie beschäftigt sich mit intermodalen Hafenhinterlandverkehren, bei denen der kombinierte Verkehr eine große Rolle spielt. Am Beispiel des Bundeslandes Nordrhein-Westfalen, welches im Einflussbereich mehrerer Häfen liegt, wurde der Einfluss der 2021 eingeführten CO2-Steuer untersucht. Das verwendete Simulationsmodell führt hierbei zu interessanten Erkenntnissen potenzieller Verkehrsverlagerungen. Die dritte und finale Studie beschäftigt sich mit den neuen Möglichkeiten des China Railway Express, einer direkten Zugverbindung zwischen Europa und China. Da sich die Verbindung steigender Beliebtheit erfreut, wurde mit einem an die zweite Studie angelehnten Simulationsmodell untersucht, welche Gegenden in China für Exporteure in Hessen wirtschaftlich erreichbar sind. Zusätzlich wurde untersucht, wie sich dieser Bereich bei Einführung einer (hypothetischen) globalen CO2-Steuer verändern würde. Alle drei Studien bilden zusammen sowohl einen Überblick über aktuelle Herausforderungen des kombinierten Verkehrs in Europa, dessen mittelfristige Veränderungen aufgrund von politischen Regelungen, als auch einen Ausblick auf Möglichkeiten des interkontinentalen Schienentransports.

Abstract

This dissertation investigates the topic of combined rail-road transport with a focus on Europe. In addition to an introduction to the subject and a description of the research design utilized, it consists of three distinct studies whose results build upon one another. In the first study, a Delphi study combined with a systematic literature review, explicit measures were identified on how combined transport can be strengthened from a practical perspective and which topic areas related research deals with. By synthesizing the results of both methods, a practice-oriented research agenda was created. It is intended to be a document of the current challenges of combined transport and an effective solution to them. The second study deals with port competition through hinterland connectivity, in which combined transport plays a major role. Using the example of the federal state of North Rhine-Westphalia, which is within the geographical scope of ports of the northern range, the influence of the CO2 tax introduced in 2021 is examined. A simulation model is used to investigate the impact of the tax, leading to interesting insights into the potential shift in competitive scope. The third and final study deals with the new possibilities of the China Railway Express, a direct train connection between Europe and China. Since the connection is enjoying increasing popularity, a simulation model, inspired by the second study, was used to examine which areas in China are economically accessible to exporters in Hesse utilizing this train connection. In addition, it was examined how this area would change if a (hypothetical) global carbon tax was introduced. All three studies together provide an overview of the current challenges of combined transport in Europe, its medium-term changes due to political and environmental regulations, and an outlook on the possibilities of intercontinental rail transport.

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1 Introduction

1.1 Motivation

Research in transportation is inherently practice driven. Economic needs, scarcity of resources, fierce competition and developments in markets, policies and technologies provide a constantly changing environment actors within the field have to deal with. Optimization of existing operations and networks clearly plays a huge role in enabling the proper functioning of transport systems. Yet, the socio-economic view on transportation research, although not less important for its proper functioning and development, provides plentiful opportunity for investigation as well. Transportation systems can vary in complexity. From simple point to point transports, usually involving trucking, they can become severely complex multi-mode systems with unique characteristics. Intermodal transport systems show this complexity with their increased need for organization and coordination of multiple involved actors. While these transport systems provide a potential cost advantage over less complex systems, mainly due to less costs per transported unit and larger capacity, this advantage can only fully come to fruition when operations are functioning reliably and smoothly. In order to achieve this reliable functioning, intermodal transport systems can be improved and adjusted at various points. Favorable policy can change the attractiveness of this transport mode by tweaking market rules for all participants. This can either make intermodal transport more attractive or decrease the attractiveness of politically less desirable transport modes likes trucking. Similarly, investments in infrastructure components enable increased capacity and reliability, yet come at high costs and require large time spans to complete. Setting the environment for intermodal transport is essential that it can compete with more flexible trucking. Yet, also intermodal transport can create attractive business models and organisation to benefit all actors involved. Multiple forms of cooperation, potentially in a fully digital way, and the penetration of the market with technological innovation can have severe influence on the functioning of intermodal transport systems overall and increase the efficiency and reliability of them.

Major arguments for fostering of intermodal transport systems usually revolve around two aspects. First of all, rising transport demands are projected for national, international and continental freight transport for Germany and Europe [159, 107]. The increased need for transport capacity might bring road transport systems and networks to their limit. As intermodal transport systems enable efficient transport over large distances, and provide increased capacity compared to road transport, they can alleviate the pressure on infrastructure and transport systems with rising transport demands. Secondly, and as an argument prominently present in public discussions, is the need for environmentally efficient transports. The transport sector emits carbon dioxide and other externalities to a large extend [108]. Improving the carbon footprint of the sector is therefor crucial on combating the on-going climate crisis, reduce the consumption of scarce energy resources and make transport more sustainable overall. Intermodal transport, especially rail-road combined transport, allows for a low emission movement of goods due to its mostly electrified tracks. It can therefore make use of electricity from renewable sources that allow for a severely carbon emission reduced transport, especially compared to truck transport. For the development of a sustainable interconnected Europe with regard to transportation, intermodal transport mustn't and can't be neglected. On the European level, development efforts of cross-border infrastructure, most prominently through the Trans-European Transport Networks (TEN-T) and corridors, aim at enabling the use of intermodal transport throughout Europe. With this process intermodal transport can be organized over larger distances which allows the benefits of this transport mode to come at full play.

Sadly, intermodal transport in Europe does currently not live up to its potential. For the case of Germany, profit margins within in the sector are low, infrastructure components are at their limit as investments have been neglected, or in some cases infrastructure, e.g. train tracks and rail yards, has even been demolished in order to enable a profitable initial public offering (IPO) of the German railway company Deutsche Bahn (DB) [369, p.48f]. The IPO was postponed due to the financial crisis of 2008 [125] until further notice. The road network on the other hand has seen capacity increases, especially for highways [88, p.101], which strengthened the position of road freight transport. Historic developments have led to monopolistic structures in the railway sector with an on-going discussion of the separation of infrastructure and operations [341], yet with the liberalization of markets this position slowly changes. The transport industry as a whole suffers from a lack of digitization [146], which further hinders efficient complex transport systems. Intermodal transport chains are especially at a disadvantage here as they require the exchange of information across multiple actors. Looking at the topic of intermodal transport from a European perspective is especially complex as regulations across member states are not yet unified and the process of this unification through supra-national entities requires thorough negotiations and policy developments. Research regarding intermodal transport in Europe can impact and accompany the a proper development of the sector. For intermodal transport it is especially interesting to get practice-oriented input as most problems arise from practical considerations than from theoretical grounding. Conducting research and empirical qualitative analysis of the intermodal transport sector can show its shortfalls and improvement opportunities. Potential future developments can be made visible for researchers, practitioners and policy makers alike.

This dissertation aims to aid this goal. On one hand, practice-oriented guidance for research opportunities and practice-driven problems is determined. By developing a practice-oriented research agenda, relevant actors can find guidance for research opportunities, policy adjustments and future practical developments and direction of investments within the transport sector. Making the inherent complexity of the intermodal transport comprehensible can benefit the sector and show ways and tools on how to analyze and guide developments within it. Furthermore, the topic of climate change is pressuring governments worldwide to adjust their policies. Their aim is to combat emissions and to enable environmentally friendly transport. This clearly has (side-)effects on the competitiveness of the affected transport systems. Within Germany, a tax on carbon emissions was introduced in 2021. This tax impacts the cost structure of transport modes, especially the ones with high resource consumption. Infrastructure components in a transport system are bound by their geography and therefore inflexible. Additionally transport networks have grown around this infrastructure. With an increase of taxation, these grown networks are especially impacted due to their limitation of adjustment. For intermodal transport systems this is true for terminal and port locations, the railway network and to a lesser extend the highways. Environmental policies are expected to have an impact on the competitiveness of transport systems bound to infrastructure and enable potential shift in market scope. The economic effects of environmentally driven policies are worth to investigate, especially as their impact is likely to increase. Scenario based analysis can provide guidance on the effects of such policies on economic variables. A study regarding the potential scope of intermodal hinterland transport for ports of the northern range in Europe investigates this impact. Finally, an outlook on intercontinental transport opportunities is an interesting way to investigate the potential of intermodal transport and develop the transport mode from a European perspective. With the establishment of the belt and road initiative, a Eurasian rail corridor is emerging that is increasing in popularity. Chinese efforts in infrastructure investments and subsidies for the transport itself foster the land bridge between China and Europe for geopolitical and economic reasons. As this transport corridor is rather new, its opportunities and challenges are topic of on-going investigations and research. Rail transport on such intercontinental scale is faster, yet more expensive than maritime transport, whereas air transport is more expensive yet faster than rail transport (and provide challenges in transporting high capacity and heavier goods). Indications show the establishment of a new transport market segment, especially when comparing rail and maritime transport for shippers between Germany and China. By investigating this new transport opportunity, its opportunities and boundaries can be made more transparent. Additionally, using the new transport corridor can serve as a facilitator for European trade with landlocked central Asian countries. As the transport mode has been fueled by subsidies form the Chinese side, a European perspective needs to show economic benefits of its usage first. This is best done by comparing the existing alternatives and by looking at potential policies that might benefit the Eurasian rail corridor.

1.2 Research Objectives

Intermodal transport systems, and combined rail-road transport systems in particular, with their complexity and advantageous environmental properties, lead to the research objectives of this dissertation. Generally, three research objectives guide the investigations at hand. They are subsequently introduced.

Providing a practice-oriented research agenda enables researchers, practitioners and policy makers alike to effectively improve and understand developments in combined transport systems. The aims is to scientifically provide empirical data collection and analysis to combine practical and scientific views on the issue. This helps to get a thorough picture on current developments in combined transport. The first research objective is therefore formulated as:

> (I) Provide guidance for the development of and practice-oriented research for combined transport by synthesizing practical and scientific input

With the help of the practice-oriented research agenda developed to satisfy the first research objective, further directions for investigations are given. In total six major topic areas for research are developed that range from environmental considerations, operational improvements to assessments of digital and physical infrastructure. As combined transport systems are heavily influenced by policy, focus is laid on environmental regulations. Their influence, especially on economic aspects of transport systems, are likely to increase and change competitive geographic scopes. Investigated through a case study on hinterland transports for ports of the northern range, the effect of economic policies on combined transport system competitiveness can be made visible. Hence the second research objective is as follows:

> (II) Visualize and analyze the economic (side-)effects of environmental policies on the competitive situation of intermodal transport systems in a port hinterland setting

Finally, the development of the trans-Eurasian rail corridor between China and Europe as part of the belt-and-road-initiative offers new opportunities for transcontinental intermodal transport. The benefits for this new transportation segment are clear for countries without proper access to sea ports, yet for well-connected parts of Europe the benefit is still to be investigated. Especially shippers in central Germany, which have both access to several maritime ports and several intermodal rail terminals. Their connection to the trans-Eurasian rail corridor provides an interesting case study to show potential scope of the transport connection. Especially interesting is to make the opportunities and the scope of the transport alternatives visible. This provides opportunity for analysis and enables the assessment of further questions. The third and final research objective is as follows:

> (III) Visualize and analyze intermodal transport opportunities for shippers in central Germany aiming to utilize the trans-Eurasian rail corridor for transports to China

These research objectives set the scope of this dissertation. Each of the research objectives is addressed with a separate investigation, whereas the investigations built upon each others results.

1.3 Scientific Contribution

Scientifically, this dissertation as a whole contributes to the understanding of current challenges and developments of combined transport in Europe and provides an outlook on how the competitive landscape of transportation modes are about to change regarding the implementation of environmental policy measures. Each of the conducted study contributes individually, honoring the set research objectives. First, the development of a practice-oriented research agenda, based on practice oriented input and a structured literature review, aims at providing guidance for researchers, policy makers and practitioners alike, referring to research objective (I). The research approach is distinct to other approaches as it investigates both practical and scientific input. As this thorough assessment is both less common and more complex, this is seen as a unique contribution to the scientific body and addressing a research gap. The developed practice-oriented approach stands in contrast to popular purely literature-based assessments in transportation research and yields interesting results for a wide interest group. The developed research agenda provides six distinct topic areas for further investigation. These topic areas are based on current and future needs of the combined transport sector and highlight gaps and opportunities. The results can be used to effectively improve existing combined transport systems, accompany developments within the sector and suggest efficient use of upcoming technologies to make combined transport more effective and efficient.

Second, a case study is investigated that focuses on North Rhine-Westphalia. The state serves as an interesting and unique case for port hinterland competition of ports of the northern range. It lies in within the reach of several ports, is well connected by several modes and provides large freight transport demands. Honoring research objective (II), a simulation model has been developed to show the current potential scope for hinterland transports per mode and port. Additionally, the model allows for the investigation of the pricing of carbon emissions for transport, essentially a carbon tax, which has recently been implemented in Germany [39]. While the region analyzed presents a unique case for port competition through hinterland connectivity, being in close proximity to five major ports, the model can be used to analyze further regions. The addressed research gap lies in the development of the model at hand and showcasing the suitability of NRW as a model region for analyzing port hinterland competition. Additionally, the analysis of economic effects of environmental policies, especially on the competitive situation of market participants, is a promising field for transportation research and presents a unique scientific contribution of this study.

Third, mode competition on the new trans-Eurasian rail connection to China is addressed. Honoring research objective (III), a case study for exporters in Hesse is developed. Hereby the scope of this new transport route for exports to China is visualized. Hesse as a case has been chosen due to its location and economic importance. The case study shows that rail transport can be economically viable for exports to western, central and potentially some north eastern Chinese provinces. Difficulty in competing with maritime transport can be seen on the densely populated eastern coastal regions, which also present the most economically developed. The employed simulation model was also used to investigate how a (hypothetical) global carbon tax would change the competitive situation. The study contributes to the scientific body two-fold. First, it developed an easily adaptable model to investigate the suitability of utilizing the trans-Eurasian rail corridor. It shows that central Europe might, despite its economic importance, not be the ideal region to establish connections to. Additionally, the study contributes to the scientific body by showing how environmental policies might have an impact on intercontinental transport mode competitiveness which inevitably would lead to redirection of transport flows. The simulation model can easily be adapted to other regions in Europe and to changes in parameters of the transport corridor. This can be especially interesting as eastern European countries are more viable for the use of the rail route due to their geographical location compared to western European countries.

1.4 Structure of Dissertation

The dissertation at hand is structured into seven chapters. Beginning with this introduction chapter, which describes the motivation, scientific contribution and structure of the dissertation, the second chapter gives an introductory overview and theoretical background of intermodal transport systems, the intermodal transport infrastructure in Europe and the intermodal transport market. The goal of this chapter is twofold. Aside from providing background information for the understanding of the subsequent studies its aim is to highlight and explain the complexity of intermodal transport systems. This complexity stems from the organizational needs of intermodal transport systems, its various involved actors, the extensive need for infrastructure and the economic peculiarities of intermodal transport markets in Europe.

The third chapter explains the scientific design and methodological background of the dissertation. Two distinct research designs have been used within the studies of this dissertation. They are research agenda development and case study research. Both research designs make use of multiple methodologies. These methodologies are assessed and explained in detail with a focus on their typical processes and applications within intermodal transport research.

The chapters four, five and six each contain the content of separate studies that were conducted for this dissertation. The chapter have been arranged in the style of scientific journal papers to make them as concise as possible. Verbosity, especially for theoretical and methodological backgrounds are covered in the previous chapters. This writing style has several advantages, as it forces one to write concisely and present results in a clear manner. While the studies build upon each other, the writing style allows for potential publication in scientific journals. All three conducted studies are subsequently introduced.

Within chapter four, a practice-oriented research agenda is developed. This is done by using the delphi method to collect practitioners' input which is then contrasted by a structured literature review. The practitioners' input identifies concrete measures on how to improve combined transport systems. The literature review highlights research efforts of the last decade and shows the focus of the scientific community with regard to Europe. The resulting practice-oriented research agenda is then compiled into six distinct topic areas for further investigation.

The fifth chapter investigates the impact of the newly implemented carbon tax on potential hinterland scope of ports of the northern range in Europe. For this, the case of North Rhine-Westphalia (NRW) has been investigated which presents an interesting focus point for analyzing port hinterland competition, as the region is competed by all ports in the northern range and by multiple transport modes. After the development of a cost-based model incorporating a carbon tax, the model is implemented in a GIS model and different carbon tax levels simulated. With the help of this simulation a sensitivity analysis for potential hinterland scope is conducted, visualized and assessed.

The third study, laid out in chapter six, takes a look at the new possibilities regarding the intercontinental intermodal rail corridor between Europe and China. The investigated case study for Hessian exporters looks at the spatial scope when utilizing the rail connection. After the construction of a cost-based model and its implementation in a GIS model, various simulation runs are conducted. The implementation allows for the visualization of different scopes for maritime and rail transport in China. Aside from different cargo values and their potential scope for this transport mode, a (hypothetical) global carbon tax is investigated to see, if such a tax could significantly improve the competitive situation of rail transport for this relation.

Finally, in chapter seven, the conducted studies are recapped. The results of all studies and the overall dissertation are discussed according to their contributions. Additionally, the limitations of all studies and the overall dissertation are laid out. Finally, an outlook is given on how to build upon and extend the presented studies. Also advice for continuing future research and practical considerations are given.

2 Theoretical Background - Intermodal Transport

The theoretical background for intermodal transport systems is depicted in three main sections. The first section provides general definitions, an overview on how intermodal transport systems are organized, their different actors and operative challenges. Also the different types of intermodal transport are presented. The following section depicts the infrastructure for conducting intermodal transport systems. Hereby the focus is on road, rail and terminal networks, and ports and their respective hinterland in Europe. Finally, the market for intermodal transport in Europe is assessed regarding market segments, volumes and an outlook on transport demand.

2.1 Intermodal Transport Systems

Intermodal transport reflects the movement of goods in one and the same loading unit or road vehicle, which uses successively two or more modes of transport without handling the goods themselves in changing modes [351, p.17]. Combined transport is intermodal transport where the major part of the European journey is by rail, inland waterways or sea and any initial and/or final legs carried out by road are as short as possible [351, p.18]. Intermodal transport therefore reflects the combination of at least two modes for the transport of freight or people with a transshipment at an intermodal terminal [66]. Keeping pre- and on-carriage as short as possible in this case leads to economic benefits due to the more economic transport via rail [298]. The terms intermodal transport, multimodal transport, combined transport and co-modality are often used synonymous for transports involving more than one transport mode [296], although having slight differences in their concepts. A modern approach on intermodal transport is synchromodality, which aims at enabling the switch between transport modes based on real-time information [4]. Aside from containerized transport, intermodal transport systems allow for various types of

cargo. They provide the ability to transport containers, unaccompanied semi-trailers, either cranable or non-cranable or even full truck units in a so called rolling highway [55]. The need for special transshipment capabilities in this case has been the source for various infrastructural and operational innovations in the intermodal transport sector [354].
Intermodal transport has several advantages over uni-modal transport. Among the advantages are requirement for less truck drivers, the use of standardized equipment and less consumption of resources and therefore better sustainability [186]. Among the disadvantages are lack of speed, reliability issues due to the involvement of multiple modes, lack of delivery frequency, high infrastructure costs and potential for damage due to the transshipment process. Also certain goods can't be transported via intermodal transport due to regulations [186]. Especially the dependence on infrastructure for main-carriage and transshipment limit the flexibility of transport. Shippers need to transport their goods to certain intermodal terminals for transshipment, which adds additional costs, and their goods arrive, in the case of continental intermodal transport, again at a terminal from where it needs to be carried on. To organize such a transport chain, the coordination of multiple actors is necessary. Aside from pre-carriage and on-carriage, that are conducted via trucking, the main-carriage involves multiple actors from the infrastructure, suppliers of rail services, operators for combined transport and terminals and forwarders. This makes the process highly coordination intensive. Here lies a challenge when dealing with intermodal transport, both from a practical and from a research perspective.
The cost and sustainability advantage of intermodal transport shows especially in transports over large distances. As intermodal transport necessarily needs at least two transshipments, the cost advantage of the main-carriage via rail offsets the higher transshipment costs only after a certain distance. Figure 2.1 shows a typical intermodal cost function with the cost of trucking in comparison. As can be seen, pre-carriage and on-carriage have the same variable costs as truck transport. The transshipment costs are set as fixed. For the main-carriage variable costs are assumed, yet the transport mode has high fixed costs due to the equipment and organizational preparations required. Usually a distance of 300km is assumed as the threshold for intermodal transport to be viable. Yet for port-related transport chains and barge transport this has been challenged [234]. Statistics confirm this threshold as figure 2.2 shows. By tonne-kilometer the transport volume can be classified into a 300km-900km bracket and a bracket over 900km. Both brackets represent roughly the same transport performance.

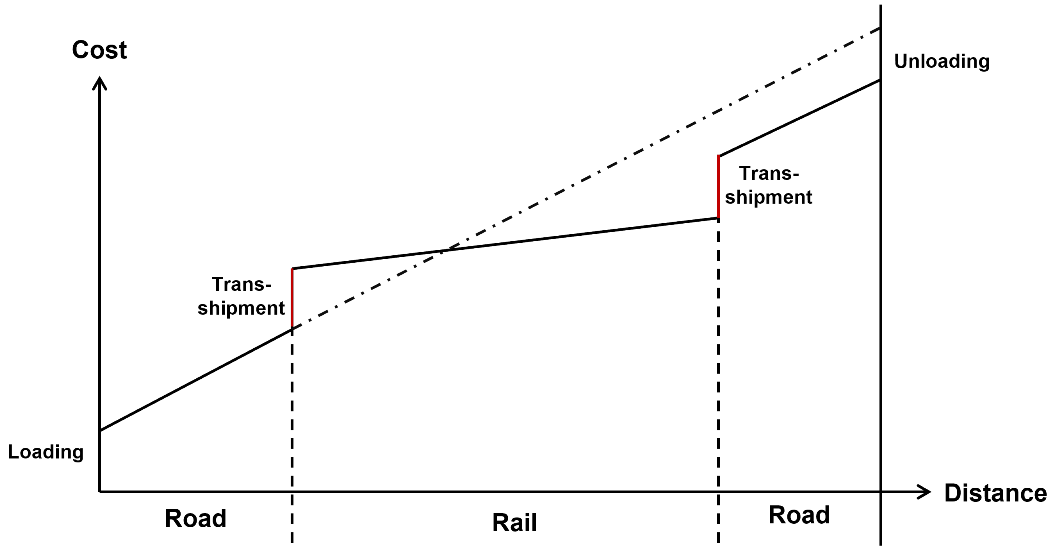


Figure 2.1: Intermodal and unimodal transport costs by distance
Source: Own design adapted and extended after Monios [249, p.412]

2.1.1 Organization of Intermodal Transport Chains

Intermodal transport has more complex challenges than its unimodal competitors. The organization of the main-carriage, the multiple actors and infrastructure involved, and more complex planning problems add to the challenges in assuring seamless intermodal transport. To make the process of organizing intermodal transport comprehensible, a typical transport chain and the actors involved in it is depicted. Furthermore, the different types of intermodal network designs are explained. Finally, for a better comprehension of the uniqueness of intermodal transport, common operative challenges are discussed.

Intermodal Actors & Transport Chains

According to the International Union for Road-Rail Combined Transport (UIRR) there are essentially five major actors in an intermodal transport chain. These are infrastructure managers (IM), railway undertakings (RU), intermodal or combined transport (CT) operators, terminal managers and the clients or users of intermodal transport which are usually shippers or forwarders [349]. Additionally, as they are large users of intermodal transport capacity, the role of port authorities is described as well. Figure 2.3 provides a system model of typical supplier relationships of actors in an intermodal transport chain.

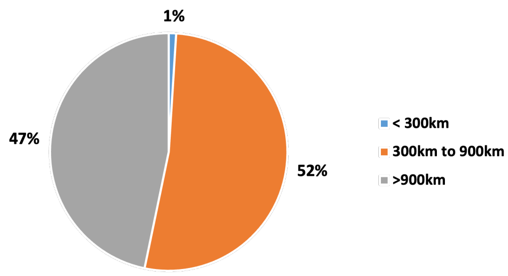


Figure 2.2: Transport share of different distance segments for intermodal transport (by tonne-km) in Europe (2022)
Source: Own design based on European Commission [98, p.71]

There are multiple ways on how to operationally organize an intermodal transport chain. In a typical transport chain a shipper commissions a forwarder with the transport of goods. The forwarder then organizes the pre- and on-carriage to and from the terminal by commissioning a road haulier, or transporting the goods themselves, and buys transport capacity on a train provided by the intermodal operator. The capacity provided by the intermodal operator had previously been organized by ordering trains from a railway undertaking, which have reserved routes in a network managed by a railway infrastructure manager. The physical transport is then conducted by the railway undertaking, the terminal operator and the road haulier that have been commissioned for the transport. Although less common, it is also possible for the intermodal operator to be more vertically integrated into the transport chain. Here functions from the forwarder are conducted by the intermodal operator, e.g. the organization of pre- and on-carriage. Especially larger logistics and transportation companies offer this service as it potentially reduces the complexity of transport operations yet requires a transport network to integrate the operations in. In this scenario the shipper can potentially commission the intermodal operator directly [386]. For better comprehension, all actors mentioned, their specific tasks and peculiarities are laid out in more detail. Actors working closely together are grouped for better overview. Additionally to the actors mentioned the role of port authorities is explained as well due to their importance for maritime intermodal transport chains.

Shipper & Forwarder Shippers are the starting point of intermodal transport processes. They usually commission a freight forwarder to arrange the transport for their cargo [214, p.11] if they don't want to operate on an own account model which comes with additional

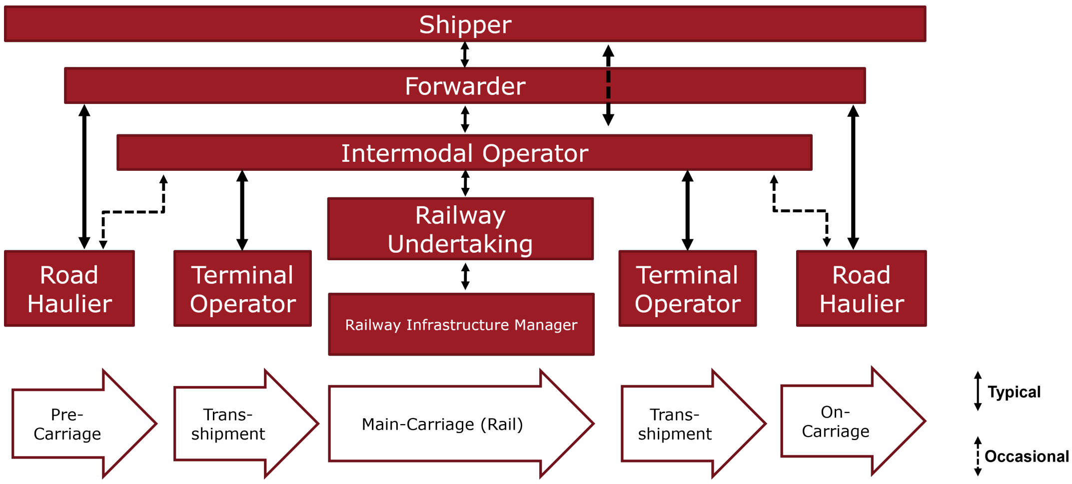


Figure 2.3: System model of typical supplier relationships of actors in a continental intermodal transport chain
Source: Own design adapted after Woxenius and Bärthel [386, p.21]

challenges [121]. Depending on the needs of a shipper, e.g. type of freight and service quality requirements, shippers' cargo might be suitable for intermodal transport. With a growing awareness of environmental impact, shippers are more and more considering sustainable transport organization, which, among other alternatives, favors intermodal transport [205]. Among the advantages for shippers using intermodal transport are lower costs and emissions, yet the increased coordination efforts might bring issues of reliability and integration into logistics concepts with it. Therefore the preference for intermodal transport for shippers depends, among other factors, on the perception a shipper has of it [111, 345].

The freight forwarder usually gets commissioned to handle the transport process and both decide on key aspects of the transport process and handles the administration. In this way it acts as an intermediary between the shipper and the transport sector [294, p.18]. When deciding for intermodal transport, forwarders need to arrange both pre- and on-carriage, either using own trucks or transport service providers, and buy capacity for the needed rail routes provisioned by an intermodal operator. As the commission of a freight forwarder comes with the liability to properly conduct the transport, they need to handle reliability and service quality issues, which becomes difficult compared to trucking due to the multiple actors involved. Furthermore forwarders handle all the administrative tasks that are associated with the transport like handling of documents. A key aspect for forwarders is the choice of transport mode. Intermodal transport has its strength in longer distance transport as its cost advantage comes to fruition [390]. Yet there are investigations on how to enable economic intermodal transport even for shorter distances [293]. Aside from economic aspects of mode choice, sustainability aspects also have an influence on the relationship between shippers and forwarders as mode choice is influenced by the shipper's perspective on it [92] and by the way contracts are set up [93]. Finally, the mode choice needs to match the logistics concepts and needs of the shipper, which always has to be estimated by the sectors the shippers operate in, e.g. retail [248].

Intermodal Operator & Terminal Manager Intermodal operators are the general organizers of rail transport, yet it is difficult to define their clear role depending on their vertical integration and it may encompass the organization of rail transport and pre-carriage and on-carriage [72]. Yet, there are some functions unique to this role. One of the main tasks is the commission of railway undertakings to serve certain routes. The transport capacity of these trains are then marketed to forwarders or directly to shippers with the goal of fully utilizing the train's capacity. Also they are responsible to reserve transshipment capacity at the respective terminals.
A terminal operator is the actor that provides services within a terminal, typically the transshipment of goods and certain other value-adding services, e.g. storing freight temporarily at the terminal [294, p.19]. With intermodal transport, depending on the type of transport chain e.g. port hinterland or continental transport, multiple transshipments need to occur giving terminals a central role in the transport system.
There are several typical questions arising around intermodal terminals. The assessment of establishing new intermodal terminals involves a multitude of stakeholders and properties like the location of it and its potential customers [25]. These factors, especially the size of the terminal, has an impact on the cost structure of it [375]. Aside from these fundamental investment aspects of terminals, its layout design [332] and the optimization of its operations [82, 142] are other typical challenges. Terminals are a focal point for innovation in the intermodal sector, especially for atypical freight types [344], yet it seems difficult for these innovations to penetrate the market due to their perceived neutral value [376]. Also strategic questions, e.g. which services to offer, are arising around intermodal terminals [286].

Railway Undertaking & Railway Infrastructure Manager Railway undertakings provide the operative conduction of rail transport. They provision the trains and conductors and reserve routes within the rail infrastructure. Their goal is to fully utilize their trains in order to avoid standing times due to the cost of them. Railway infrastructure managers provide the tracks for conducting rail transport. There are several tasks and responsibilities for railway infrastructure companies. Among the most important tasks is the maintenance of the infrastructure with the goal of increased availability, reliability, and safety, along with decreased maintenance costs [83]. Maintaining infrastructure consumes large budgets due to its high investment costs [202]. Therefore a challenge lies in making it cost effective and to measure the performance of it [327]. Another main task is the regulation of access to the infrastructure, which usually occurs by charging access fees. This alone can lead to several planning problems as different fees for routes and operations can make sense [263]. The European Union (EU) aims at harmonizing these access charges, which would lead to a convergence of them across borders [67].

An on-going debate is the separation of railway operations from infrastructure provision as to incorporate more market mechanisms into the sector. A separation has several advantages like reduction of unit costs, creation of intra-rail competition, better focus on services provided and a clarification of public policy and a better balance between the roles of the public and private sectors. With separation two main challenges come along, capacity management and pricing policies [341]. This has led to several approaches in railway liberalization and access. Liberalization efforts are usually country specific due to the peculiarities of their markets and there are various forms of governance approaches to it [119]. Sweden has been one of the early adopters of liberalization [5] with a dominant state-owned actor while more recent liberalization efforts in the newer EU member states have led to far more fierce intra-rail competition [216]. Liberalization usually improves the operative performance of the railway sector, especially regarding the utilization of resources and technical improvements [13]. While non-discriminating access to railway networks across Europe has been mostly established, several problems for new market entrants, due to the natural monopoly of infrastructure intensive services, occur. An interesting approach could be asymmetric regulation that allows to charge new entrants lower fees to fuel competition [256].

Port Authority Port authorities are commissioned and responsible to manage sea ports. Regarding intermodal transport, they usually operate multiple intermodal terminals within the port area. The regions where transport to and from these terminals originate is the so-called hinterland of the port and can be seen as its marketable area. Traditionally port authorities have being responsible for managing operations within the port area. With a growing competition among ports [58], focus shifts from inner port efficiency to hinterland connectivity, especially with ports having overlapping hinterland [3, 130]. The development of intermodal transport services to port hinterlands therefore becomes more important, which leads to a more active role of port authorities in establishing such connections [357, 14].

Operative Challenges in Organizing Intermodal Transport

Aside from the stated advantages and disadvantages of intermodal transport, there are several challenges that occur when organizing and operating intermodal transport chains. For better comprehension of the complexity of intermodal transport systems, three major challenges are presented in detail.

Matching short-term demand with long-term supply A major challenge in organizing intermodal transport chains is matching the necessities of long-term planning for operators with the often short-term demand fluctuations by shippers and freight forwarders. Figure 2.4 shows the stepped cost function for intermodal transport with a linear demand revenue function. If the actual demand is below full train capacity, the train runs underutilized and potentially at loss, if actual demand is higher than train capacity, potential revenue is lost. The problem is severe, as the planning and organization process for the main-carriage via rail of intermodal transport is not flexible due to the need to reserve routes and provide equipment. Also once reserved routes can't easily be handed over to other rail undertakings which results in high fixed costs. The variable costs of intermodal transport are mainly the pre-carriage and on-carriage and the transshipment. Intermodal operators therefore need to project transport demands and plan their frequency of main-carriage runs accordingly. If transport demands fluctuates, trains might be underutilized. This will result in lost profits or even losses if the fixed costs of the train can't be balanced with shipped freight. Aside from better forecasting of transport demands and selling transport capacity in bulk to forwarders offsetting the capacity problem to them, there are several approaches in solving this problem. Reinhardt has investigated this capacity problem for maritime transport chains by looking, among other things, at overbooking strategies [291]. A modern concept for solving this problem is synchromodal transport. Here the mode of transport is decided shortly before the transport takes place, trying to keep most freight on rail, yet allows for flexibility when freight can't be transported with the sufficient quality levels [4]. The implementation of synchromodal transport is difficult as it requires various aspects like policy, information and communication technology (ICT) and transport infrastructure, planning approaches and awareness among shippers to be aligned [283]. Research conducted in synchromodal transport has focused mainly on quantitative approaches as it offers plenty of optimization potential [297].

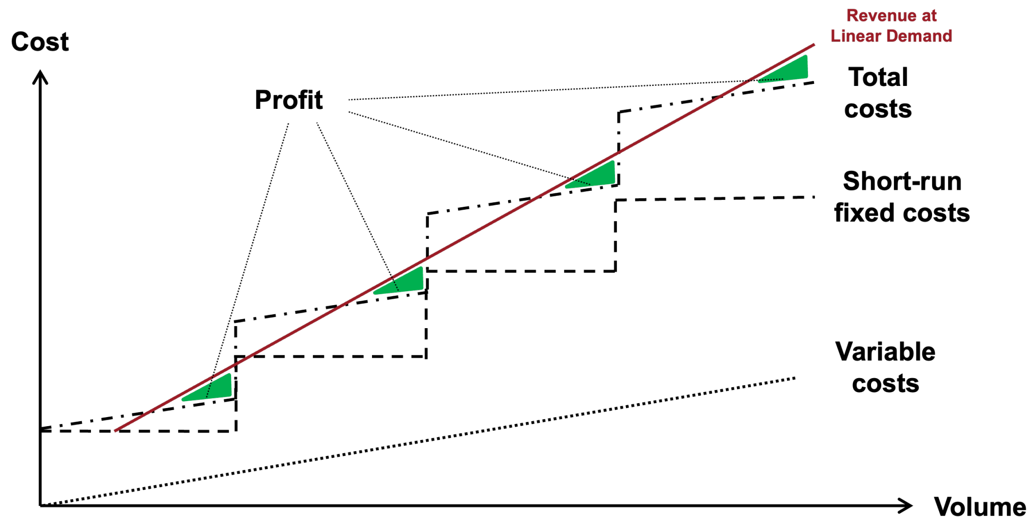


Figure 2.4: Stepped cost function for intermodal transport
Source: Own design adapted and extended after Monios [249, p.413]

Capacity Limits of Railway Infrastructure The railway network is essential to conduct seamless intermodal transport. For most European nations the infrastructure is used by multiple ways of transport meaning that high-speed and local passenger trains share the same tracks as freight transport [6]. As figure 2.5 shows both passenger transport and freight transport have tremendously increased for Germany since 2005 while the length of the railway network has stayed almost the same size [88, p.52ff]. This heavy utilization brings additional pressure on the railway infrastructure. This heavy use of the railway infrastructure leads to potential bottlenecks, especially with busy routes. If any of the trains running on them have delays, this will spread through the system. Due to regulations in Europe, passenger transport runs at higher priority than freight transport [364]. A delay in passenger transport causes delays in freight transport as assigned railway blocks and time-slots for freight transport might be missed. This can lead to a cascading line of delays where freight transport is at the major disadvantage. A way to improve the existing infrastructure are operational technological developments like the European Train Control System (ETCS). The goal of ETCS is to harmonize over 20 existing train control systems in Europe. By doing so it creates free market access, assures safe operations and interoperability, increases rail capacity and reduces life cycle costs of rail infrastructure and maintenance [315, p.13f]. There are three levels of ETCS that can be subsequently implemented. In the final implementation ETCS-3, a continuous

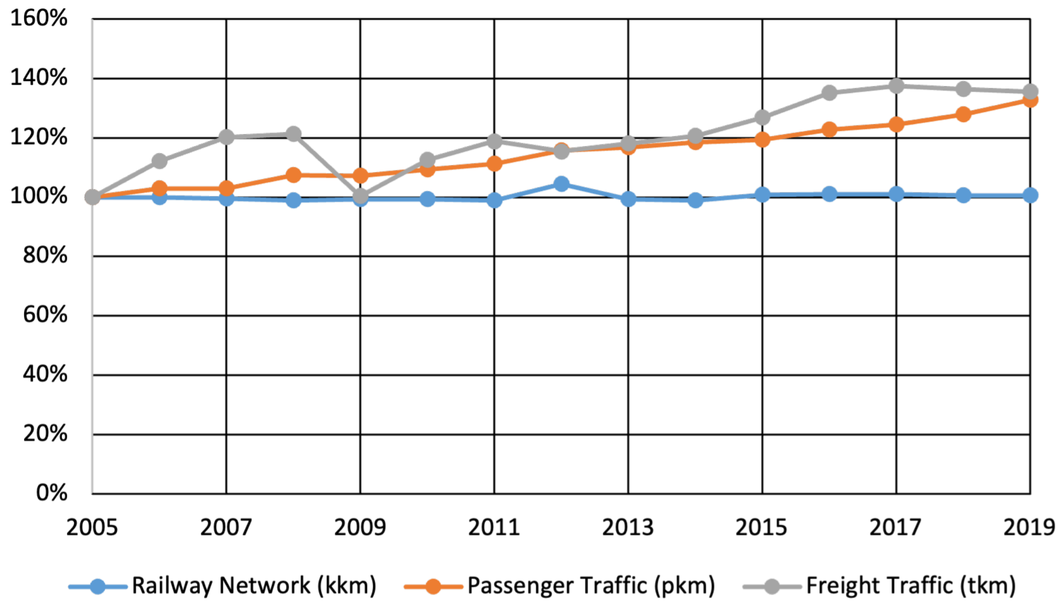


Figure 2.5: Development of railway network and traffic performance in Germany (2005-2019)

Source: Own design based on Eisenmann et al. [88, p.52ff] (Kraftfahrt-Bundesamt)

data tracking and position reporting occurs relieving the railway infrastructure managers from locking track sections statically, an overview of the different levels with illustrations can be found with the European Commission [97]. The capacity increase of railway infrastructure, which heavily benefits intermodal transport, comes at level 3 by allowing moving blocks instead of static block assignments [378].

Coordinated information provision along the transport chain Coordinating intermodal transport chains can be a challenging task as information flows become complex. There are two main sections of information exchange when it comes to intermodal transport. In the bidding and negotiation stage contractual needs and information need to be exchanged between the actors to set up a business relationship. In the production stage information about the physical flow of freight needs to be exchanged, where different intermodal network designs add to the complexity of this process [295]. The difficulty in information provision is that there are multiple actors involved in the transport chain that need information that other actors can't or don't want to provide as the transparency it brings might give them a disadvantage. Questions of data formats, common platforms and their operator and charges for the usage of these platforms are difficult to solve. First digital platforms that try to solve both the market function and the transport organization needs have been developed for intermodal transport, e.g. Modility [244] or RailFlow [289]. Yet the development of data exchange standards in the intermodal transport sector needs to keep up. A first attempt to standardize information exchange has been the project KV 4.0, funded by the German Federal Ministry for Digital and Transport and conducted by a wide consortium of industry player [40]. The work packages and scope of the project are depicted in figure 2.6. The goal of the project was to create a common data hub for all actors involved and involves data provision from these actors in a commonly agreed format.

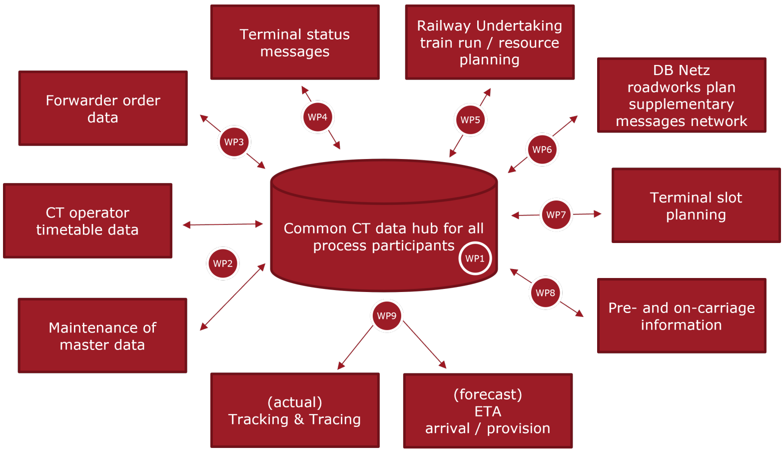


Figure 2.6: Work packages of project 'KV 4.0'

Source: Own design adapted and translated based on Kombiverkehr press release for 'KV 4.0' project [181]

2.1.2 Types of Intermodal Cargo

Making use of intermodal rail transport can be done in various forms. Essentially three major ways of transport are used, which are containerized transport using swap-bodies or standardized containers, the transport of unaccompanied semi-trailers and the so-called rolling highway where full truck units are loaded onto a train. All these modes of transport have their peculiarities which require different transshipment facilities and organization in transport. Figure 2.7 shows the shares among intermodal rail transport in

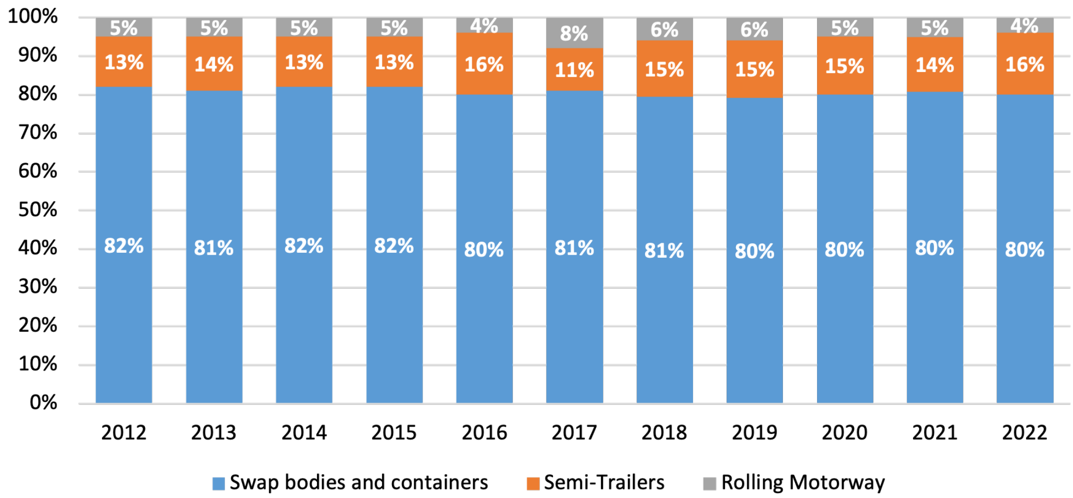


Figure 2.7: Consignment shares by tkm of combined transport in Europe
Source: Own design based on European Commission [98, p.71]

Europe by consignments. Consignments in this case mean that a transported semi-trailer is equivalent to one unit of the rolling motorway or one swap body / container over 16t and over 8,30m length or two swap bodies / containers under 16t and below 8,30m length. It clearly shows that containers and swap bodies are the most popular type of intermodal rail transport, followed by semi-trailers and the rolling highway on the last spot. For a better understanding, all three types are introduced subsequently.

Containers and Swap-Bodies

Containerized transport of swap-bodies or containers is the most popular way of conducting intermodal transport [98, p.71]. Within this type of intermodal transport goods are loaded into a standardized container which are transported via trucking to a terminal, then transshipped onto a train, transported to another terminal on that train, transshipped again on another truck and transported to the final destination. There is a wide variety of different container types available for intermodal transport. The most common types are standardized 20ft (20’ L x 8’ W x 8’6Ḧ) or 40ft (40’ L x 8’ W x 8’6Ḧ) containers which have been established for international sea trade [299]. Aside from the regular sizes these types of containers can also come in a high cube version, which allows for loading higher goods and a half height version. Figure 2.8 depicts the containers. Aside from these multi-

(a) 20ft container (b) 40ft container

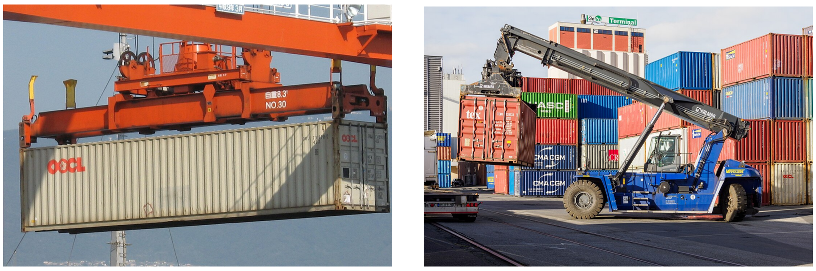
Figure 2.8: Standard container
Author: Gazouya-japan **Source:** commons.wikimedia.org - (a)|(b) **License:** CC BY-SA 4.0 - no changes made - see chapter 'Copyright Licences & Notices' for further information

purpose containers there are also specialized container types that have been designed for special purposes and to different customer needs. Reefer containers are used for transporting temperature sensitive goods like vegetables or fruits and usually come with an active cooling system which is energetically independent from the transport mode it runs on. Insulated containers also aim to keep the temperature of goods, yet don't provide active cooling. Then there are containers for specialized loading, e.g. open top containers and flat racks that allow for loading bulk goods. Double door and side door containers allow for better loading depending on the goods transported. Finally, tank containers allow for the transport of liquids and are commonly used by the chemical industry. The

(a) Reefer (b) Tank (c) Flat Rack

Figure 2.9: Selection of special container
Author: Gazouya-japan **Source:** commons.wikimedia.org - (a)|(b)|(c) **License:** CC BY-SA 4.0 - no changes made - see chapter 'Copyright Licences & Notices' for further information

biggest advantage of using containers for transport is their standardization. They can usually be loaded on any truck and transshipped at most intermodal terminals. Depending on their sturdiness it might be able to stack multiple containers on top of each other to save space in terminals. A reason for being non-stackable comes along with a general disadvantage of containerized transport. The equipment requires additional constructions that make them heavier which takes away payload as in Europe truck transport weights are inconsistently restricted [157]. For Germany legislation allows for intermodal pre-carriage and on-carriage to be 44to of weight [366]. Figure 2.10 shows the transshipment process at an intermodal terminal using a crane for standardized containers and a reachstacker.



(a) Gantry Crane (b) Reachstacker

Figure 2.10: Transshipment of containers for intermodal transport
Author: (a) Gazouya-japan (b) JoachimKohler-HB **Source:** commons.wikimedia.org - (a)|(b) **License:** CC BY-SA 4.0 - no changes made - see chapter 'Copyright Licences & Notices' for further information

Unaccompanied Semi-Trailer

The use of unaccompanied semi-trailers has become more popular in recent years. Within this mode of transport a semi-trailer is transported to a terminal, detached from the trucking unit and then transshipped onto a train. After rail transport and arrival at a terminal, the transshipped semi-trailer needs to get picked up by another trucking unit again and delivered to the final destination. By using this type of intermodal transport, lighter semi-trailers with potentially higher payload can be used. At the disadvantage it binds the semi-trailers for a longer time which can be especially difficult for smaller forwarders and transporters and requires additional planning. A problem with transporting semi-trailers intermodal is that the majority of semi-trailers, between 85% [343] to 90% for semi-trailers in the European Union [50], are not cranable. These non-cranable semi-trailers require special equipment and facilities to enable transport via rail. These facilities incur investment costs, additional to existing intermodal terminals or wagons,

(a) Transshipment (b) Rail transport

Figure 2.11: Transport process for cranable semi-trailers
Author: (a) Kögel (b) Reinhold Möller (Ermell) **Source:** commons.wikimedia.org - (a)|(b) **License:** CC BY-SA 4.0 - no changes made - see chapter 'Copyright Licences & Notices' for further information

and require therefore a high initial investment to enable intermodal transport for this transport type. Several solutions for non-cranable semi-trailers exist. Figure 2.12 depicts the solution of three exemplary ways. NiKRASA[1] has been developed by TX Logistik [346]. Its functioning is to park a semi-trailer on a special platform that then can be lifted by standard vertical transshipment facilities onto a wagon. CargoBeamer are specialized wagons that enable horizontal transshipment by extending a platform from the wagon to park the semi-trailer on and then retract the platform into the wagon [50]. Finally, the solution of Modalohr, which has been renamed to simple LOHR-system, has wagons with a swivel function to let truck units drive on it from the side, park the semi-trailer (or potentially also up to two trucks) and then swivel them back in [211]. Despite these advancements in technology the market potential might be limited [344].

Rolling Highway

The so-called rolling highway, a form of accompanied intermodal transport, loads whole trucking units including their semi-trailers onto trains. These then transport these units to another transshipment point where they get unloaded and continue their transport to the final destination. At the whole transport process, the driver usually stays on the train in a

[1] An acronym for 'Nicht kranbare Sattelauflieger' which translates to 'non-cranable semi-trailer'

(a) NiKraSa (b) CargoBeamer (c) Modalohr

Figure 2.12: Transport solutions for non-cranable semi-trailers
Author: (a) TX Logistik (b) Handpl1b (c) Poudou99 **Source:** commons.wikimedia.org - (a)|(b)|(c) **License:** (a)(b) CC BY-SA 4.0, (c) CC BY-SA 3.0 - no changes made - see chapter 'Copyright Licences & Notices' for further information

special compartment. Figure 2.13 shows the loading and transport of the rolling highway. The advantage of this rolling highway are, aside from the saving of fuel and other financial

(a) Loading (b) Rail Transport

Figure 2.13: Rolling Highway
Author: (a) JoachimKohler-HB (b) JoachimKohlerBremen **Source:** commons.wikimedia.org - (a)|(b) **License:** CC BY-SA 4.0 - no changes made - see chapter 'Copyright Licences & Notices' for further information

obligations, the possibility for drivers to use the time on the train as recovery time and therefore not adding to their driving time limits [180]. A disadvantage of this type of intermodal transport is the need for specialized train sets that can accompany the whole truck units. Due to this fact, several providers with solutions are in the market.

2.1.3 Regulations and Policy for Intermodal Transport

Regulations for intermodal transport can take place on different levels. For reference, figure 2.14 provides an overview and a hierarchy of the different regulatory environments relevant for Europe. Policy regulations aim at setting market rules (e.g. subsidies, regulations and taxes) and provide infrastructure. Supranational entities have been given power

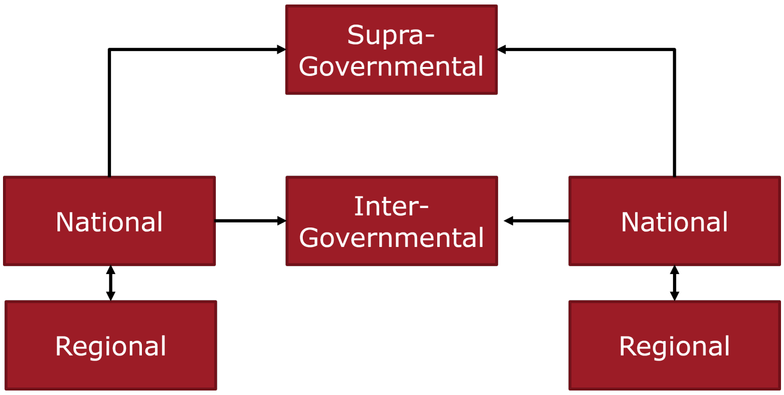


Figure 2.14: Regulatory Bodies for Intermodal Transport
Source: Own design

over sovereign entities to set policies. For Europe the most influential supranational entity is the European Commission. It both assigns budgets and sets rules for the development of European transport market [46] and aims at unifying standards [133]. With its focus on cross-border infrastructure, the Trans-European Transport (TEN-T) network, set up in the treaty of Maastricht in 1992 [340], aims at completing a single European transport market [328, 227] with benefits on a European level but causing cost on a national level [144]. The transport corridors aim to increase the efficiency of transport [1], connect major transport hubs (e.g. the ports in western and southern Europe with its hinterland) and in its latest revision the easy movement of military capacities [339]. Aside from supranational regulations, decentralized approaches can lead to intergovernmental competition [353]. Regulations on a national level have changed over time. With the rise of the European Union, national regulations aim at harmonizing rules within the member states of the EU [270, 173]. In accordance with these regulations, national governments can still provide subsidies, set specific rules for the conduction of transport and build infrastructure. Within the national setting, regional policies usually concern business developments and details of infrastructure planning.

2.2 Intermodal Infrastructure

As intermodal transport incorporates at least two transport modes, it relies heavily on road infrastructure for its pre- and on-carriage and inland waterways, railways and related terminals for its main-carriage and transshipment. In the case of hinterland transport, maritime ports in Europe play a major role as an origin and destination of transport capacity. Historically, infrastructure has been of national and regional concern. Regulation and funding aimed to cater the needs of the economy in proximity. This led to different (and potentially incompatible) transport systems, where standard setting has been a requirement, like in railway infrastructure. These different standards make cross-border traffic more difficult, potentially hindering easy traffic.

2.2.1 Road & Railway Network

Europe has an extensive road and railway network. The current state of the main motorways and railways that are included in the TEN-T networks in Europe can be obtained through the European Commission's TENtec Interactive Map Viewer [104]. Motorways allow for fast transit of freight and are supplemented by main and national roads. The countries within the European Free Trade Association (EFTA) with the longest network are depicted in figure 2.15. Railways can be distinguished by their electrification. The countries with the longest network for railways are depicted in figure 2.16. With a more extensive railway network, more opportunity for intermodal rail transport is available. The largest European countries, Germany, France, Poland, Italy and Spain, also have the longest railway network. The electrification of railways is important in two ways. First of all, electrified railways can be operated more efficiently due to the substitution of diesel trains. This not only makes transport cheaper but also more environmentally friendly. The second aspect is that thorough electrified railways allow for the operation of purely electrified trains, which is not possible if certain parts of the railway network are obliged to use non-electrified trains or dual powered ones. There is a lack of technical unification in European railway networks that makes cross-border traffic more difficult. Two aspects are especially important as they require infrastructure investments to adjust. Due to historic developments and belongings, central and eastern European countries use different gauges that requires additional transshipments or specialized transport equipment to allow for cross-border transport. While for most of central and western Europe the standard gauge of 1435mm applies, there are two main special cases. The Iberian peninsula uses a wider gauge with 1668mm just like the states from the former eastern block with the gauge of 1520mm and Finland with 1524mm. The second aspect

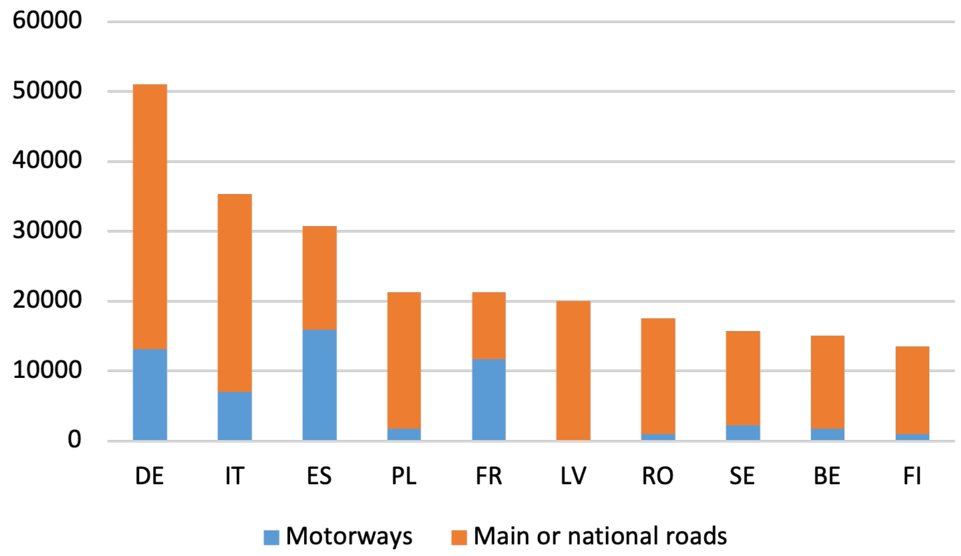


Figure 2.15: Top-10 countries in EFTA by road network length (in km) (2021)
Source: Own design based on European Commission [98, p.79f]

is electrification standards. Throughout Europe there are multiple systems in place that differ both in current and frequency [98, p.82]. Historically grown, these systems are difficult to standardize although technical solutions for cross-border traffic exist in the form of modern locomotives that can handle multiple electric systems [326]. Alternatively diesel locomotives can be used at the disadvantage of higher costs and emissions, although hybridization efforts could make them more sustainable [62]. An overview of the different gauge and electric systems can be seen in Figure 2.17. To foster cross-border trade, the European Union has set the goal to make different traffic systems inter-operable and connect different countries through corridors. The directive (EU) No 1315/2013 regulates the Trans-European Transport Network (TEN-T) [105]. Fostering the development of 11 different corridors for rail, barge and trucking, the goal is to establish the 9 core corridors by the year 2030. A thorough connection of the member states of the EU should be completed by 2050. With the completion, an easier and seamless transport of goods and people will be achieved and positive economic effects for regions connected to them can be expected [138]. Figure 2.18 shows the five out of nine core corridors within the TEN-T framework that run through Germany. Especially two corridors are interesting to notice as they have gotten lots of coverage in recent years. The so-called 'North Sea–Baltic

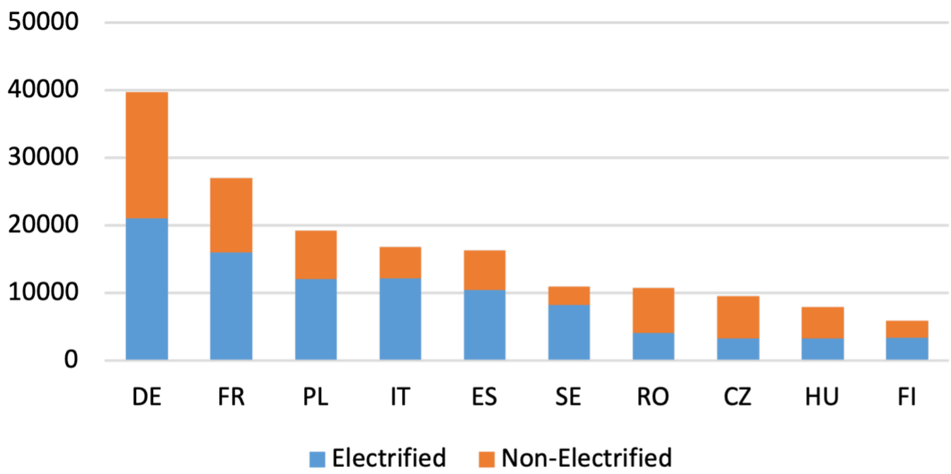
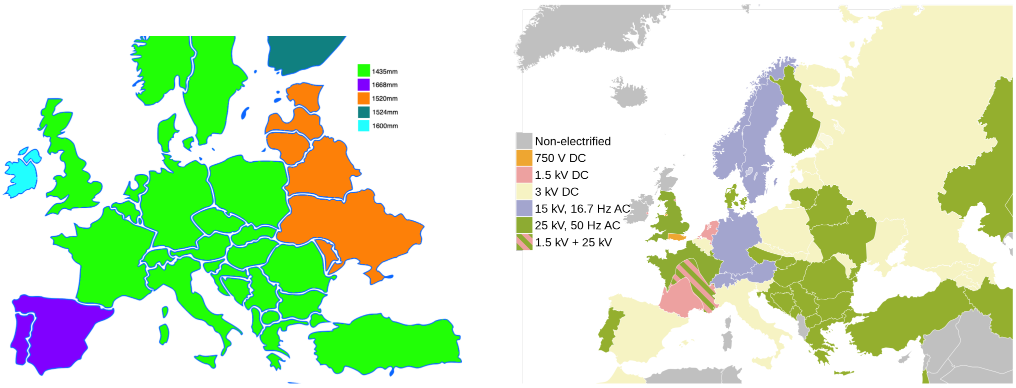


Figure 2.16: Top-10 countries in EFTA by railway network length (in km) (2021)
Source: Own design based on European Commission [98, p.79f]

Corridor', corridor 02, aims at connecting Helsinki in Finnland with a tunnel to Tallinn in Estonia and then via rail through the Baltic states and Poland all the way to the ports of the northern range. Under the name Rail Baltica, the corridor will strongly benefit a deeper integration of the European east to the central countries [189].
The 'Rhine-Alpine Corridor', corridor 06, aims at connecting Rotterdam in the Netherlands and Antwerp in Belgium with their large ports all the way through Germany and Switzerland, with the port city of Genoa in Italy. The corridor is one of the busiest in Europe which has sadly come to mind after a construction site collapse near Rastatt in southern Germany that led to large re-routing of freight [288]. It also aims to make use of the Gotthard base tunnel, which is the worlds longest traffic tunnel [113]. It became operational in 2020 [43].

2.2.2 Terminal Network

Europe has an extensive network of terminals. A current map of locations of both rail terminals and tri-modal terminals, which include facilities for barge, rail and truck transport, can be obtained through Intermodal Map [156]. While the density of tri-modal terminals follows the main rivers and port locations in Europe, the train terminals are mostly located in regions with higher population density. Especially noticeable are the terminals in the



(a) Gauge **(b)** Electrification

Figure 2.17: Railway gauge and electrification systems in Europe
Author: (a) Own design (b) Jklamo & N299 **Source:** (a)(b) based on European Commission [98, p.82]
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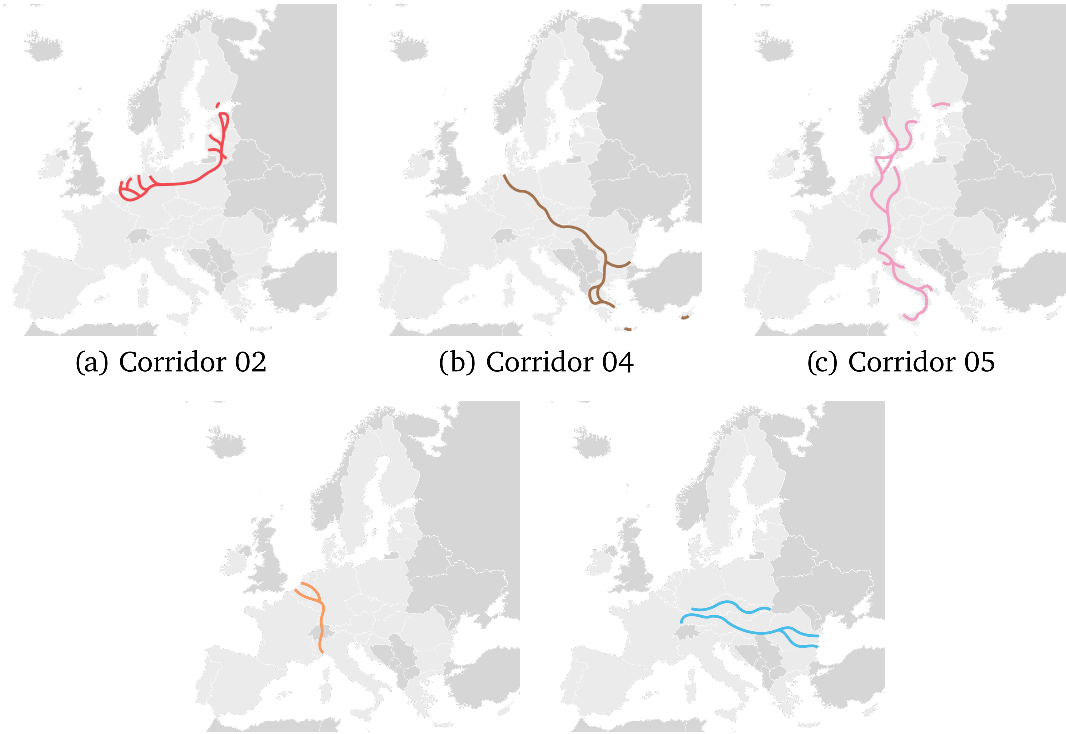
area of the so-called 'blue banana' [114], that spans from southern England, through the Benelux countries and Germany all the way down to northern Italy. When zooming in on terminals in Germany at Intermodal Map [156], it can be seen, that tri-modal terminals mostly follow the rivers Rhine, Danube, Elbe and Weser, while rail terminals are mostly located in regions with high population density. Terminals have certain characteristics like the number and types of transshipment facilities (e.g. gantry cranes and reachstackers), available storage areas, capability for different intermodal cargo types and services around the transshipment and rail transport [377], which offer opportunities for additional value-added services at terminals [286]. With a potential permissible length of freight trains in Europe for 740m, line throughput can be increased [320] and according to the TEN-T regulations there is a goal in making this kind of train the standard length by 2030 [339, p.19] putting terminals under pressure to comply.



(a) Corridor 02 (b) Corridor 04 (c) Corridor 05

(d) Corridor 06 (e) Corridor 09

Figure 2.18: TEN-T Core Corridors through Germany

Author: Enekorga **Source:** commons.wikimedia.org - (a)(b)(c)(d)(e) **License:** CC BY-SA 4.0 - no changes made - see chapter 'Copyright Licences & Notices' for further information

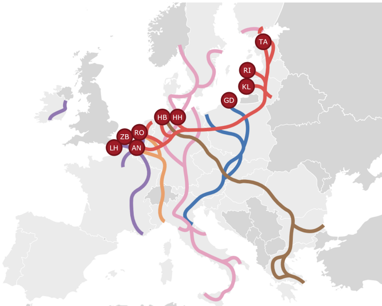
2.2.3 Ports

Ports, as an infrastructure component, play an important role for intermodal transport chains as origin or destination of large transport capacities. Their reach, the so called hinterland, can be served via rail, waterway or truck depending on geographical and infrastructural circumstances. Usually multiple modes are used due to the sheer capacity of maritime ships, which in case of the 'Suezmax Megamax 24' class can hold up to 23.000 twenty-foot equivalent units (TEU) [112]. The 10 largest ports in Europe by containerized throughput are depicted in table 2.1. The TEN-T strategy of the European

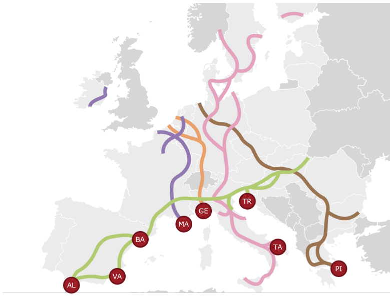
#	Name	Country	Throughput (mio. TEU)
1.	Rotterdam	Netherlands	14.455
2.	Antwerp	Belgium	13.500
3.	Hamburg	Germany	8.262
4.	Valencia	Spain	5.052
5.	Piraeus	Greece	5.001
6.	Algericas	Spain	4.767
7.	Bremerhaven	Germany	4.573
8.	Barcelona	Spain	3.523
9.	Gioia Tauro	Italy	3.380
10.	Le Havre	France	3.100

Table 2.1: Top-10 EU ports by container throughput (2022)
Source: Lloyd's List [210]

Union encompasses 319 ports of which 83 are in the core network and 236 in the comprehensive network [99, p.17]. There are several clusters of ports in Europe that serve their respective regions. Figure 2.19 depicts the major ports of the northern, Baltic and Mediterranean range. The so-called northern range spans from Le Havre in France to Hamburg in Germany including the large ports of Antwerp and Rotterdam [342]. Their hinterland encompasses central and western Europe and the ports in its range are by far the busiest in Europe. Another interesting range is the western and eastern Mediterranean range. The western Mediterranean range encompasses ports in Spain, with the largest being Algeciras, Valencia and Barcelona, in France, with the largest being Marseilles, and in Italy, with the largest being Genoa. The ports serve the southern European regions at the Mediterranean coastline. The ports of the eastern Mediterranean range are located in Italy with Trieste and Taranto, and Greece with its busiest port in Piraeus. Especially for trade with Asia the Mediterranean ports, especially Piraeus with its large Chinese direct investments in terminal concessions for it [174, 361], have a severe advantage as they save several days of maritime travel compared to the northern range ports [207]. Finally, the ports at the Baltic sea are not only growing in importance with the economic growth of the region, their landscape is also diverse regarding cargo types and strategies [237, 203]. The most busy ports for containerized transports in this range are the Port of Gdansk in Poland, the Port of Riga in Latvia, the Port of Klaipeda in Lithuania and the Port of Tallinn in Estonia.



Northern and Baltic range



Mediterranean range

Figure 2.19: Major ports of Europe and their TEN-T corridors
Author: Compilation and extension based on works from Enekorga **Source:** commons.wikimedia.org - (1,2, 3, 4, 5, 6, 7, 8) **License:** CC BY-SA 4.0 - compiled as overlay work with additional port descriptors - see chapter 'Copyright Licences & Notices' for further information

2.3 Intermodal Transport Markets

Intermodal transport makes heave use of infrastructure, especially roads, railway tracks and terminals. Due to this nature, competition in the transport market might not be ideal. As Saeedi et al. pointed out, within European intermodal transport, the markets for transshipment and main-haulage are highly concentrated which has implications on pricing and policy. The transport market along the corridors, meaning relations between two points, is in contrast not concentrated as usually multiple transport alternatives exist [309]. A more recent study by Saeedi et al. comes to a similar conclusion and labels the structure of the European transshipment market as oligopolistic [306]. Also entry to the intermodal sector is difficult as it requires large coordination efforts in arranging the transport chain, although digitization [368] or asymmetric access charges for new participants [256] might be a way to alleviate this disadvantage alongside liberalisation of the market in general [216]. With the liberalisation of the German railway market, privately owned railway undertakings are increasing their market share over recent years as figure 2.20 shows.

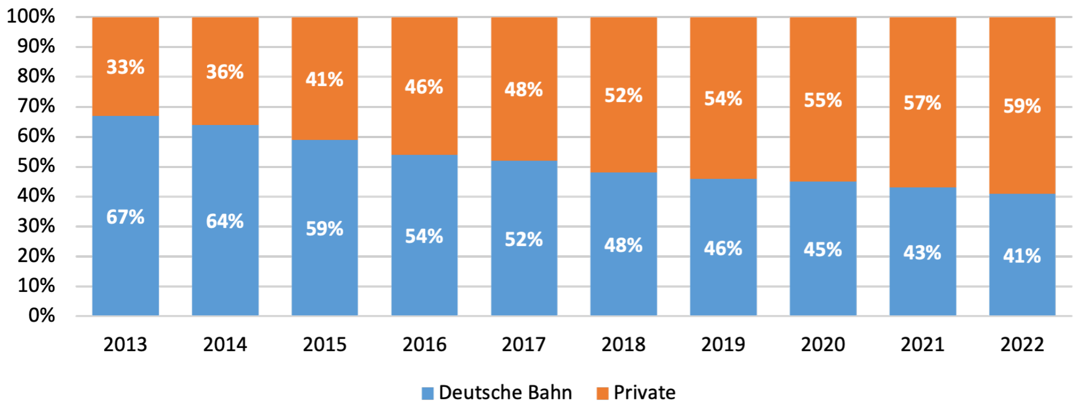


Figure 2.20: Development of the freight market shares of railway undertakings (by tkm) in Germany

Source: Own design based on Bundesnetzagentur [41, p.22][42, p.20]

2.3.1 Transport Volumes

The transport market in the EU is among the largest worldwide. Figure 2.21 shows the total transport performance of inland modes in the EU by tonne-kilometers. Road transport has by far the largest share with around 77.3%, followed by rail transport which is roughly 17% of transport volume. Inland waterway transport accounts for roughly 5.6% of inland transport volume. In total roughly 2408 bln. tkm are transported inland within the EU in 2021. When looking at intermodal rail transport, the volume transport

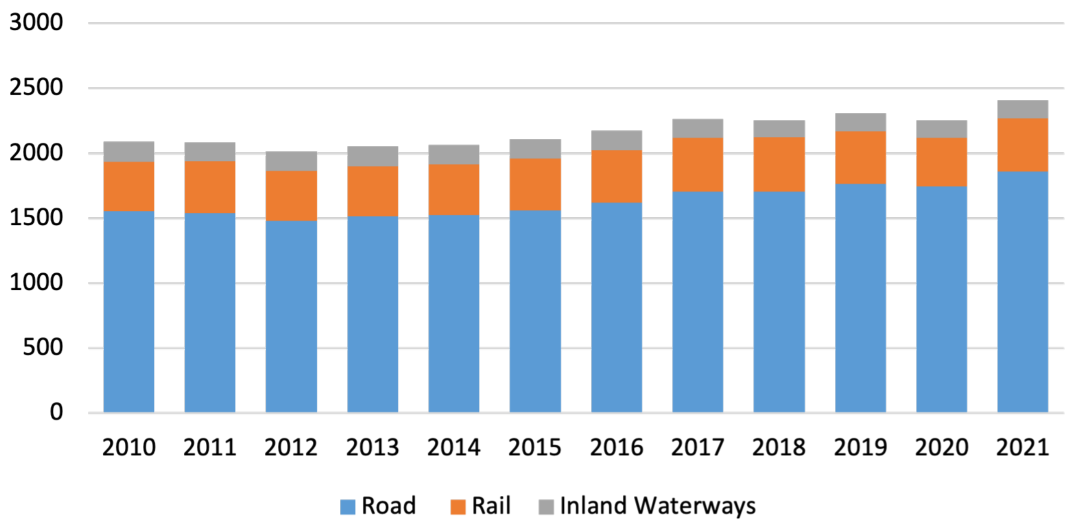


Figure 2.21: Transport performance (in mio. tkm) by inland modes in EU
Source: Own design based on European Commission [98, p.36]

in the EU has increased tremendously over the years. In 2022 it is roughly 88.8 bln. tkm for companies organized within the UIRR [350]. Figure 2.22 shows the volume of the Top-10 users of combined transport in EFTA (excluding Belgium and Austria due to data confidentiality). Germany is not only the country with the most freight transport volume, it is also by far the largest user of intermodal rail transport, followed by France and Italy. Very noticeable is the share of transport semi-trailers in Germany, Italy, Switzerland and Sweden. The rolling highway plays a minor role within European transport and mostly in the alps crossing traffic.

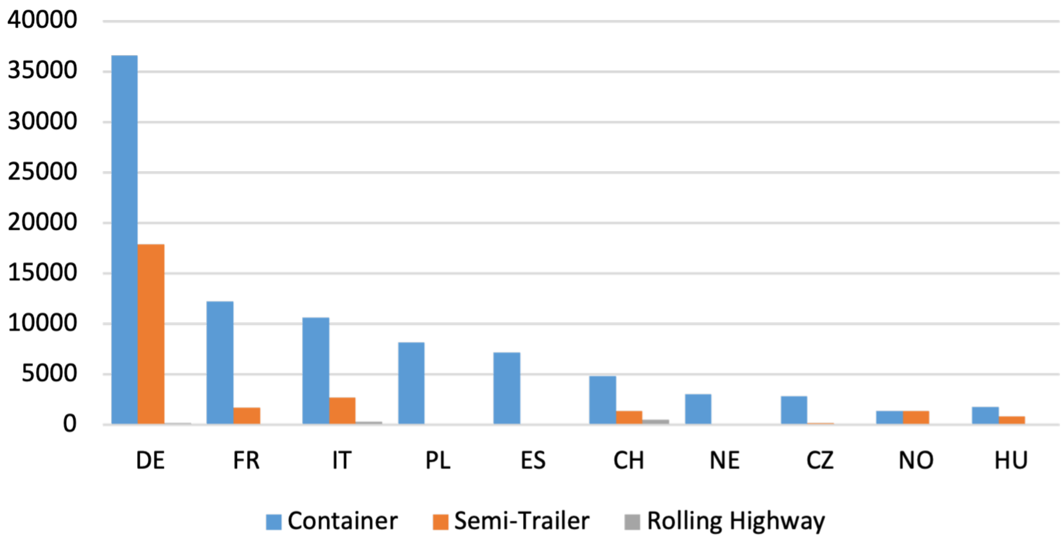
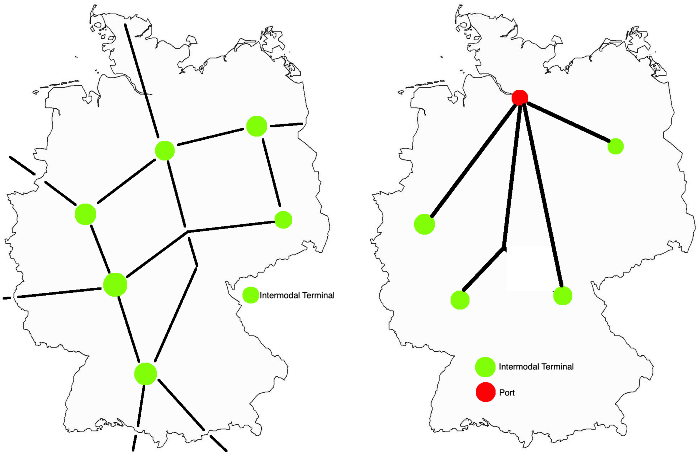


Figure 2.22: Top 10 countries in EFTA for intermodal rail transport (mio. tkm) (2022)
Source: Own design based on Eurostat [109]

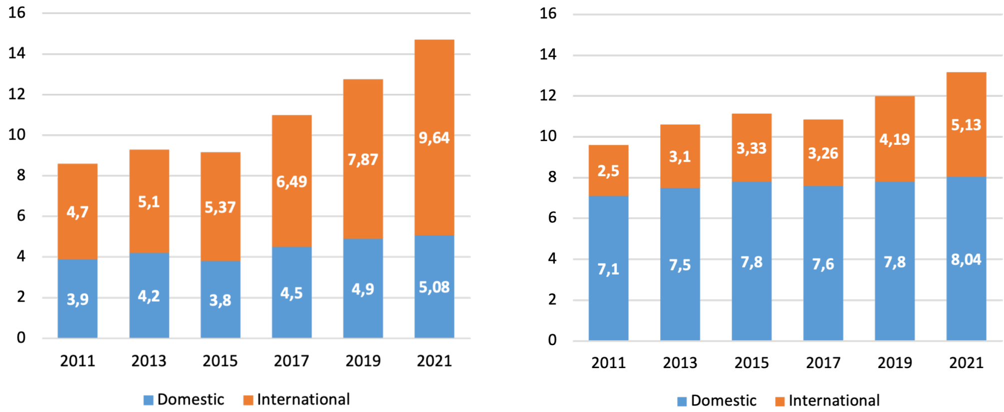
2.3.2 Transport Market Segments

Intermodal transport essentially encompasses two major market segments from a transport chain perspective that differ in their complexity of organization. They are port hinterland related transport chains and continental transport chains [253, p.58]. Both of these transport chains require different planning approaches as they differ by standards, homogeneity of infrastructure and equipment, and transport organization [133]. Figure 2.23 shows schematically the two distinctive modes of operation for intermodal transport chains. Figure 2.24 shows the share of unaccompanied maritime hinterland and continental transport both for domestic and international transports. While for domestic transport the maritime hinterland transport dominates, international transport is having larger shares of continental intermodal transport. In the last decade international continental transport has severely increased by more than double the transport volume of 2011. Port-related intermodal transport chains are aiming at transporting sea freight containers to or from the respective hinterland of the ports. Therefore its organization is highly depended on the arrival or departure or maritime vessels and due to their high transport capacity, the limited storage space within the sea terminals and the peculiarities of trains entering the port [8]. As ports are major infrastructure components, they are usually heavily



Continental transport   Port hinterland transport

Figure 2.23: Intermodal transport operation modes
Source: Own design



Continental   Port Hinterland (Maritime)

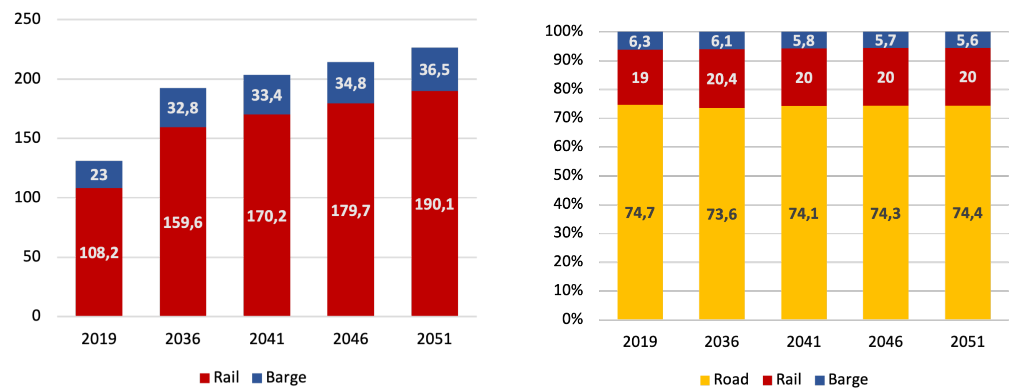
Figure 2.24: Containerized port hinterland and continental intermodal transport in Europe (mio. TEU)
Source: Own design based on International Union of Railways (UIC) [158, p.18]

supported by their national government and usually have a distinctive hinterland, whose concept is ever evolving depending on transport network organization and technological developments [316]. With increased efficiency of ports, available transport capacities and better connectivity, competition between ports has emerged. Due to comparable port efficiency, this competition has more and more shifted towards the hinterland, with multiple connections to several transport modes [396].

For continental intermodal transport chains, the main-carriage transport occurs between two terminals and a pre- and on-carriage via truck to the respective destinations. Continental intermodal transport has to deal with many peculiarities. First of all, policies across Europe are not yet aligned for cross-border transports, which defies intermodal rail transport partly of its economic advantages [133]. The involvement of two transshipments also makes it less appealing than its use in maritime transport. Also, as continental transport allows for more diverse cargo types like unaccompanied semi-trailers and rolling highway, requirements towards transshipment capabilities and equipment in the market are more pronounced compared to the standardized containerized maritime transport chains.

2.3.3 Transport Demand Predictions

The German Federal Ministry for Digital and Transport has published their projections for freight transport for the year 2051. They predict a general growth of intermodal freight transport over the years for Germany both for port hinterland transports and intermodal continental transport [159, p.52]. Figure 2.25 shows the prediction for intermodal transport in Germany from 2019 to 2051, both for the total freight tonnes and the expected modal split. The growth in freight tonnes is attributed both to a rising demand in rail transport for maritime hinterland transport as well as continental transport. The main intermodal competitor, barge transport, is expected to come to limits in its growth. Nonetheless, the projected numbers of growth are significant and require a further strengthening of intermodal transport system to accommodate for it. Despite general transport demand increasing, the modal split (excluding bulk goods, groupage and mailings) is expected to remain the same for rail with about 20%.



Freight (in tonnes)

Modal Split (excl. bulk goods, groupage and mailings)

Figure 2.25: Predictions for intermodal freight in Germany until 2051
Source: Own design based on Intraplan / Trimode [159, p.52, p.55]

3 Research Background - Design and Methodology

The work at hand consists of three distinct studies. All studies stand in relation to each other, either content wise or by making use of developed methodology. The first study of this dissertation determines current problems and potential measures regarding combined transport in Europe. It derives a practice-oriented research agenda from input both from practice and literature. For this, the research agenda makes use of the Delphi method by consulting and creating consensus among experts and practitioners in the combined transport sector. With a systematic literature review research efforts of the last decade are determined. By synthesizing the results of both methods, a practice-oriented research agenda is derived. The agenda encompasses six broader topic areas. These are the impact of sustainability policies, digitization of combined transport systems, strategic alignments of terminals, the human factor in combined transport, establishment of seamless cross-border transport and technological aspects of rail transport.

Furthermore, assessing the topic area regarding impact of sustainability policies from the research agenda, two distinct case studies are conducted. Hereby, the impact of these policies on the competitiveness of intermodal transport is investigated. The first case study focuses on central European port hinterland whereas the second case study investigates intercontinental transport options. Chronologically, the work at the intercontinental study had been conducted prior to the hinterland study and laid the methodological base for the following assessment. Nonetheless, for reasons of content presentation, the case study of hinterland competition is presented first followed by the case study of intercontinental rail transport.

The first of the two case studies investigates the impact of an environmental policy on the potential hinterland scope of ports in the European northern range. For this, a model of port competition through hinterland connectivity was developed and implemented in a geographic information system (GIS) model. With the help of this implementation, depicting the state of North Rhine-Westphalia and its unique competitive situation among

the northern range ports, a sensitivity analysis for the rate of a recently implemented carbon tax was conducted.
The second study takes a look at the potential of intermodal trans-continental transport between Europe and China. With the reestablishment of the trans-Siberian railway through the China Railway Express (CRE) as part of the Chinese One-Belt-One-Road (OBOR) or Belt-and-Road-Initiative (BRI) a new transport option arises. This option enables faster transports between Europe and China, compared to current maritime transport, at the disadvantage of significantly higher costs. For the case of exporters from Hesse a GIS model is developed that shows transport scope of export opportunities for the provinces of China. Analyzing different cargo values and comparing rail and maritime transport, it shows that the railway transport can be a cost effective alternative for western, central and north-eastern Chinese provinces. To further the analysis, a hypothetical global carbon tax at different rates is investigated.
Figure 3.1 shows how the different studies are connected to each other. While the case studies build upon one topic of the practice-oriented research agenda, they both share the same methodology and approach. To allow for a better comprehension, the research design and methodological background are subsequently introduced. Here, the peculiarities of how to develop a research agenda and how to conduct a case study, alongside the approach at hand are described. After the introduction of the research design, the methodological background of the methods used, their implementation and analysis are described.

3.1 Research Design

There are essentially two research designs followed in this dissertation. For comprehension, the development of a research agenda is introduced first followed by an introduction to case study research. Hereby, the reasoning for choosing the research design, how to conduct research based upon such a design, and examples on how it was applied in intermodal transport research are presented. Finally, how the research design has been applied for this dissertation and which methodologies were used in the process is shown.

3.1.1 Research Agenda Development

Developing a research agenda, especially based on empirical insight, can lead to structuring of further research and provide inspiration for the assignment of resources. It channels available knowledge, condenses it and derives recommendations for further assessment. As research agendas are based on current needs, they are always a product of their time

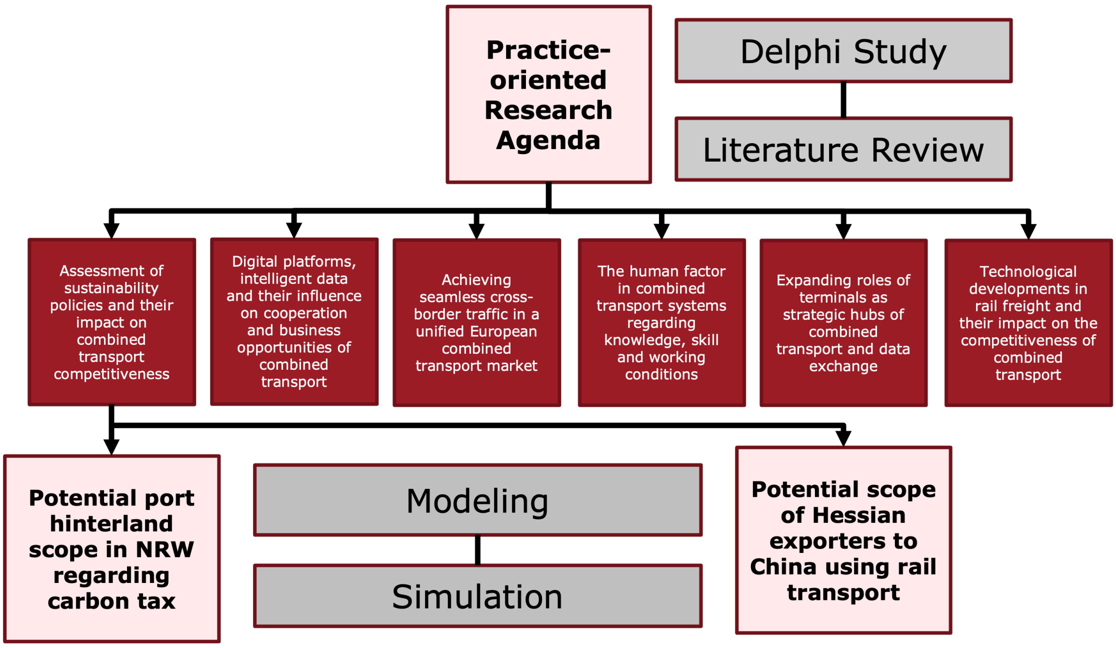


Figure 3.1: Research Design
Source: Own design

and their knowledge gain comes from the immediate needs of research and practice. To attain required empirical input, several methodologies can be used and therefore there is a wide variety of ways on how to conduct and how to derive knowledge from research agendas.

Research agendas have several advantages for the scientific community. They provide a structured approach by assessing fields of research and provide guidance to conduct impactful research. They also provide guidance for researchers in adjacent fields to get an overview of current common problems in the area and how to apply their methodological and contentual knowledge to it. With its results, a research agenda can also be used to assess the historic development of the area and to summarize conducted research within a certain time span. Yet, as the development of a research agenda is a qualitative task, certain limitations exist. First of all, a research agenda has to be assessed in the context of its creation. This means that it has to be reevaluated in certain time spans to assess changes in the area, closed research gaps and new directions of research. Especially in transportation research, an area driven by technological developments, this span can potentially be short-lived. Yet, the research agenda can serve as a historic document of the development of the research area nonetheless.

Intermodal transport is regarded as an environmentally beneficial transport option, especially compared to road only transport. Ongoing efforts to reduce carbon emissions in transportation, new technological developments for connectivity and cross-actor information exchange and an increase in the complexity of the transport sector as a whole demand for a structured classification of these challenged. The development of a research agenda for combined transport in Europe can contribute therefore to the field and provides the rationale in conducting the study at hand.

How to Develop a Research Agenda

Developing a research agenda usually requires data collection and analysis to identify potential research gaps and possibilities for further research. Popular for this data collection and gap analysis for transportation research is the use of systematic literature reviews (e.g. [89], [34], [31], [26]). In this case the research agenda is based upon previously conducted research that might not necessarily fit current developments in the transportation sector. To make research agendas more practically viable, it can can be supplemented by additional primary empirical data, e.g. expert interviews, surveys or workshops [217], to identify issues arising from practice and to increase impact of further research. Using empirical input in this case can help in the prioritization and determination of research needs as well (e.g. [22]).

Examples of Research Agenda Development in Intermodal Transport

There are quite some research agendas about and around intermodal transport which should subsequently be illustrated. Bontekoning et al. have defined areas of interest when the research field of road-rail transport was in its emerging phase [34]. Caris et al. have taken a deeper look at decision support models for actors in the intermodal transport sector [51]. Lam and Gu look at intermodal port hinterland transport with a focus on environmental concerns [190]. A recent research agenda comes from Saeedi et al. who have taken a look at performance measurement in intermodal transport [307]. Aside from this clear focus on intermodal transport, related research agendas in transportation deal with sustainability, which is a major driver of intermodal transport and technology. Marchet et al. look at the environmental sustainability of logistics and transport and their main themes and methods [225]. Perego et al. have a look at ICT applications in the logistics and freight transport sector by assessing research and methodologies used [281]. Finally, there is a pool of research agendas concerning maritime and port transport. Heilig and Voss look at inter-terminal transport within ports by providing a chronological overview and an annotated bibliography [147]. Gülmez et al. provide an overview of maritime logistics which include shipping and port operations. They find a lack in studies regarding sustainability [141]. Finally, Ghorbani et al. look at strategic alliances in the container shipping sector providing a research agenda for the areas of formation, management and optimization of such alliances [134].

Approach at hand

The research agenda developed for this dissertation is two-stepped as depicted in figure 3.2. The novelty in this approach is that a practical view on current problems of combined transport in Europe is developed first. This is done by using the Delphi method to gain insight from experts in the sector. The input, a total of 27 recommendations for practical measures, is then condensed into generalized categories. In a second step, these generalized categories are used as a structural basis for a systematic literature review. Focus is laid upon research from the last decade for actuality and the focus is set upon Europe and empirical, qualitative and analytical research as opposed to quantitative and optimization approaches. Here a systematic overview of research conducted within the last decade is provided using the generalized categories from expert input. Finally, by analysing and synthesizing the practical input from the Delphi method and the scientific input from the systematic literature review, a practice-oriented research agenda is derived. Methodologically, the literature review makes use of the Delphi method and a systematic literature review. While the Delphi method is a good way to obtain practice-driven input,

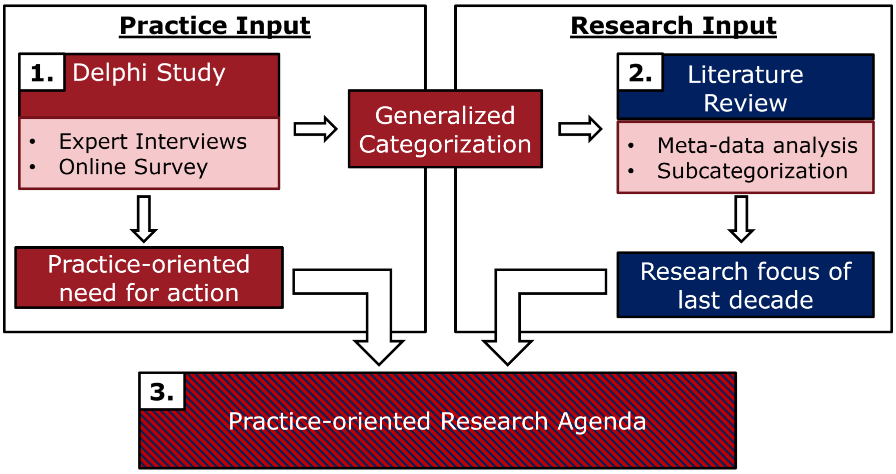


Figure 3.2: Design approach of research agenda development
Source: Own design

the systematic literature review can show past efforts and trends in the scientific body. The procedures of both methodologies are depicted in figure 3.3. The Delphi method applied

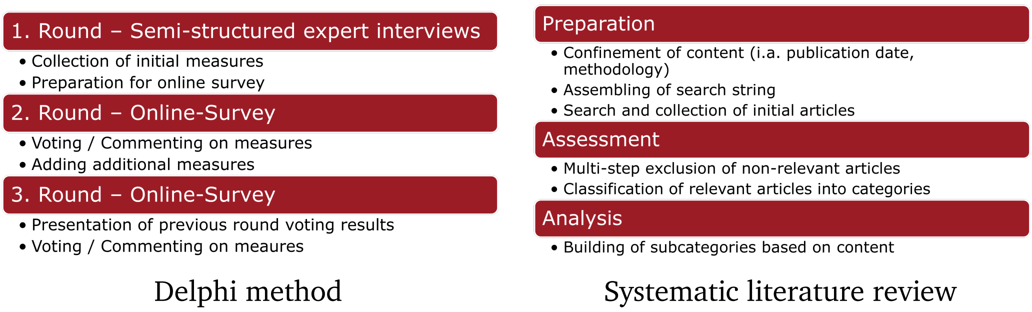


Figure 3.3: Process of used methodologies
Source: Own design

in this study consists of three rounds. In the first round semi-structured expert interviews are conducted. The results from these interviews are then color coded to determine matching measures to improve combined transport for each of four different perspectives. With the use of an online survey tool, the determined measures are then prepared with a short title and a description. The list of these measures are then presented to the experts again. The participants can comment on existing measures and add new measures to the

survey. Additionally they can vote on the measures on two dimensions, the effectiveness and the difficulty of a potential implementation. The third round then consists of a final voting to derive an indication of importance of the different potential measures.
The systematic literature review aims at finding relevant research of the last decade regarding combined transport. Hereby the selection of articles is limited to peer-reviewed journals, a focus on European-related studies and methodologically on qualitative, analytical and empirical research which essentially excludes quantitative assessments. Within a multi-step exclusion process, from title over abstract to full-paper, relevant articles are determined. The found articles are categorized according to the generalized categories from the output of the Delphi method. Finally, a detailed content analysis is conducted. In this process several subcategories are formed for analysis, that represent research streams within the specific area of combined transport research.
Finally, by synthesizing the practical input and the input from the systematic literature review, the final practice-oriented research agenda is derived. Here the goal is to assess all practical measures and find gaps and topics currently not assessed in literature for further investigation.

3.1.2 Case Study Research

Case study research design is popular in transportation research as it allows for the investigation of the peculiarities of specific transportation problems. Case studies are conducted with various qualitative and quantitative methodologies. With the help of case studies, the effects of past changes on the case can be analysed as well as future developments be assessed, e.g. through scenario analysis. Especially for the analysis of policy changes the method has gained some popularity (e.g. [177], [312], [302]). The advantage for using case study research is to investigate complex real-world issues. It enables detailed insight into a specific problem and allows for potential comprehensive investigation. Challenges when applying the method are potential lack of rigor, difficulty to generalize obtained results and excessive data collection that makes purposeful analysis difficult [276].

How to Conduct Case Study Research

There are multiple ways on how to design case study research. Figure 3.4 shows basic types of case study designs. According to Yin, case study designs can be distinguished on two dimensions, their unit of analysis and the amount of cases investigated. Holistic case designs take a look at the whole case, investigating it as a single entity. Embedded designs

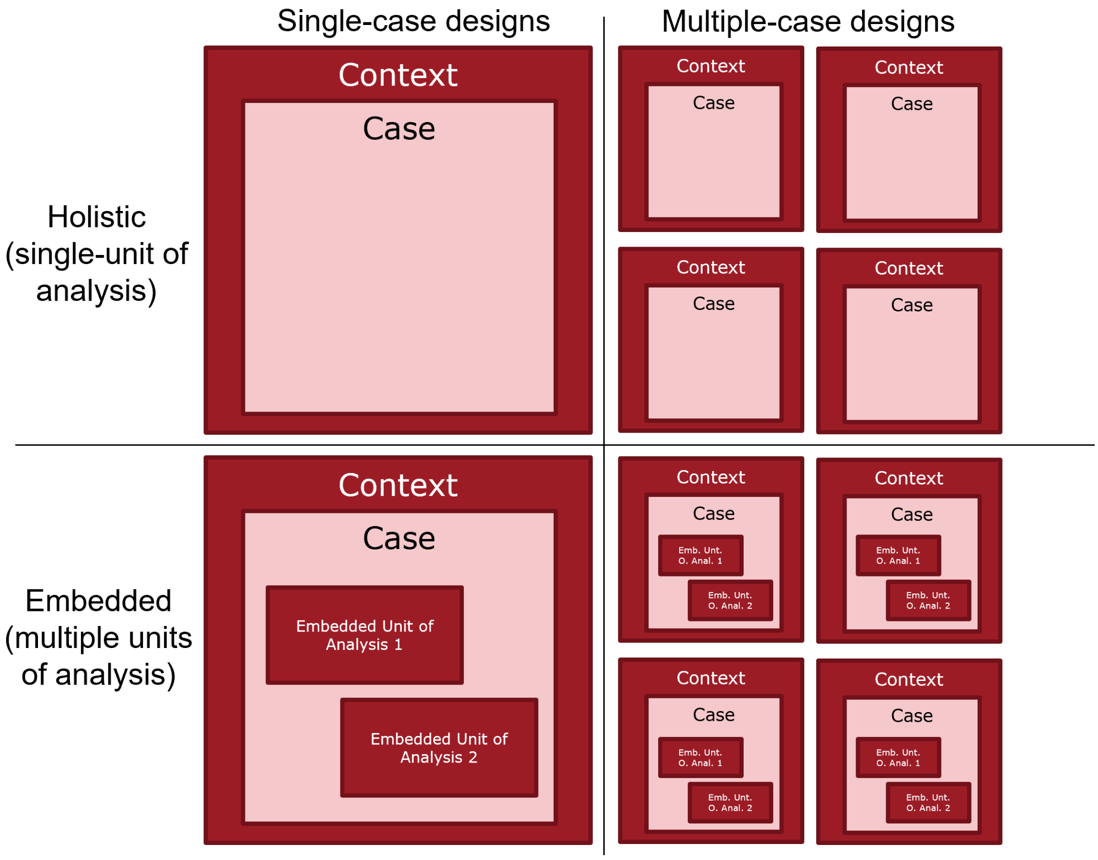


Figure 3.4: Basic types of case study designs
Source: Own design adapted after Yin [388, p.46]

take several characteristics or entities within the case and differentiate the analysis. When using a multiple-case design, the different cases can be analyzed in comparison to each other [388, p.46ff]. Essential for good case study design is the selection of the right case. For single-case designs Yin explains five major types of cases. Within the analysis of critical cases, theories with a subset of prepositions can be analyzed. As a result these theories can be tested, confirmed, challenged or extended based on the outcome of the case. Unique cases are rare occurrences of a phenomenon that is worth to be documented and analyzed. Typical or representative cases show commonplace situations whereas revelatory cases have previously been inaccessible for research. Finally, longitudinal cases look at the same case at two different points in time and allow for a temporal analysis

[388, p.47ff]

Examples of Case Study Research in Intermodal Transport

Case study research has been applied in multiple ways within intermodal transport. Mostly single case design studies have been conducted which can be attributed to the uniqueness of intermodal transport systems and geographic and regulatory particularities that make cross-case analysis more difficult. A selection of meaningful case studies is presented here for comprehension of possibilities, especially regarding the areas of sustainability, terminals, business development and market liberalization. Kim and Wee have compared different carbon emissions of trucking and intermodal transport modes. They developed a detailed model on how to assess these emissions and applied it to a route between Gdansk and Rotterdam [177]. Santos et al. have assessed different policies and their effect on intermodal transport competitiveness in the case of Belgium. Alongside subsidies they investigated the internalization of external costs [312]. Similarly, Rotaris et al. have investigated the effectiveness of policies in the Italian market and describe the case of a company that successfully shifted to intermodal transport alongside the benefits it brings [302]. Intermodal terminals have also been a popular aim for case study research. Bergqvist et al. have investigated how intermodal terminals are established and which factors are relevant in the process. They investigated the establishment of two Swedish terminals as their cases [25]. Lizbetin and Stopka looked at ways to revitalize non-functional intermodal terminals based on their investigation of a case in the Czech Republic [209]. Aside from these assessments the location of terminals is a popular application for case study research as done by Lizbetin et al. for a case study in Slovakia [208] or Roso et al. for a case in Croatia [301]. Murillo and Liedtke have developed a model for analyzing the colloidal structures of hinterland terminals and applied their model to the case of Germany. Another application area for case study research is the development of intermodal services. Monios has taken a look at Italian freight villages by investigating 25 of such villages quantitatively and more detailed 5 villages. He finds a misalignment of national policies and regional developments [250]. Woodburn has investigated how the enhancement of the railway network between Southampton and the West Midlands has impacted intermodal rail services especially regarding its efficiency [383]. Regarding port hinterland network development, van den Berg et al. have taken a look at the role of port authorities in developing new intermodal connections for the case of the Port of Barcelona [357]. Mostert et al. have developed a network design model and applied it to the case of Belgium [259]. And Zhang and Pel have taken a look at synchromodal transport and how these transport systems can be modeled strategically. They apply their model to the case of the Port of Rotterdam hinterland. Finally, taking a market look, Floden and Woxenius investigate the effect the withdrawal of CargoNet had on the Swedish intermodal transport market and how the market found ways to organize new intermodal transport systems. CargoNet has been the monopolistic provider of intermodal transport services and lost its position after the market had been liberalized [122]. Cowie has investigated the case of the British market after liberalization, especially regarding the entry of new providers and a propagated rise in efficiency and entry of new providers. Both assumptions seemingly can't be attributed to the market changes [65].

Approach at hand

Two case studies are investigated within this dissertation. Both represent a single case study design. Within the case studies sensitivity analysis is conducted. Both case studies analyse the potential marketable area or (hinterland) scope for combined transport regarding the (hypothetical) implementation of an environmental policy. The approaches of both studies are shown in figure 3.5. For both studies, GIS modeling and simulation has been used to assess geographic peculiarities and to enable visual analysis of the effects of the environmental policy. The first case study investigates the hinterland scope of northern

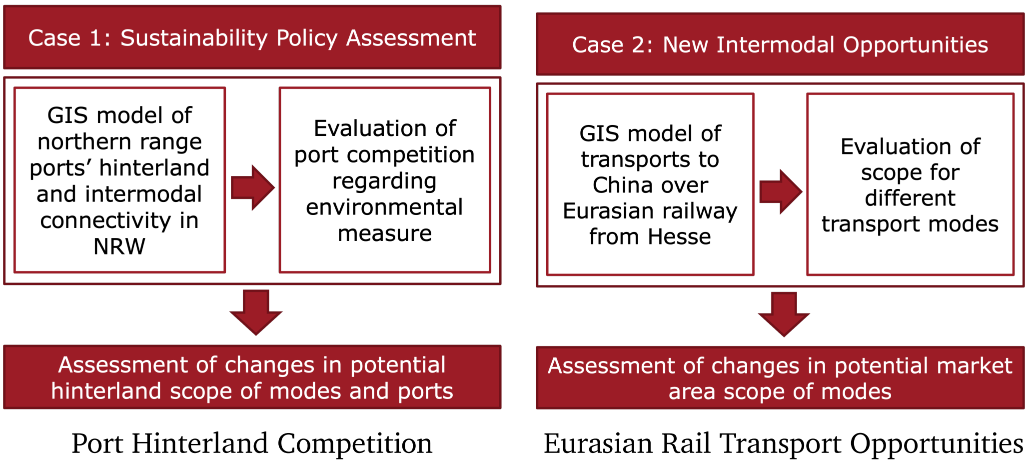


Figure 3.5: Investigated case studies
Source: Own design

range ports in Europe as a single-case study. For this a GIS model and simulation has been developed depicting the state of North Rhine-Westphalia (NRW), which is prone for inter-port and inter-mode competition. It represents a critical case as competition between modes and ports is fierce in the state due to similar catchment areas. Also policy changes are expected to cause shifts in hinterland scope. NRW is the most populous German states, has a strong economy and is well connected to all ports of the northern range. Empirical data regarding the intermodal connectivity of both rail and barge, containerized transport volumes and economic power of the different districts within NRW have been collected and used within the model. As Germany has implemented a carbon tax in 2021, making emission intensive transport modes more expensive, a sensitivity analysis for a typical international transport chain, from NRW to Shanghai in China, has been conducted focusing on the hinterland transport component. With this analysis, different levels of carbon tax can be analyzed and the potential hinterland scope for ports and modes depicted.

The second case study investigates the new transport possibility from Europe to China utilizing Eurasian rail transport in form of the China Railway Express (CRE). This transport alternative has emerged as a viable option as it offers superior speed and reliability at the disadvantage of higher costs. While the benefits of such a connection are more obvious for landlocked countries like the countries of eastern Europe, the CRE reaches several terminals in Germany. As Hesse is a state within Germany with well established infrastructure, connections to these terminals and export oriented economy, it can be regarded as a typical case for German exporters to China. By implementing CRE connections from Hesse to China, the potential scope for exporters, especially regarding speed and costs, can be analyzed. By comparing the costs of maritime and rail transport, and factoring in time costs for different cargo values, the scope for both modes for Hessian exporters to China can be depicted on a per province base. By implementing a (hypothetical) global carbon tax, the impacts of such a policy measures can be analyzed within the model. Hereby the emissions for each transport chain are added up and taxed by this hypothetical tax. The case study then allows a sensitivity analysis for different parameters depicting the results on a map of China.

3.2 Methodological Background

As this dissertation has used multiple methods in the three studies conducted, the methodological background is explained further to show how the methods are typically applied. The first study, the development of a research agenda, makes use of the Delphi method combined with semi-structured qualitative interviews to generate expert input. This expert input is then mirrored by using data from a systematic literature review. Both methods are explained therefore subsequently. The case studies of the port competition through hinterland connectivity of northern range ports in Europe and the transport opportunities for Hessian exporters to China are making use of GIS modeling and simulation. With this methodology, an analysis of the situation within the cases can be conducted and policy changes assessed. The strength of the method lies in its graphical representation which makes results comprehensible and accessible. All methods, their purpose, procedures, advantages and limitations will be shown for comprehension of the dissertation.

3.2.1 Delphi Method

The Delphi method aims at finding consensus within a panel of experts on a specific research topic. It has been applied as a method since the 1960s and keeps up its validity as a method for forecasting and supporting decision making [192]. The Delphi method is usually conducted in multiple rounds, whereas experts have the chance to evaluate the output of the previous round and add or remove content depending on their assessment. A potential focus of the Delphi method is practice-oriented theory building within communities [36] making it a method suitable for connecting practitioners' views with research. In a business context, the Delphi method can be applied to define and order a (widening) research agenda. Examples for this are Etemad et al. who defined a research agenda in the context of international entrepreneurship [94] and Reefke and Sundaram who have identified key themes and research opportunities in sustainable supply chain management [290]. Within intermodal transport, the Delphi method has been successfully applied by Cavallaro et al. [54], who have investigated barriers and potential measures among stakeholders of the alpine transit to improve efficiency and utilization. They structure their investigation among organizational, infrastructural and political categories, whereas they majority of potential improvement lies within organizational cooperation. Asenov et al. have determined optimal intermodal routes through Bulgaria by expert consultation [12]. A look into the future of intermodal transport has been conducted by Brooks et al. with a view on the role of automation in intermodal transport [37] and Makitalo and Hilmola on the role of rail freight transport in Finland [224]. Delphi studies in the transport sector have been applied in various ways with different methodological approaches. Differing number of rounds conducted, various groups of experts, different geographical focus and combination with additional methods are some examples [235]. Although there are different ways on how to apply the method, its general advantage is the generation of empirical consensus knowledge from a relevant expert group and its application to real world problems [151] while its disadvantage is the difficulty of reproduction, which is a general problem of qualitative research. Also the results of the Delphi approach can have a tendency for vagueness [284].

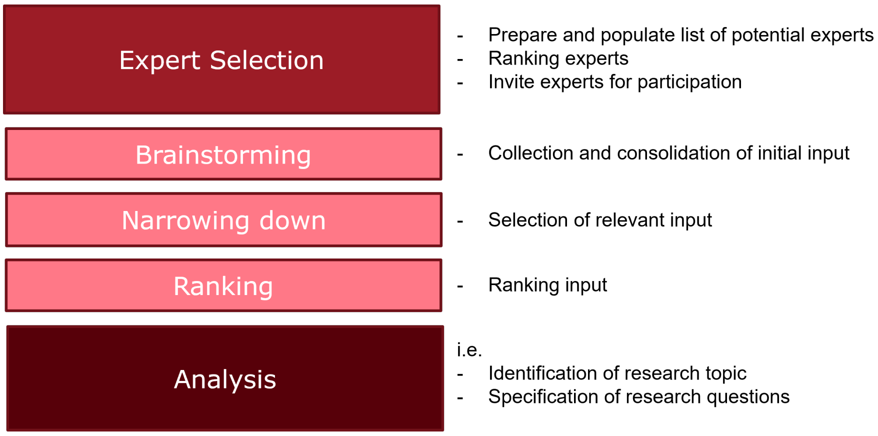


Figure 3.6: Process for delphi method
Source: Own design adapted after Okoli and Pawlowski [267]

The Delphi method can be used in various ways. Aside from modern applications of the method in the form of real-time Delphi, differing amounts of participating experts and rounds within the method are used [323]. The delphi method can be employed for theory building as Okoli and Pawlowski show [267]. The process they use is depicted in figure 3.6. They see three phases of the delphi method for theory building. First, a panel of experts needs to be selected. This can be conducted in a multi-step process, where experts are selected based on their expertise and fit to the study. Then data collection occurs with an initial brainstorming of the experts, followed by a consolidation of the results. The body of input is then presented to the experts again for selection, ranking and extension. Finally, the input is rated by the experts and a consensus presented. By using the results, research can be theorized and essential research questions derived. For the study at hand, the process has been adapted to allow for broader input. Instead of a narrowing phase, the focus lies on an extension of possible factors and a ranking of these, allowing for a broader input base.

3.2.2 Qualitative Interviews

Qualitative interviews have a long established history in qualitative scientific research. They are used to obtain extensive empirical data. This data allows to gain in-depth insights from interviewees. There are three essential types of qualitative interviews, which differ in their structure, their outcome and their possibility for analysis. Unstructured interviews

don't follow a predefined script. Their content is derived from the conversation with the interviewee and they have an exploratory focus. Semi-structured interviews usually follow a predefined interview guideline that defines the different content and stages of the interview. With this type of interview, insight into a predefined complex topic can be obtained. Finally, structured interviews are essentially a complex survey that is filled out by questioning the interviewee and potentially giving background information during the interview process. The results are then analyzed statistically and usually represent a survey method [79, 32].
The subsequent explanations refer to semi-structured interviews, as they are the method used in this dissertation. The process of conducting semi-structured interviews is usually threefold. It consists of preparation for the interviews, conduction and analysis. A typical process for conducting semi-structured qualitative interviews is depicted in figure 3.7. Before conducting qualitative expert interviews, several preparations need to be made.

Figure 3.7: Process for semi-structured qualitative interviews
Source: Own design adapted after Roulston and Choi [303]

Research that involves sensitive personal data might need an ethical board at an associated institution to be consulted. This depends on the topic of research and the involvement of participants. Once ethical considerations have been solved, an interview guideline needs to be developed. This guideline serves as help in conducting the interview, sets the frame for content and enables both the interviewer as well as the interviewee to have a structured approach to the interview. After drafting the guideline, it ideally needs to be pre-tested with a potential interview candidate. This way it can be assured that questions

are understandable and answers accordingly touch the topic at hand. Additionally, the interviewer should educate themselves on the topic of the interview to be able to guide the interview properly. Aside from these content based considerations, the technology used during the interview should be assessed and tested [32, p.27ff]. Once this is all set-up a necessary number of interviewees should be recruited for the interview. The number of interviewees depends on the research topic at hand and may vary [16].
After successful preparation, the actual interviews need to be conducted. The interviewing process usually start with an introduction of the interviewer and topic and an informed consent of the interviewee should be obtained. Ideally the interview is recorded after consent, otherwise notes need to be taken during the interview. The actual interview then consists of asking questions laid out in the interview guideline. Depending on the dynamic of the interview, certain deviations from the guideline are possible [32, p.49ff]. Once the interviews have been conducted and recorded, the recordings need to be transcribed. The transcription is then used for further analysis. This analysis can take various forms. While there is no general method for analyzing interviews, due to the variety of contents and focus, several popular methods of analysis exists. With coding, certain topics are marked by color in the transcripts for further analysis and with sequential analysis different sequences of the interviews are analysed in depth [32, p.71ff]. Once the interviews have been analysed, the results need to be condensed into representative results.

3.2.3 Systematic Literature Review

Systematic literature reviews are a popular way in research to identify the existing body of research on a certain topic. They can be used to synthesize the contents, identify gaps in existing research and also to draw new knowledge from them. Xiao and Watson have identified various forms of systematic literature reviews, that serve different purposes. Among the identified reviews are descriptive reviews that aim to show the content of current literature, testing reviews that aim to test hypothesis and critical reviews that aim to find consensus in literature [387]. Despite the different aims of reviews, they have identified a common process framework for reviews as depicted in figure 3.8. In a first step, the goal of the literature review needs to be defined and which problem is addressed through the review. After this, the details of the review protocol are defined. There are several aspects to determine in this phase. The used search string, usually using boolean logic, defines the body of articles able to be found. For the database to use there are several options. Aside from singular databases, scientific meta-search databases that access multiple relevant scientific databases have become popular with examples like

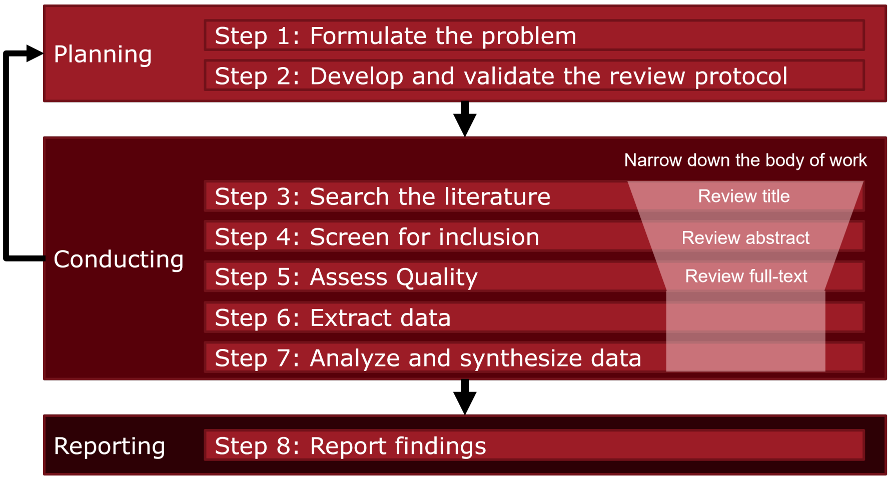


Figure 3.8: Process for systematic literature reviews
Source: Own design adapted after Xiao and Watson [387]

Scopus [90] or WebOfScience [63]. When using general purpose search engines like Google Scholar [139] the search results obtained can be widened at the cost of precision and relevance. Finally, the search protocol needs to define criteria for inclusion into the review. These can be qualitative criteria, e.g. certain forms of publication or quality of the respective journal, or content criteria and meta-data.
The conduction of the review process then occurs in multiple steps. First, the literature is assessed by title and non-matching articles are excluded. This process continues for article abstracts and finally are full-text assessment [245]. By conducting these process steps, due to the clearer picture of literature, a readjustment of the review protocol can occur and the steps of the review repeat. After determining the final selection of full-text articles, relevant data is extracted from the articles. Hereby the articles can be assessed by several criteria, e.g. the methodologies used, the research focus and metrics regarding its content. By analyzing meta-data, key journals and researchers, chronological and temporal publishing and key themes can be identified. By assessing the content of the articles, a thematic analysis can take place. The data obtained through this process can then be analyzed and synthesized to answer the aforementioned research problem. Finally, the results of the literature review need to be processed and presented in the form of a report.

3.2.4 GIS Modeling & Simulation

Geographic information system (GIS) modeling has become a popular application to analyse spatial peculiarities and scenarios [212, p.363ff]. It makes use of spatial data such as vector or raster data, employs them in a software tool and allows for the flexible conduction of investigations. To obtain data for GIS models various commercial and free sources are available of which OpenStreetMaps, an online repository of map data maintained by volunteers, is among the most extensive [268] and of which data extracts especially of transport infrastructure are available free of charge [132]. An example for the application of GIS modeling and the flexibility of the method is the Location Analysis Model for Belgian Intermodal Terminals (LAMBIT). This model depicts the country of Belgium with its transportation options via road, rail and waterways. The model has been used in various investigations like policy analysis [220], assessment of external costs in transportation [219], mode choice between intermodal and uni-modal modes [221] alongside transportation business models [277]. A typical process for spatial modeling and analysis using GIS modeling is depicted in figure 3.9. GIS modeling encompasses roughly

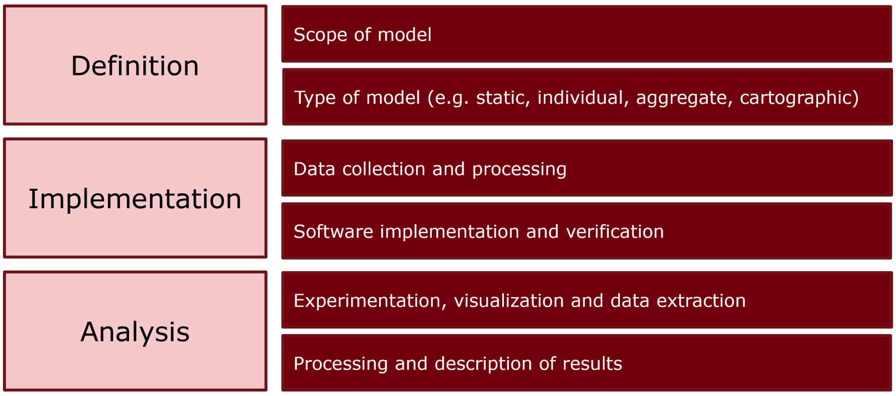


Figure 3.9: Process of spatial GIS modeling
Source: Own design adapted after Longley et al. [212, p.363ff]

three steps. First, the scope of the model and goal of the modeling need to be defined. Hereby, the type of model needs to be determined based on the research question and needs. After formulating the model it needs to be implemented in software capable of handling GIS input, e.g. the multipurpose simulation tool AnyLogic [10]. Relevant GIS data, e.g. infrastructure and topology, needs to be collected and processed for use in the software. After the model has been implemented it can be used in various ways. By visualizing the model in a map, conclusions can be drawn through visual analysis or by analyzing collected statistics. Additionally, depending on the software implementation, experiments can be run to allow for what-if analysis. Finally, the results from the simulation, e.g. visualization or extracted data, need to be analyzed and processed for presentation.

4 Combined Rail-Road Transport in Europe - A practice-oriented Research Agenda

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4.1 Abstract

Combined rail-road transport, with its complex regulatory, infrastructural, organizational and technical environment, presents numerous opportunities for practical improvements and impactful research. A strengthening of this transport mode can serve rising transport demands and make freight transport more ecologically sustainable. Due to the complex nature of combined transport systems, there are various possibilities for improvement, of which a subset of 27 measures have been identified in a Delphi study. Synthesized with a systematic literature review for the last decade of combined transport research, a practice-oriented research agenda was developed, providing guidance for further research. Six research topics have been identified, ranging from the assessment of sustainability policies, digital platforms, seamless cross-border traffic, human factor, changing terminal roles and technological developments in rail transport.

4.2 Introduction

Intermodal freight transport reflects the combination of at least two transport modes with a transshipment at an intermodal terminal [66] with freight being transported in containers, swap-bodies or semi-trailers, with most of its way traveled by rail, inland waterway or ocean-going vessel [218]. While the terms intermodal transport, multimodal transport, combined transport and co-modality are often used synonymous for transports involving more than one transport mode [296], their concepts differ. In the case of combined rail-road transport, the main transport leg is conducted via rail transport with pre- and on-carriage kept as short as possible [116], leading to economic benefits due to the use of more economically viable rail transport [298]. Also, in a so-called rolling highway, whole truck units can be transported via rail [55], which has been the source for various infrastructural and operational innovations in the intermodal transport sector [354]. Advantages and disadvantages of combined transport are apparent. While it presents a transport option using less resources, providing better sustainability and higher transport capacity and potentially lower costs, it requires additional transshipments, relies heavily on infrastructure and offers less frequent transports [186]. Additionally, the involvement of multiple actors in organizing combined transport chains makes their operation highly complex [386, p.302].

By volume, unaccompanied transport in containers and swap-bodies, are the most important transport operations for combined transport in Europe, while the rolling highway only plays a significant role in alp-crossing transports [98]. The largest users of combined transport within the EU are Germany, France and Italy which can partly be attributed to their size, yet in Germany the transport of unaccompanied semi-trailers has gained popularity. The rolling highway is especially interesting for alp-crossing transits [54] and has importance for countries in proximity like Germany, France, Switzerland, Austria and Italy. The importance of combined transport for Europe is expected to increase. The EEA projected an increase in freight of 1.7% each year for Europe until 2030 [107] and the German Federal Ministry for Digital and Transport expects a 75% increase from 2019 to 2051 for rail transport [159]. Combined transport plays a major role in long-distance transports. Its volume of transport is roughly evenly split in a 300km to 900km bracket and a over 900km bracket [98]. With a unified European market, this advantage might come into play reinforcingly. Additionally, there is pressure to increase sustainability of freight transport in Europe with intermodality playing a major role [19].

In order to cope with this increased need for combined rail-road transport, optimization research can contribute to an efficient functioning as called for by Macharis and Bontekoning [218]. Taking a broader view on intermodal transport as a research area, Bontekoning et al. [34] have proposed several fields of research on intermodal transport in a rather general sense. A rather common phenomenon is that these research agenda suggestions are usually based on literature analysis as also more recently proposed agendas related to combined transport show (e.g. [51, 307]).

For a proper assessment of combined transport, we regard taking the practitioners view into account as essential. This makes both research efforts and improvement measures potentially more effective. A purely consideration of research efforts might represent a good overview of areas interesting for thorough investigation, yet they might struggle to provide a recent practical view on the issue. Taking both views on combined transport into consideration has two main advantages. First and foremost, the presentation of recent practical and pressuring problems can highlight the need for action for combined transport in Europe and create awareness. Second, based on this practical input, it can be determined which problems have recently been addressed by research and where further research is needed. Hence, this article presents a practice-driven research agenda for current needs in combined transport in Europe while also showing how the research community has recently dealt with them. Hence the approach at hand comes from a practical view first and considers research efforts subsequently.

4.3 Research Question & Design

Improving combined transport systems is a complex task. The interplay between policy, infrastructure, organization and technology allows for a wide range of improvement efforts and make prioritization difficult. The potential measures available, with the highest potential yield, and how research has and should contribute, is the aim of this study. The leading research questions aim at aligning practical input with research efforts and come out as:

- RQ1: What are potential measures identified by experts to improve combined rail-road transport in Europe?
- RQ2: What are current trends identified in the body of research for combined rail-road transport for Europe in the last decade?
- RQ3: By synthesizing the results from RQ1 and RQ2, which recommendations for a practice-oriented research agenda for the improvement of combined transport in Europe can be given?

The paper is structured as follows: Firstly, a Delphi study is used to derive practice driven advice and categorization. Secondly, a systematic literature review of European combined transport research of the last decade is presented. Finally, a practice-oriented research agenda is derived by combining the outcome of both studies. Figure 4.1 shows the research design approach.

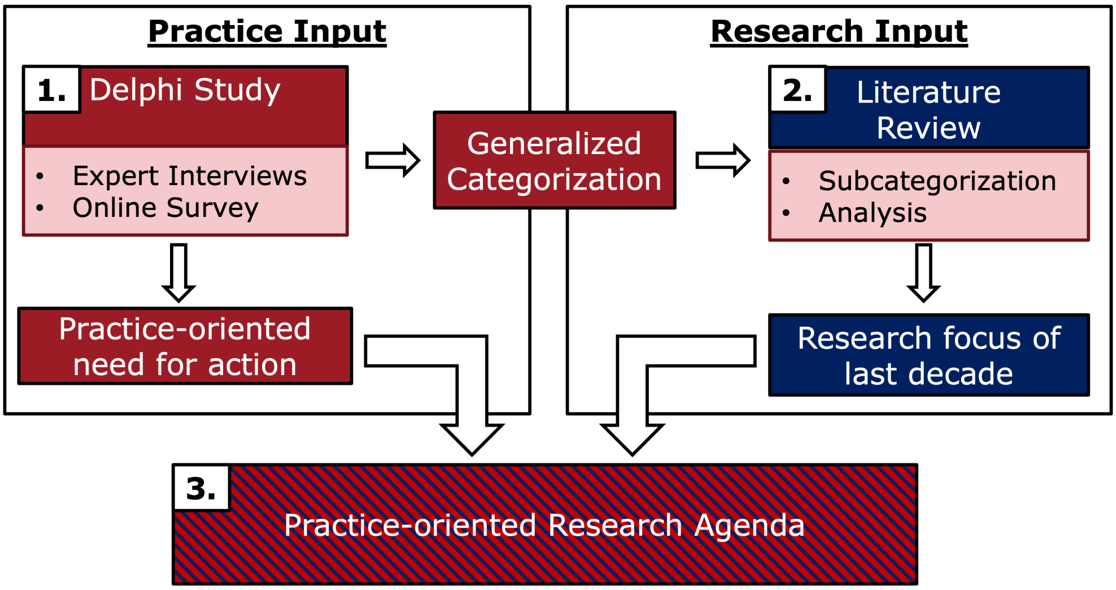


Figure 4.1: Research Design
Source: Own design

4.4 Delphi Study - Identifying practice-oriented need for action

The Delphi method aims at finding consensus within a panel of experts on a specific research topic where it can be used for forecasting and supporting decision-making [192], practice-oriented theory building within communities [36] and defining research agendas [94, 290]. Within combined transport, the Delphi method has been successfully applied. Cavallaro et al. [54] have investigated barriers and potential measures among stakeholders of the alpine transit to improve efficiency and utilization. Asenov et al. [12] have determined optimal intermodal routes through Bulgaria by expert consultation. Brooks et al. [37] have taken a view on the role of automation in intermodal transport and Mäkitalo and Hilmola [224] on the role of rail freight transport in Finland. The advantage of the Delphi method is the generation of empirical consensus knowledge from a relevant expert group and its application to real-world problems [151] while its disadvantage is the difficulty of reproduction, which is a general problem of qualitative research. Also, the results of the Delphi approach can have a tendency for vagueness [284].

4.4.1 Methodological Approach

The Delphi method necessarily involves multiple rounds to reach consensus among the participating experts. Hsu and Sandford [152] propose the conduction of four rounds, whereas the first round is supposed to be an open questionnaire that aims to serve as a data delivery for the subsequent round's questionnaires. This data can be enhanced by experts in rounds two and three, whereas in the fourth round they propose a final voting. The number of rounds conducted is mainly dependent on expert availability and complexity of the topic. In our case, we opt for a three-round Delphi study due to expert availability and the usual sufficiency of three rounds as stated by several methodological investigations [68, 69]. In the first round, experts from the combined transport sector are interviewed via semi-structured interviews. This aims to generate a wide range of initial ideas for the study. After transcription of the interviews, they are analyzed according to the four content areas marked. Key ideas are identified, processed and presented for the second round. In the second round, the determined measures from the interviews are arranged in an online questionnaire. Experts in the second round must rate the measures according to the two dimensions difficulty of implementation and effectiveness on a five-level Likert scale. Additionally, experts can add measures previously not mentioned and comment on existing measures. In the final third round, additionally mentioned measures are added to the online survey and a final voting is conducted. To allow for an assessment of one's own vote, the voting from the previous round is visually presented including the average of all votes. This way the participant can assess and compare their own vote to that of the others.

4.4.2 Complexity of investigating Combined Transport

The complexity of combined transport systems makes it challenging to be investigated all-encompassing. In order to channel the complexity into meaningful separations, different thematic areas of combined transport can be used. Cavallaro et al. [54] have incorporated a policy, cooperation and infrastructure view in their Delphi study of alp crossing combined transports. Lordieck and Corman [213] have additionally included a technology view in their literature and expert survey. Taking these approaches as inspiration, a thematic separation of combined transport regarding policy, infrastructure, cooperation and coordination, and technology, is seen as a meaningful structure to the content of the studies at hand.

Policy

Regulations for combined transport can take place on different levels, e.g. supranational, national, intra-governmental and regional, with policies aiming to set market rules (e.g., subsidies, regulations and taxes) and provide funding and guidelines for infrastructure. The most important regulatory body is the European Commission as a supranational entity. It assigns budgets and sets rules for the development of the European transport market [46] and aims at unifying standards [133]. With its focus on cross-border infrastructure, the Trans-European Transport (TEN-T) network, set up in the Maastricht Treaty of 1992 [106], aims at completing a single European transport market [227, 328] with benefits on a European level, yet causing national costs [144]. The transport corridors aim to increase the efficiency of transport [1] and connect major transport hubs (e.g. the ports in western and southern Europe with its hinterland) and in its latest revision the easy movement of military equipment [100]. Aside from supranational regulations, decentralized approaches can lead to intergovernmental competition [353]. Regulations on a national level have changed over time. With the rise of the European Union, national regulations aim at harmonizing rules within the member states of the EU [173, 270].

Infrastructure

Combined rail-road transport relies heavily on road infrastructure for its pre- and on-carriage and railways and related terminals for its main-carriage and transshipment. In the case of hinterland transport, maritime ports in Europe play a major role as the origin and destination of transport volumes. Historically, infrastructure has been of national and regional concern. Regulation and funding aimed to cater the needs of the economy in proximity. This led to historically developed legacy rail transport systems that make interoperability among them challenging both from a technical and administrative perspective. The development of differing gauge and electrification standards [98] make cross-border traffic difficult. The European Union aims to standardize the different traffic systems with their TEN-T networks [105]. Aside from transport corridors, there is an extensive network of terminals in Europe, serving rail and/or barge transport. They are usually scattered around densely populated areas. Ports as a major demand for combined transport capacity are connected to these terminals in their hinterland, with ports of the northern range being the most busy in Europe.

Cooperation and Coordination

Compared to unimodal transport chains, combined transport adds complexity to its organization with many involved actors and processes. A typical intermodal transport chain starts with a shipper commissioning a freight forwarder with their transport needs. This forwarder then organizes the pre- and on-carriage via truck and reserves capacity with an intermodal operator, which has previously bought traction services of a railway undertaking and transshipment services at intermodal terminals. The railway undertaking has reserved the needed routes with the infrastructure manager [386]. A major challenge in organizing intermodal transport chains is matching the need for long-term planning of operators and short-term demand by shippers and freight forwarders. This potentially can lead to underutilized trains or the need to shift transport to road as rail capacity is restricted [249].

Technology

A technological view on transport systems, especially combined transport systems, has two key aspects to them. Firstly, they need to deal with the physical flow of goods. Especially the efficiency of the railway and transshipment system is crucial for functioning intermodal transport chains. The European Train Control System (ETCS) aims at harmonizing over 20 different European train control systems and potentially allows for autonomous trains [315]. Secondly, data exchange is crucial. A first effort in standardizing intermodal data exchange is the project KV 4.0 [40]. Platforms for booking services, allowing for a fully digital experience and transparency are currently developing (e.g. Modility [244], Rail-Flow [289]), although they haven't significantly penetrated the market yet. Overall, the sector of transportation and warehousing, compared to other industries, is lacking behind in digitization [146].

4.4.3 Conduction of Delphi Study

Using these thematic areas provides a useful framework for expert input. Yet, a clear separation between these areas is difficult, as for example policy measures can radiate into the highly regulatory nature of infrastructure and required careful assessment. Although a clear separation was challenging, the subsequent data analysis provides further classification. The thematic areas haven proven to be of great value to the participating experts, as they set a frame for content and reduce barriers for input. The Delphi study was conducted in the German language. Results were translated for this publication. Table 4.1 gives an overview of the participating experts and their roles within the combined transport chain. For the second and third round the group of experts was extended by other experts to broaden the voting base and assess the presented ideas.

First Round - Initial expert interviews

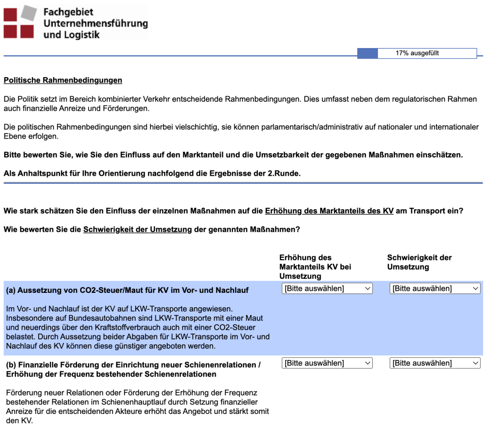
The previously determined thematic areas regarding combined transport have been used to develop an interview guideline for semi-structured interviews. With the help of this guideline a starting set of measures is determine for the subsequent rounds. It also stands as the first round in the Delphi study. Each of the four thematic areas of combined transport, policy, infrastructure, cooperation and coordination and technology, were assessed within the guideline separately. Experts were selected based on their seniority, management position, and experience in the combined transport industry. The study included all major actors of the combined transport chain such as shippers, intermodal operators, terminal operators and forwarders. Each participating expert was asked to describe current problems in the respective thematic area of combined transport and suggest solutions. Finally, they were asked to give an outlook for the next ten years and predict how the use of combined transport will change. The interviews were conducted using the online meeting tool Zoom, and interviews took about an hour. Eight expert interviews were conducted, recorded (with the interviewee's permission) and transcribed. These transcriptions were color-coded, discussed among the authors, and used to derive an initial set of measures.

Nr.	Role	Interv.	Surv. (a)	Surv.(b)
(a)	Freight Forwarder	x	x	x
(b)	Intermodal Operator	x	x	x
(c)	Shipper	x	x	x
(d)	Railway Comp. Manager	x	x	x
(e)	Terminal Operator	x	x	x
(f)	Intermodal Operator	x	-	-
(g)	CT Interest Group	x	x	x
(h)	Railway Comp. Manager	x	x	-
(i)	Railway Comp. Manager	-	x	x
(j)	Business Advocacy	-	x	x
(k)	Business Advocacy	-	x	x

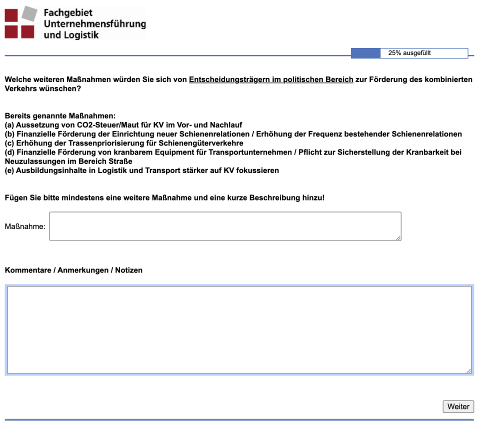
Table 4.1: Participating Experts / Roles in Delphi Study

Second Round - Online Survey

The measures identified from the interviews were given short titles and descriptions. Using these initial measures, an online survey was conducted using a survey tool (SoSci Survey [322]). The survey provides a brief introduction to each thematic area and presents the measures that require ratings based on their impact on market share and difficulty of implementation. Participants can also provide comments on existing measures and suggest further measures to be included in the survey. Since the online survey is less time intensive than conducting interviews, we decided to invite additional experts through e-mail, social media and the chair's contact database.



Voting on measures

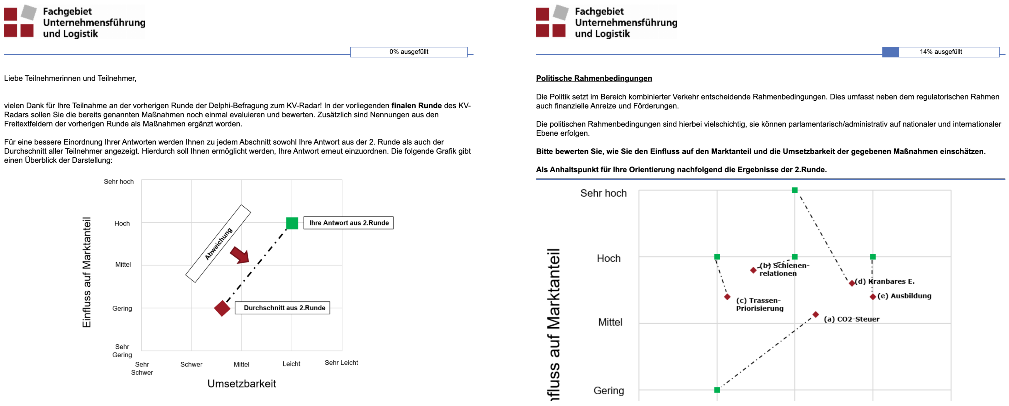


Additional measures / comments

Figure 4.2: SoSci Survey - Second Round - Example of survey pages
Source: Own design

Third Round - Online Survey

In the third round of the Delphi study, participants are presented with an overview of the voting result from the second round, including their own position. This allows participants to evaluate their own positioning in relation to other experts and fosters consensus building. During this round, participants will cast their final votes on the proposed measures. The results will be graphically processed into two-dimensional diagrams, with impact on market share and difficulty of implementation as the dimensions.



Explanation of survey | Final voting

Figure 4.3: SoSci Survey - Third Round - Example of survey pages
Source: Own design

4.4.4 Results of Delphi Study

For each thematic area, the mentioned measures with their title and brief description are presented. The extended list can be found in the appendix in Table 4.6. Additionally, the measures are mapped onto a grid that represents the two dimensions. The voting should serve as a first indication as it is not statistically verified.

Policy

In setting the environment for the proper functioning of combined transport markets, policy is one important component. Policy can both be set on a national and supranational or intergovernmental level depending on the scope of the respective topic. Next to setting regulations, policy can also subsidize transport modes for the desired outcomes or impose additional costs on undesired modes. Policy measures, as shown in Table 4.2, range from measures that aim at increasing subsidies for combined transport like financial support for equipment, new connections and sidings or reducing costs through tax/tolls. Another group of measures aims at easing the pre- and on-carriage for combined transport by lifting restrictions on cabotage for foreign transporters. Equaling the comparative advantage of trucking by enforcing collective wages nationwide, which foreign trucking companies might circumvent currently, and raising tolls and taxes to equalize the cost advantage would be other measures. With policy measures regarding the payload disadvantage, nationwide concepts for handling areas and prioritization of railway freight services, infrastructural disadvantages of combined transport should be mitigated. With focused training in combined transport, potential knowledge gaps for professionals should be addressed. Looking at the voting in Figure 4.4, regarding the practicability, especially

Id.	Short Title	Rd.
P01	Suspension of CO2 tax/toll for CT in the pre- and post-carriage	1st
P02	Financial support for setting up new rail connections / increasing the frequency of existing rail connections	1st
P03	Increase in route prioritization for rail freight traffic	1st
P04	Financial support for cranable equipment for transport companies / obligation to ensure cranability for new road registrations	1st
P05	Focus training content in logistics and transport more on CT	1st
P06	Compensation for the payload disadvantage of semi-trailers that can be craned by increasing the permissible weight (truck + trailer)	2nd
P07	Exempt pre-carriage and on-carriage from the cabotage regulation	2nd
P08	Financial support for the maintenance costs of sidings	2nd
P09	Introduction of a nationwide concept for (handling) areas for combined transport	2nd
P10	Increase of the truck toll on actual and consequential costs	2nd
P11	Enforcement of collective wages nationwide for all truck drivers	2nd

Table 4.2: Results Policy

measures that just require a change in policy like training, cabotage, compensation for payload disadvantage and tax/toll, mitigation can be easily implemented with a moderate influence on market share. Measures that require additional financial investments and administrative coordination, like the usage of sidings, adjusting wages, remitting tolls, prioritization of rail freight, and concepts for handling areas are somewhat more difficult to implement with a moderate influence on market share. Increasing rail relations through subsidies is expected to have the largest impact on market share, which might show that existing relations are either not sufficient or economically viable in the current market environment.

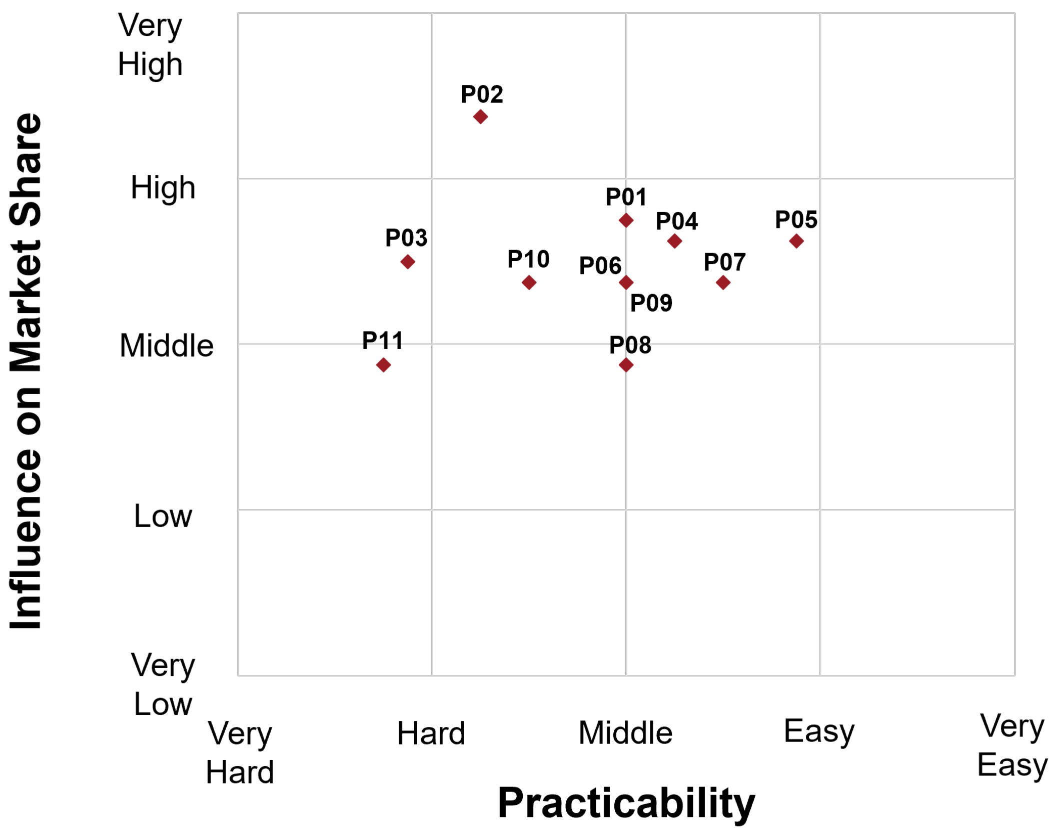


Figure 4.4: Final Results - Policy
Source: Own design

Infrastructure

Infrastructure measures revolve around the improvement of terminal and rail infrastructure. As combined transport also makes extensive use of truck transportation, this can be regarded as infrastructure as well. Infrastructure measures, as listed in Table 4.3, have three major groups. The largest group of mentioned measures revolves around terminals. A general assessment whether additional terminals, especially for densely populated areas in Germany, should be built, is mentioned. As building new terminals is both costly and time-intensive, thorough analysis of transport needs, market areas and existing infrastructure should be conducted. Next to building new terminals, the improvement of

Id.	Short Title	Rd.
I01	Alleviation of the shortage of truck drivers by increasing the attractiveness of work in the pre-carriage and on-carriage of CT	1st
I02	Increasing the terminal density in high-demand regions by building new terminals	1st
I03	Increasing the capacity/productivity of existing terminals / automating terminals	1st
I04	Expansion of the rail infrastructure with a view to freight transport	2nd
I05	Extension of storing areas of existing terminals	2nd
I06	Expansion of terminals for 740m trains	2nd
I07	Accelerated introduction of ETCS Level 3	2nd

Table 4.3: Results Infrastructure

existing terminals is important. Expanding usable storage area, making terminals ready to accept longer trains and increasing automation. Additionally, the railway infrastructure both from a capacity view by looking at dedicated freight lanes and technology view by introduction of the ETCS level 3 (ETCS-3) system enabling shorter block distances and potential autonomous trains are addressed. Improvements to the railway infrastructure both benefit cargo and passenger traffic, especially with technical improvements like the ETCS-3 system. This system potentially allows for shorter block lengths increasing the number of trains on certain tracks. Allowing for dedicated railway tracks for cargo would allow cargo to utilize certain corridors fully by limiting availability for passenger trains. Finally, the alleviation of truck driver shortage, a problem that has come up in the recent past as a huge proportion of current truck drivers retire soon and local and foreign drivers in the sector are not available in numbers required, making the work in combined pre- and on-carriage more attractive might alleviate the shortage at least for combined transport. Infrastructural measures, as Figure 4.5 shows, are regarded as rather difficult to implement, yet seen to have a rather high impact on the functioning of combined transport systems. An assumed explanation can be the rather high cost of building or changing infrastructure while combined transport heavily relies on same. Especially measures that require building new infrastructure like new terminals or expanding existing terminals or building dedicated rail freight lanes and equipping existing lanes with the ETCS-3 technology, are regarded as effective, yet difficult to implement. Alleviating the shortage of truck drivers is regarded as a problem that might be sufficiently practicable to be solved.

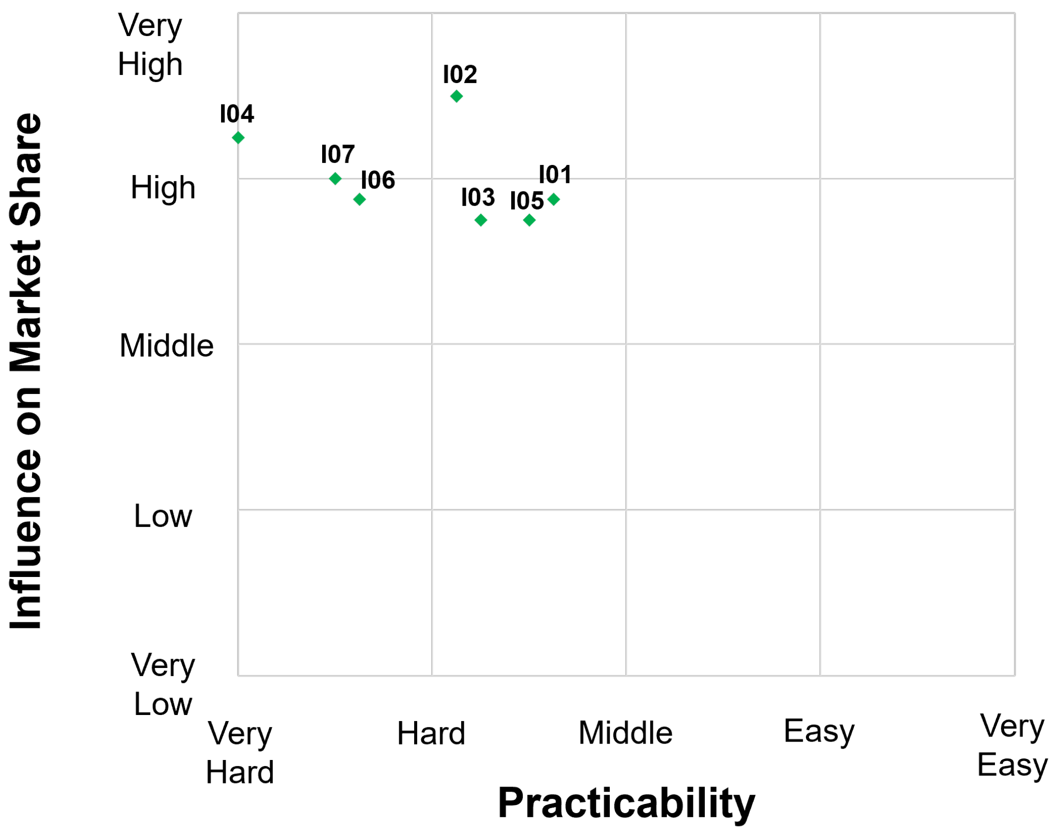


Figure 4.5: Final Results - Infrastructure
Source: Own design

Cooperation and Coordination

Measures regarding the cooperation and coordination among actors in combined transport aim at enabling smoother transport processes and the cooperation between them to enabling business opportunities. Table 4.4 gives an overview of the mentioned measures. A topic of various complexity is the strengthening of cooperation within the European railway system. As the European Union is investing heavily in cross-border infrastructure through its TEN-T program, regulations in the rail sector are still having national limitations. A unified railway market would have tremendous advantages, as combined transport on a continental scale can show its advantages at higher transport distances. As an example, for

Id.	Short Title	Rd.
C01	Strengthening European cooperation in the rail sector	1st
C02	Establishment of digital platforms for data exchange in the field of CT	1st
C03	Bilateral cooperation between terminals for the best possible utilization of trains	1st
C04	Creation of opportunities to consolidate LTL shipments in terminals	2nd

Table 4.4: Results Cooperation and Coordination

problems in cross-border transport, it was mentioned in the interviews, that when crossing the German-Dutch border, the conductors need to provide certain certificates and ensure the functioning of the equipment, e.g. by break tests, before continuing their journey. A harmonization of the inner European rules would have a positive impact on cross-border traffic, yet would require intergovernmental cooperation between the involved nations. Digital platforms for data exchange are necessary, to provide proper information for planning to all actors involved. As customers have complained about the reliability of rail transport services, especially in Germany where cargo and passenger traffic share the same highly utilized tracks, having proper information about the current state of transport would be beneficial. First efforts to unite the information needs of all actors involved have been conducted in the project KV 4.0 grant-aided by the Federal Ministry for Digital and Transport [40], implementation and market penetration are still pending. At last, two measures were mentioned with regard to terminals. Firstly, the cooperation between terminals in close proximity to increase utilization and avoid congestion by arranging and sharing transshipment requests. And secondly, establishing the possibility to consolidate less-than-truckload (LTL)-shipments within a terminal to allow for smaller shipments to be shifted to rail. Both suggestions would require the terminal operators to expand their processes and potentially rethink business models and organization. As Figure 4.6 shows the establishment of terminal cooperation and LTL-consolidation, representing new business opportunities and processes within and between the terminals, are rated relatively lowest regarding the influence on market share, while establishment of terminal cooperation is rated better on practicability. Fostering European cooperation is rated rather difficult to implement while having a high impact on market share. The highest influence on market share is given to digital data exchange platforms with a medium practicability.

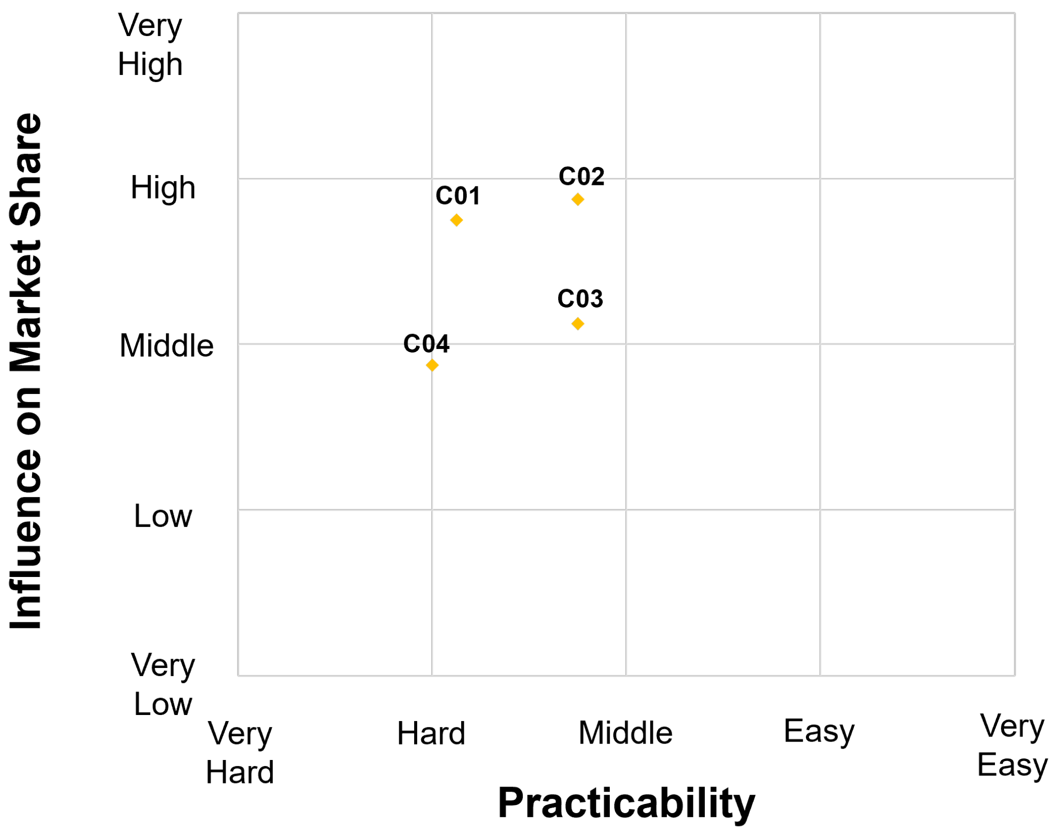


Figure 4.6: Final Results - Cooperation
Source: Own design

Technology

The technological view aims at explaining, how technological developments can have an impact on combined transport. These developments are usually in the making, due to the nature of railway systems, changes to them take a considerable amount of time to implement. Table 4.5 shows a summary of all mentioned technology measures. Mentioned measures to improve combined transport touch on various recent topics from the transport sector. Regarding efficient terminal operations, the promotion and introduction of innovative handling technologies for non-cranable equipment might increase the reach of combined transport. By equipping terminals with these handling technologies, also

Id.	Short Title	Rd.
T01	Promotion of innovative handling technologies	1st
T02	Expansion of the continuous tracking of modes of transport (lorry, train, inland waterway) and the containers located on them	1st
T03	Establishment of central digital booking platforms in the area of CT	1st
T04	Accelerated introduction of the central buffer coupling	2nd
T05	Introduction of a 10-foot standard container	2nd

Table 4.5: Results Technology

smaller customers without the capacity to invest in cranable equipment might be able to shift to combined transport. A major problem that was mentioned in the interviews extensively was the issue of tracking where both transport means and containers are. For the trucking industry, this issue seems to be easily solvable by installing tracking devices in the trucks, for combined transport this becomes more complicated as tracking might need to occur at the containers themselves. As containers need to be transshipped at least once during their journey, this creates opportunity for information gaps. Therefore, tracking needs to be considered either on the transport mean or infrastructure level (train, truck or terminal) or at the containers themselves. Due to the high number of different actors, getting involved in combined transport requires a lot of coordination, both for getting the transport processes running smoothly as well as arranging all financial processes. Established transport chains with multiple actors might run efficiently but make it hard for outsiders to fully grasp and estimate transport capabilities, prices and reliability. Digital forwarders in the trucking sector are an upcoming phenomenon, a notorious name in the field is Uber Freight [347], the equivalent in combined transport, like the start-up Rail-Flow [289], is yet waiting for its breakthrough as the coordination between the multiple actors is way more difficult. The central buffer coupling aims at making the composition of trains easier as it eliminates major need for manual labor to couple trains at yards. This way rail bound transport can become a lot more efficient. The technology itself is available but requires major investments by the owners of rail equipment and the establishment of adjacent processes. The introduction of a 10 ft. standard container aims at expanding the market possibilities by allowing for smaller shipments. The idea in this case is to allow for the coupling of two 10 ft. containers into one 20 ft. container that can easily be handled at terminals. The 10 ft. containers both allow for smaller shipments and smaller trucks for pre- and on-carriage. Figure 4.7 shows the voting on practicability and effectiveness. As can be seen, measures that require both major investments in equipment, technology and processes like the central buffer coupling technology, innovative handling

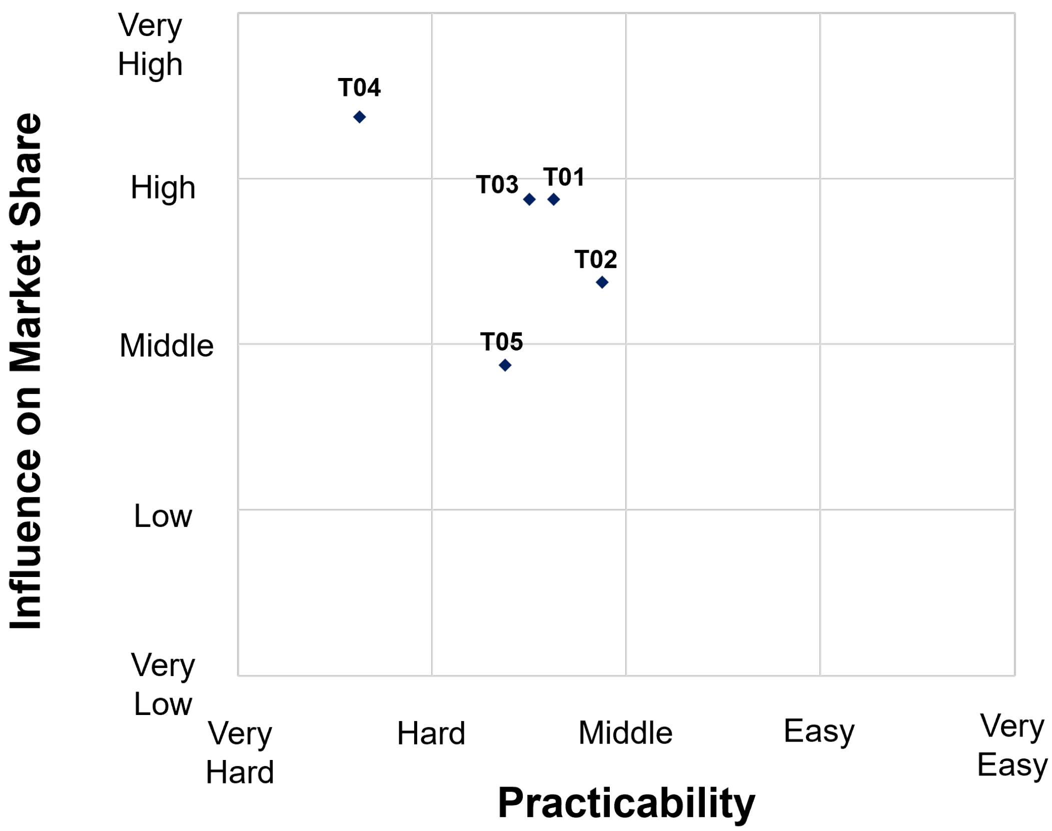


Figure 4.7: Final Results - Technology
Source: Own design

or central booking platforms are rated quite effective in their market share impact, while being somewhat difficult to implement. The introduction of 10ft containers is assessed as having a medium impact on market share, while being relatively easier to implement. Offering a service with 10ft containers basically doesn't require huge investments, yet the possibility for the business model needs to be evaluated. Finally tracking capabilities, rated as rather practical to implement with a medium impact on market share, need to be assessed from a process point of view. As the technology for tracking is more or less widely available, determining where to track containers and how to share the data are issues to look into.

4.4.5 Generalization of Measures

A total of 27 specific measures have been identified in the Delphi study. They suggest potential areas for improvement of combined transport. For a better structuring of the measures, they have been grouped into 8 generalized categories by consensus of the authors. The goal of the clustering was to define meaningful categories that take into account the main aspect of the different measures while maintaining clear boundaries between categories. The results of this process are shown in Figure 4.8. The subsequent section explains the reasoning and content for the categorization of the measures.

(a) Foster mode choice towards combined transport

- P01 - Suspension of CO2 tax/toll for CT in the pre- and post-carriage
- P06 - Compensation for the payload disadvantage of semi-trailers that can be craned by increasing the permissible weight
- P07 - Exempt pre-carriage and on-carriage from the cabotage regulation
- P10 - Increase of the truck toll on actual and consequential costs
- P11 - Enforcement of collective wages nationwide for all truck drivers
- I01 - Alleviation of the shortage of truck drivers by increasing the attractiveness of work in the pre-carriage and on-carriage of CT

(b) Increase capacity/efficiency of rail transport

- P02 - Financial support for setting up new rail connections / increasing the frequency of existing rail connections
- P03 - Increase in route prioritization for rail freight traffic
- P08 - Financial support for the maintenance costs of sidings
- I04 - Expansion of the rail infrastructure with a view to freight transport
- I07 - Accelerated introduction of ETCS Level 3
- T04 - Accelerated introduction of the central buffer coupling

(c) Increase capacity/efficiency of transshipment

- P04 - Financial support for cranable equipment for transport companies / obligation to ensure cranability for new road registrations
- I02 - Increasing the terminal density in high-demand regions by building new terminals
- I03 - Increase the productivity of existing terminals through automatization
- I05 - Extension of storing areas of existing terminals
- I06 - Expansion of terminals for 740m trains
- T01 - Promotion of innovative handling technologies

(d) Increase knowledge and skills of combined transport

- P05 - Focus training content in logistics and transport more on CT

(e) Increase efficiency of transport markets through European and national cooperation and regulation

- C01 - Strengthening European cooperation in the rail sector

(f) Establish fully digital processes and transport chain visibility

- C02 - Establishment of digital platforms for data exchange in the field of CT
- T02 - Expansion of the continuous tracking of modes of transport (lorry, train, inland waterway) and the containers located on them
- T03 - Establishment of central digital booking platforms in the area of CT

(g) Foster cross-actor cooperation for increased utilization and efficiency

- C03 - Bilateral cooperation between terminals for the best possible utilization of trains

(h) Enable new business models in combined transport

- C04 - Creation of opportunities to consolidate LTL shipments in terminals
- P09 - Introduction of a nationwide concept for (handling) areas for combined transport
- T05 - Introduction of a 10-foot standard container

Figure 4.8: Generalized Measures from Delphi Study
Source: Own design

(a) Foster mode choice towards combined transport [P01 | P06 | P07 | P10 | P11 | I01]

Fostering mode choice towards combined transport can be achieved with essentially two strategies. The first strategy is to make unimodal transport less competitive. This can be done by increasing its costs by raising tolls for road use to incorporate external costs (P10), enforcing collective wages nationwide for trucking as combined transport can't easily make use of cabotage (P11). The second strategy is to alleviated disadvantages of combined transport by implementing favorable regulations, e.g., exempting pre- and on-carriage from certain taxes and tolls (P01), compensate for payload disadvantages due to heavier cranable equipment (P06) and exempting combined transport from cabotage regulations (P07). Also, as a general truck driver shortage in Europe is predicted, increasing the attractiveness to work in this sector through regulation and subsidies can make it more competitive (I01).

(b) Increase capacity/efficiency of rail transport [P02 | P03 | P08 | I04 | I07 | T04]

Combined transport heavily relies on the railway infrastructure for its main-carriage. Mixed use of the railway network in Europe for passenger and freight services and a general overloading of the network, effectively decreases the capacity and reliability of the railway network for freight transports and diminishing the reliability of such transport. In order to increase railway capacities and efficiency, three ways are identified. Infrastructure measures like subsidizing sidings (P08) and building railway lines especially for freight transport (I04) can increase the capacity. Establishing new combined transport connections can be costly as profitability highly depends on utilization. By providing initial subsidies this burden might be alleviated (P02) and a change in the priority of rail freight might lead to increased capacity as well (P03). Finally, wide implementation of technological developments like the ETCS system for (partly) autonomous traffic and improved tracking (I07) and the implementation of the central buffer coupling for faster train provision (I07) are just two technological advances that can make rail freight more efficient.

(c) Increase capacity/efficiency of transshipment [P04 | I02 | I03 | I05 | I06 | T01]

Aside from the railway network, availability of terminals and transshipment capacity play a decisive role in choosing combined transport. Increasing the general availability of terminals (I02) or expanding existing terminals for longer trains (I06) and more handling areas (I05) can increase available capacity. Also using innovative handling technologies (T01) and making transport companies invest in cranable equipment, will increase transshipment potential (P04). Finally, with the advance of robots and intelligent systems, terminals should be further automated (I03).

(d) Increase knowledge of CT [P05]

As combined transport is a rather complex system of different actors and transport particularities, proper education and knowledge is a prerequisite to participate in it (P05). This is not only relevant for staff within the transport process, but also for shippers that are potential users of it and researchers that expand their focus.

(e) Increase efficiency of transport markets through European and national cooperation and regulation [C01]

With the unification of Europe, cross-border traffic has increased in importance and regulations on a European level have become more important. The European Union fosters transport corridors with its TEN-T program, provides subsidies for infrastructure and aims on harmonizing national regulations and infrastructure to make cross-border traffic interoperable. As this is an ongoing process, the call for deeper integration of the European market will lead to a larger transport market (C01).

(f) Establish fully digital processes and transport chain visibility [C02 | T02 | T03]

Digitization has become an important part of business processes and cross-actor interaction. For combined transport, with its multiple actors and cross-actor processes, digitizing processes can lead to big efficiency improvements. The basis for these digital processes can be set by providing data exchange capabilities between the different actors in the transport chain (C02) and by enabling digital offerings and bookings on a common platform (T03). The provision of continuous tracking capabilities further enhances transparency and enables potentially intelligent applications (T02).

(g) Foster cross-actor cooperation for increased utilization and efficiency [C03]

Due to the high fixed costs of providing freight train services, full utilization of transport equipment is economically crucial in combined transport. Therefore, the cooperation between actors in the transport chain aims at increasing this utilization factor. One possibility mentioned is the cooperation between nearby terminals to increase train utilization (C03), yet there are a lot more possibilities to achieve this.

(h) Enable new business models in CT [C04 | P09 | T05]

Functioning business models are at the heart of any economic operation. Expanding the reach of combined transport to apply to more market segments could be fruitful. A suggested business model is enabling LTL shipment consolidation at terminals (C04), which would allow smaller shippers to use combined transport. With a nationwide concept for the management of handling areas, transport can be made more flexible, allowing for additional business model opportunities (P09). Finally, aside from these terminal centered business models, the introduction of new transport equipment like a 10 ft. container that can be coupled into 20 ft. containers, would enable smaller shipments (T05).

4.4.6 Conclusion of Delphi Study

The Delphi study has highlighted various possibilities to improve combined transport systems by presenting a total of 27 potential measures. These measures are generalized into 8 broader categories which cover major factors of influence for combined transport systems. The generalized categories range from policy calls, improvements in infrastructure for rail and transshipment, the human factor in combined transport systems, efficient transport markets, digital processes and the corresponding cross-actor cooperation up to enabling new business models and markets.

4.5 Literature Review - Trends in Combined Transport Research

Taking the generalized categories from the Delphi study, relevant research can be classified within it to provide a practice-oriented view on research. This also further provides confirmation of the generalization as an additional qualitative assessment as requested by Melander [235] for Delphi studies. The relevant literature is identified in a systematic literature review. Within this review, the focus is put on qualitative, analytical and empirical research, excluding quantitative assessments.

4.5.1 Methodological Approach

Following the approach of Seuring and Gold [317] to content-based literature reviews, the literature review is conducted in multiple phases. The initial search string comes out as:

> ((intermodal OR inter-modal OR multimodal OR multi-modal OR comodality OR co-modality OR synchromodal OR synchro-modal) AND (transport*)) OR ('combined transport' OR 'combined transportation')

The conjunction of search terms comes due to the often synonymous use of the terms intermodal, multimodal, co-modality and combined transport according to Reis et al. [296]. Additionally, the emerging concept of synchromodality has been included as described by Kurapati et al. [188]. The term combined transport has been set as a fixed term as otherwise a lot of irrelevant research from other fields like chemistry are found. We limit the search for research within the last decade, from 2012 to 2022. As a meta-search engine WebOfScience by Clarivate is used and the search is limited to peer-reviewed journal articles. The initial set of found literature is subsequently assessed by content. Inclusion criteria are a focus on European markets (European Free Trade Association (EFTA) members [87], the United Kingdom (UK) and countries of the Balkan), thematic focus on rail-road combined transport or adjacent rail transport, and methodologies of qualitative, analytical and empirical nature. Analogous, exclusion criteria are non-European focus, intermodal transport aside from rail-road combined transport and quantitative or optimization approaches. The assessment is done in multiple steps, from title to abstract and finally full-text assessment. The results of each step after Moher et al. [245] are depicted in Figure 4.9. Finally, the included full-text articles are grouped into the generalized categories from the Delphi study and further assessed by their content.

4.5.2 Assigning literature into generalized categories

The literature identified in the review has been assigned to the generalized categories determined from the Delphi study. The assignment process has proven to be clear to conduct indicating meaningful categorization. After the assignment, the content of the papers in each category were further grouped by content similarity. This has led to subcategories for each generalized category. The subcategories are depicted in Figure 4.10. This section subsequently provides a description of the assignments into the generalized categories and the content assessment for each subcategory.

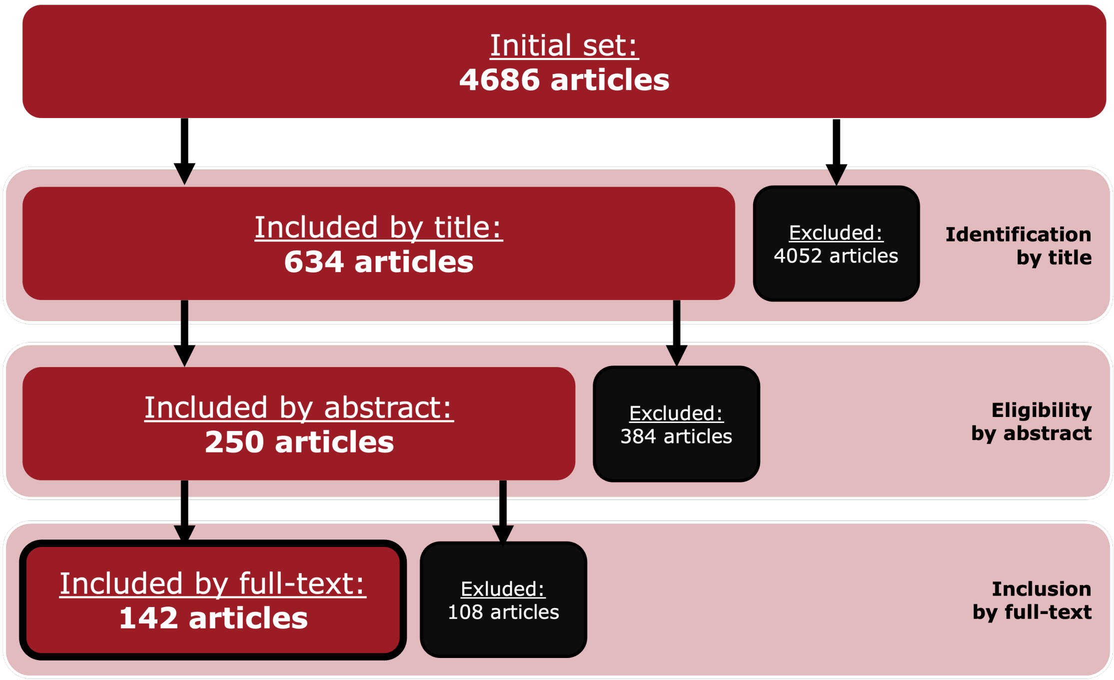


Figure 4.9: Selection process of literature
Source: Own design adapted after Moher et al. [245]

(a) Foster mode choice towards combined transport

Fostering mode choice towards combined transport is an important aspect for its strengthening. Sustainability aspects play an increasing role when considering the more environmentally friendly rail transport compared to trucking, nonetheless the analysis of further mode choice factors is of similar importance. Finally, the strengthening of trucking and its effect on combined transport through long vehicle trucks has gained attention.

Sustainable Transport A major advantage of combined transport is its lesser impact on the environment and increased sustainability. Van den Berg and De Langen [355] investigate shippers' and forwarders' choices for environmentally friendly transport by conducting a literature review and a survey in the Netherlands. Among their conclusions is that shippers focus more on environmentally friendly transports than forwarders. With larger size of a shipper, transparency requirements regarding sustainability increase. Similarly, by taking a look at the environmental impact of transport and the interplay

Figure 4.10: Overview of subcategories from literature review
Source: Own design

between a logistics service provider and an intermodal operator, Lammgård [191] has investigated which side pushes sustainability. In-depth interviews at a logistics service provider and with the CEO of the intermodal operator have revealed a stronger pressure by customers for sustainable transport and the challenge of reducing cost and emissions alike. This perceived competitive pressure is one of the key insights when arranging sustainable transport. Liljestrand [205] has created a tool for shippers to evaluate the possibility for modal shift regarding climate impact and cost parameters of their shipments. In total three different actions for a shipper were evaluated, engaging combined transport, double-stacking pallets and using high-capacity vehicles. Kos et al. [182] have compared different transport modes by their external costs, especially regarding emissions of different types like carbon dioxide, nitrogen oxide, particles and fatalities. While there is a benefit of rail freight regarding these costs, results for intermodal waterways compared to road freight are inconclusive or leaning towards road freight. Looking at trucking in Europe, Mayer et al. [230] have taken a look at vehicles in operation in Europe. According to them, as not all vehicles operate within the proposed guidelines, the mode is environmentally even worse. They take into account the emissions of noise as well, which can be a problem for rail freight too. They propose several policies on how to deal with these issues. Mostert et al. [258] assess different transport modes for Belgium. Different emission classes of trucks in operation are compared with intermodal transport. Their model allows for the optimization of transport towards human health costs and therefore leans towards intermodal transport. Zhang et al. [393] investigated the impact of a carbon tax and using bio-diesel on modal shift in the Netherlands. Their model estimates the impact of these policies, concluding an influence on modal shift. Finally, Ingrao et al. [155] have investigated the Italian market for environmentally focused mode choice by calculating life-cycle related and external costs for different uni- and multi-modal transport alternatives.

Mode Choice Analysis Arencibia et al. [11] have employed advanced choice experiments to determine mode choice variables. By analyzing the freight traffic between Spain and the western ports, they determined the willingness to pay for service level improvements and the elasticity of choice probabilities. Bask and Rajahonka [19] have looked at mode choice variables in EU to determine their importance. Analyzing Request for Quotations (RfQ), tenders and contracts, they reveal that utility and cost-based considerations still dominate over sustainability aspects. Khakdaman et al. [175] have investigated the willingness of shippers to hand over control of the mode choice to their service provider. They present different types of shippers with differing willingness for such a transfer of power. Meers et al. [233] have looked at mode choice in short-distance hinterland container transports by investigating mode choice of Belgian shippers in the port hinterland. For being competitive in such a short range, they conclude that daily connections, high reliability and better information for potential customers is needed. Similarly, Reis [293] has investigated the short-haul potential of intermodal transport in Portugal and concluded that intermodal transport can outperform road transport only in the price variable. Román et al. [300] have developed a mode choice model with attribute cut-offs to understand and estimate the heterogeneity of shippers' preferences. Černá et al. [56] have determined different factors for mode choice in the Slovak market. Among the factors in their framework are price, transport time, services and properties of the carrier with a ranking of these factors. Carboni and Chiara [47] compare road and intermodal rail transport on a cost basis and take into account external costs like noise and pollution. Comparing different distances to terminals in the pre- and on-carriage they assess different decisions for mode choice. By looking at multiple shippers from the fast-moving consumer goods sector who made their transports intermodal, Eng-Larsson and Kohn [92] try to identify success factors for a modal shift. Among the factors for it are high carrier performance, low demand volatility and centralized control systems. Finally, Eng-Larsson and Norrman [93] take a look at the contractual set-up between logistics service providers and intermodal operators and the influence on modal shift. They find that for their case a modal shift only occurs in a low-capacity risk or high shipper pressure environment. They propose a risk-sharing contract to circumvent this limitation for modal shift.

High-Capacity Vehicles The implications on modal shift by allowing High-Capacity Vehicles (HCV) is investigated by Pålsson and Sternberg [273] for different product groups in Sweden for different logistics attributes. Meers et al. [231] investigated the impact of HCVs on the intermodal sector in Belgium. In their simulation study, they investigate the potential cost reduction after introducing HCVs and their potential impact on external costs. Looking at the sector of fast-moving consumer goods in UK, Palmer et al. [272] investigated the impact of a collaboration between companies to achieve higher utilization of their equipment. By obtaining detailed transport data from ten companies in the sector, they analyzed different transport options namely double deck trailers, HCVs and intermodal rail transport and found that through cooperation a significant reduction in cost and emissions could be achieved.

(b) Increase capacity/efficiency of rail transport

Rail capacity is essential for combined transport. It is both influenced by railway infrastructure and the organization of combined transport connections. Additionally, sidings can increase direct connectivity to shippers.

Railway Infrastructure An investigation of the railway network in Greece, with a focus on the northwestern Peloponnese, is conducted by Carydi [52], who investigated geographic and economic particularities along with technical requirements. Marzano et al. [228] investigate gaps in the railway infrastructure of Italy and propose a new incentive scheme for railway undertakings to compensate for infrastructure gaps. They provide a way to calculate optimal incentives, e.g. a reduction in access charges for railway undertakings on origin-destination pairs. Vaičiūnas [352] evaluated the significance of railway lines in the Baltic countries. The Rail Baltica, crossing Poland, Lithuania, Latvia and Estonia, and the Viking Route running through Lithuania, Belarus and Ukraine are assessed. Which of the countries profit the most from an enhancement of the railway network is determined using several economic metrics. Woodburn [383] has investigated the effect of rail network enhancement on port hinterland container activity in the UK. Potentially higher train capacities and load factors were among the positive conclusion. Clausen and Voll [64] have compared the railway systems of Europe and north America. They assess the different ways of planning rail freight traffic, especially regarding shortest paths and train utilization. A discussion on how to use the insight from one system for the other is conducted. Mortimer and Islam [257] react to the article by additionally assessing the differences between the American railway system and its European counterpart and by criticizing several shortcomings. According to them, the market liberalization in America, competitive situation in Europe and technological advances are not discussed satisfactory. Vleugel and Bal [367] take a look on how to improve railway infrastructure in a cost-effective way through smart investments. In contrast to large projects in rail, their approach could foster a better functioning of transport chains across actors and borders. Dimitriou and Sartzetaki [80] have developed an assessment framework of the socioeconomic effects of large infrastructure projects on rail corridors. They successfully applied their framework on the corridor between the Port of Alexandroupulos in Greece and Burgas in Bulgaria.

Intermodal Rail Connectivity and Corridors Langen et al. [194] have empirically investigated intermodal connections, both for barge and rail, in the European market. Within their assessment, they provide distances, frequencies, origins and destinations of intermodal transport. Among their findings is that several intermodal connections below a distance of 100km exists and that frequency of connections play a huge role in mode choice. Pelevic [278] compares the intermodal hinterland connectivity for different Ports of the Adriatic region. Especially cross-border connections seem to be lacking in the region. Popa and Schmidt [285] investigate corridor development between central and south-east European regions. They list several measures to improve operations and infrastructure to provide better access to and from Romania to central Europe. Saenger et al. [310] investigate the potential of a periodic containerized rail freight system for Germany to accommodate for transport needs for inner and cross-border freight traffic. Stoilova et al. [330] investigate the performance of the railway network in the TEN-T Orient-East-Med corridor. They factor in various parameters regarding the railway network and the corridor as whole. Wagener [370] investigates concepts for establishing logistics centers along freight corridors. Especially the concept of freight villages, where to place them and how they should be developed, is assessed. Witte et al. [382] take a look at bottlenecks in the TEN-T network by applying a developed framework, investigating micro- and macro-level bottlenecks, to the corridor connecting Rotterdam/Antwerp with Genoa. Another transnational corridor is assessed by Islam and Eidhammer [164] who investigate, how a new entrant operator can offer pan-European rail freight services in a case study for a hub-to-hub connection between Cologne and Györ. The new service could offer benefits regarding price, transit time, reliability and information flow management while falling short on frequencies and capacity availability. Tadić et al. [333] take look at southeast Europe on how intermodal transport can be developed. They analyze different configurations of terminals and corridors by using multiple methodologies and give recommendations for intermodal transport development.

Sidings Private sidings enable shippers to do either the pre- or on-carriage on rail additionally to the main-carriage. Bruckmann et al. [38] have investigated the economic necessities of private sidings in Switzerland. Their analysis shows how such a service can be competitive, estimating a break-even distances and showing the development of the service over the years.

(c) Increase capacity/efficiency of transshipment

Another very important infrastructure component in combined transport are transshipment facilities. Articles found deal with location assessment, optimization of operations and automation, strategic management of terminals and innovative handling technologies, that not necessarily need classical terminals.

Location Assessment Ližbetin [208] has developed a methodology for determining the best location intermodal terminals and applied the model to Slovakia. For Belgium, Pekin et al. [277] have done a location analysis for intermodal terminals and investigated their relevance regarding intermodal transport chains and allowing for an assessment of the market areas. Similarly, Meers and Macharis [232] have extended the model to assess whether Belgium needs additional intermodal terminals. They propose several potential locations, yet claim that a balance of terminals, especially in the mid-sized range, need to be found so additional transshipment capacity is not cannibalizing existing terminals. Roso et al. [301] have investigated criteria for terminal locations in Croatia by determining different transport quality criteria and combining them with location criteria. The importance of a proper connection to TEN-T networks is stressed. With general assessment of the infrastructure of the Polish intermodal market, Wiśnicki et al. [381] look at locations of current and future terminals and their development. Their analysis comprises current capacities and a proposition for an intermodal terminal network. Looking at the Danube corridor, Pamucar et al. [274] have developed a multi-criteria decision-making model to investigate the optimal location of logistics centers and terminals and apply it to a three-mode terminal location. Cavallaro et al. [53] have investigated the potential for small scale terminals at the Brenner axis by conducting volume, geographical and local business analysis. By developing a monopolistic competition model for logistics structures, Murillo and Liedtke [261] have assessed spatial patterns of macro-logistics nodes, in this case inland terminals. They observed different stages of terminal development, with an initial growth in size and when size stagnation occurs a focus on specialization. They find a correlation between number of terminals and transport demand in agglomerated regions and a trend towards smaller terminals and distance between them in rural areas.

Operation and Automation Abramović et al. [2] have developed external quality assessment (EQA) criteria for terminals in Croatia. Their assessment on how to improve service quality of these terminals reveals problems in organization, management, operations and infrastructure. They recommend extended data collection and analysis to be applied to the respective terminals. Carboni and Deflorio [48] take a look at how to link automatic vehicle detection at the gates with the indicators measuring terminal performance. Their systems architecture model provides different layers and views on the vehicle detection process at terminals. In a follow up work, Carboni et al. [49] investigate the tracking of trucks inside a terminal with Bluetooth technology by scanning signals from on-board devices. Their system is tested in a large Italian rail-road terminal tracking the arrival and time of trucks at certain points in the terminal. By analyzing the operations of a reach stacker within a terminal, collecting relevant data and statistics, Kostrzewski and Kostrzewski [183] claim to provide the basis for further simulation studies for improved terminal operations. Tadić et al. [335] propose a stakeholder-based planning approach for new intermodal terminals to increase sustainability and freight flows. They apply their analysis to a terminal in Belgrade, Serbia. Tadić et al. [334] developed a model to define different types of intermodal terminals and assesses the efficiency of them. They apply their method of multi-criteria decision-making to a multitude of central, western and northern European terminals.

Strategic Management Filina-Dawidowicz and Kostrzewski [118] look at the complexity of terminal processes with growing customer demands and expectations for current terminal operations. They created a ranking method to assess the complex services offered and apply it to a terminal in Poland. Their results can aid management to determine, which services to offer. Liedtke and Murillo [204] assess two different policy strategies, investment grants for terminal operators and the internalization of external costs, to promote intermodal transport. Both policies are evaluated in a market equilibrium model for the German market. They see welfare maximizing effects for developed markets in internalizing external costs and in developing market by applying a mixture of both policies. Monios [247] identifies governance structures of intermodal terminals and compares them to governance structures of ports. The major difference in governance is that inland terminals need to maintain relationships to a multitude of actors to ensure profitability and smooth operations, whereas for port-centered terminals issues of ownership and concessions are more important. Subsequently, Monios and Bergqvist [254] have investigated how the concession system of port terminals could be applied to intermodal terminals. Investigating the four phases of the terminal lifecycle, Monios and Bergqvist [252] try to identify appropriate strategies for each phase. The goal of their research is to supply deciders with long-term strategies and to support decisions for a sustainable terminal development. Looking at which services to offer, Russo and Gronalt [304] investigate the possibility for value added services at terminals. Their model provides an estimate of the effect of added services and is tested with OCR gates and fast-lane trucks.

Innovative Handling Illés et al. [154] assess the concept of a new robotic transshipment device to improve handling and estimate its impact by looking at routes in Austria and Hungary. Assessing horizontal transshipment technologies for non-cranable semi-trailers, Truschkin and Elbert [344] look at different scenarios, e.g., subsidies or the introduction of longer trains, to estimate the market potential of the technology. van Binsbergen et al. [354] investigate how mega-projects in infrastructure, especially terminals, have adopted innovative transshipment approaches by presenting various cases.

(d) Increase Knowledge and Skills of Combined Transport

Knowledge about the rather complex structure and processes of combined transport are necessary for both organizers and shippers and a prerequisite for functioning transport chains.

Education and Knowledge Macharis et al. [222] aim to educate shippers on possibilities of intermodal transport by providing an online tool that allows for a location-based analysis of shipment options. With this tool shippers can assess whether intermodal transport suits their transport needs. Mitropoulos et al. [243] have compared business needs with training offerings and existing research for a gap analysis in the Baltic region. Based on their analysis they developed training courses and educational areas to improve knowledge in intermodal transport for Latvia. For the concept of synchromodality, Kourounioti et al. [184] have developed a simulation game to study the behavior of actors involved when employing synchromodality. The game was played both as a board game and in an online version with Dutch supply chain professionals. Kurapati et al. [188] have extended the game to infrastructure, with each participant needing to deal with planned and unplanned disruptions. Palacin et al. [271] have evaluated how innovative rail research can be implemented. Aiming at the UK market, they determined that research needs to be aligned with strategies and implementation planning to be utilized and that knowledge needs to diffuse better into the railway sector.

(e) Increase efficiency of transport markets through European and national cooperation and regulation

The efficient functioning of markets within Europe is subject to various regulations and subsidies. Legislation and regulation can happen on different levels. Firstly, EU and transnational issues, regarding either the entity of the European Union or cross-border issues are assessed. National and regional regulation and administration focus both on providing own regulations and the implementation of higher regulation.

European & Transnational Market liberalization effects regarding vertical separation in the railway industry have been investigated by Abbott and Cohen [1]. In their assessment of empirical studies several aspects like range of service, intensity of track use and the existence of intermodal competition is assessed. Further, Cantos et al. [46] investigate market liberalization of European railway markets by estimating efficiency levels of 23 national railway markets after liberalization. While horizontal liberalization seems to lead to more efficiency, the results for vertical separation are ambiguous. A combination of horizontal and vertical reforms is proposed. Gharehgozli et al. [133] take a look at European standardization efforts. They assess the relevant policy bodies for standardization. Further standardization efforts should consider a divide in policy for maritime and continental transport. Investigation of market efficiency is given by Saeedi et al. [309], who developed a model to assess the European intermodal market. Their model allows for interesting insights into the functioning of the European market and a collection of data within it. Wiśnicki and Dyrda [380] assess the efficiency of the central and eastern Europe market. They investigate intermodal transport units, transport modes, transshipment technologies and organizational aspects and give recommendations. A view on the transshipment market efficiency is given by Saeedi et al. [306], who measure market concentrations within the EU. A conclusion is that transshipment markets in Europe are rather oligopolistic, and mostly serve an area of 70km around a terminal. Looking at the impact policy implementation have, Beškovnik and Twrdy [27] analyze green policies in south east Europe. Their analysis provides an overview on how green logistics strategies can be implemented in the region and how policy, industry and logistics need to cooperate in order to achieve the desired outcome of sustainable transport. Islam et al. [165] looked at ways to achieve the aspired European shift to rail transport according to the EU Transport White Paper published in 2011. They call for several operational improvements within the rail-bound transport chain, a better integration of ICT services and a higher utilization of existing infrastructure by implementing certain measures. Aside from policy assessments, infrastructure is of European and transnational concern mostly through the TEN-T program. Marshall [227] investigates the impact of the program on spatial planning by giving an overview of the TEN-T development and analyzing tensions between European planning policy and regional spatial implications. Wagener [371] looks at new technologies, routes and concepts, hinterland activities of ocean carriers, innovative handling technologies for non-cranable trailers and freight corridors in the TEN-T network and assesses policies with a focus on financial and effectiveness metrics. The influence of the EU in coordinating processes and actors necessary for completion of the TEN-T and the single European transport market is investigated by Stephenson [328]. Looking at audits of past developments and implementations and analyzing the role of the European Commission in creating and implementing policies, the EU Commission is presented as a resilient coordination body in a hybrid coordination environment. Finally, looking at the aftermath of the financial crisis of 2008, Islam [163] investigates the austerity measures implemented in seven countries and their impact on infrastructure. A key finding is, that rail infrastructure suffered due to austerity measures in these countries whereas road infrastructure slightly improved.

National On the national level, Cowie [65] has assessed the liberalization of the UK railway market, changes in the market structure and the role of policy on modal competition. A conclusion is that few market entries have been made since liberalization and suggestions on how to foster competition through regulatory interventions are given. Also looking at the British intermodal market since the late 1990s, a period of liberalization, Woodburn [384] investigates the development of the market and determines the source of market growth. It was shown that most development happened on transport corridors between ports and hinterland, while innovation in services has attracted capacity as well. Looking at the Austrian market, Emberger [91] analyzes its transport policies and their effects on the transportation market. Kapfenberger-Poindl [173] has investigated the Austrian transport market and its potential for increasing the use of intermodal transport. The investigation suggests various improvements from better coordination to the use of ICT. The Hungarian market is analyzed by Oszter [270], who has investigated the development of the Hungarian transport market with a view on transport policies and the interplay between different administrative levels. Changes on the Swedish market have been investigated by Flodén and Woxenius [122]. As the market was impacted by the withdrawal of the main intermodal service provider, the effects of the withdrawal are analyzed. The Polish market is assessed by Foltynski [123], who takes a look at policies and barriers. Especially financial and economic, technical, legal, administrative and organizational barriers are analyzed and the influence of EU and Polish initiatives are assessed. Similarly, Mindur and Paweska [241] draw conclusions from historic developments of intermodal transport in Germany, France and Italy for the development of the Polish intermodal sector and provide a list of measures to improve the prospects of Polish intermodal transport. An assessment of the Czech intermodal market is done by Říha and Dočkalíková [298], who investigate infrastructural aspects and past developments for further intermodal developments. Finally, Santos et al. [312] investigate the impact of different transport policies on the competitiveness of intermodal transport in Belgium. In total they assess three different policies, subsidies for intermodal transport, the internalization of external costs and integrated planning approaches for terminal locations and conclude that subsidies and optimized terminal locations would benefit the Belgian market.

Regional Taking a regional view, Behrends [23] analyzes the relevance of local policies on potential modal shift towards intermodal transport by developing a framework for local authorities that should help them to integrate intermodal transport into long-term policy planning. Cavallaro et al. [54] investigate combined transport in the Alps region by looking into reasons for a difficult acceptance and providing several measures on how to improve attractiveness for intermodal transport in the alps. Monios [250] analyzes freight villages in Italy, by collecting data on 25 freight villages and conducting 5 case studies. Difficulties in establishing reliable rail freight services, especially in southern Italy, and misalignment of national funding, might clash with local development needs and strategies. A more integrated policy development is proposed. Van den Heuvel et al. [358] investigate the spatial concentration of logistics facilities in Dutch province. Among the outcomes is that intermodal terminals have a significant effect on employment around its vicinity.

(f) Establish fully digital processes and transport chain visibility

Establishment of digital processes and transport chain visibility can lead to more efficient transport chains. In general, this encompasses process digitization, ways to measure the transport chain performance and tracking mechanisms utilizing the physical internet.

Process Digitization To achieve seamless cooperation between multiple actors, information and data exchange is crucial. Bohács et al. [33] look at digital freight and warehouse exchanges to foster digital transport enterprises in the intermodal sector. They propose a conceptual framework on the integration of logistics cloud services for the fulfilment of intermodal transport services in Hungary. Taking a look at establishing digital processes, Harris et al. [145] have investigated the efforts stated in 33 EU framework program projects, linking technological adoptions and trends, discuss barriers in the adoption of ICT and resolutions for them. An application for intermodal eLogistics is investigated by Islam and Zunder [167]. Their results suggest the use of open-source software and open standards to foster supply chain efficiency through digitization. Funding of such platforms could be done by EU or national governments. Marchet et al. [226] look at the impact of the adoption of information systems and processes at terminals, looking at the potential impact an adoption would have on the processes at terminals. Vural et al. [368] have looked at how information systems might mitigate barriers to intermodal transport. They present a selection of digital tools to overcome barriers between actors and discuss how to introduce digital tools in a multi-actor environment. Adoption by market leaders, demands by service buyers and vertical integration could be potential solutions. Fostering the collaboration of actors in rail-bound transport chains, Milenković et al. [240] evaluate a digital data exchange platform, evaluated within a case study with the view from various actors like shippers or logistics service providers. Especially attributes regarding reliability are most critical for such a data exchange. Similarly, Jacobsson et al. [168] have looked at information attributes that need to be exchanged between actors of an intermodal transport chain. Their developed classification framework, encompassing static, historical and dynamic data, focus on several attributes like pick-up times, hub's loading points, hub's unloading points, occupancy rates, and queuing status.

Benchmarking and Performance Assessment Benchmarking and performance tracking are important to tell how well transport chains are functioning. Dewan et al. [78] have identified several key performance indicators (KPIs) through an online benchmarking tool, which can aid in strategic decision making. Paraskevadakis et al. [275] have developed a framework to assess the performance of modal shift and service quality of the infrastructure.

They used their approach to assess the region of Manchester and emphasize the importance of sustainable and reliable transport. Saeedi et al. [305] have developed a model to estimate the efficiency of intermodal freight transport networks. With their model, focusing on technical factors, they investigate different corridors for their efficiency.

Tracking and Physical Internet Tracking both transport means and containers and providing the data for all relevant actors severely contributes to supply chain visibility. This can be achieved with physical internet components. Ambra et al. [7] have compared current literature and trends in synchromodal transport and the physical internet to draw parallels between the two concepts. Both concepts seem not yet well aligned, but synergies and future research can aid in the merging of the concepts. Another look at integrating the physical internet concept with synchromodality is investigated by Lemmens et al. [197] by conceptualizing a decision-making model. They use a simulation model to determine thresholds for dual and real-time mode switching operations within a transport chain. In their study on how to use the Internet of Things (IoT) for improving data availability and process efficiency, Muñuzuri et al. [260] have investigated the port of Seville and attached intermodal rail corridor to Madrid and the Canary Islands and their current operational systems, container tracking, rail management and inland navigation.

(g) Foster cross-actor cooperation for increased utilization and efficiency

Cross-actor cooperation can lead to increased utilization of transport capacities and efficiency of transport processes. This can be achieved by various actors and governing mechanisms. Besides general assessment of combined transport cooperation, port hinterland coordination and resilience and safety play a role in research.

Intermodal Integration Forms of cooperation between intermodal actors can be various. Monios and Bergqvist [255] have assessed a case study between a large intermodal operator and a shipper and discovered a so-called 'virtual' joint venture, where risk and profit sharing and long-term contracts are established without formally setting it up. Looking at the vertical integration of terminals, operators and sub-contractors, Monios and Bergqvist [251] combines a resource-based view, transaction cost economics and the relational view to analyze the role of rail wagon ownership. A more general assessment of integration in intermodal transport chains is given by Reis [292] with a literature review. Its five dimensions framework, being physical, logical, contractual, financial and institutional, are tested within two case studies. Saeedi et al. [308] analyze the market implications of business consolidation strategies. They provide a model to assess vertical and horizontal mergers and their effect on market efficiencies and apply it to a numerical example.

Rail-Bound Port Hinterland Coordination Ports and their hinterland connectivity are essential pillars for intermodal transport capacity. Several operational and tactical aspects have been investigated. Jarašūnienė and Čižiūnienė [169] investigate the interoperability of maritime and railway transport systems for sustainability. Their proposed model includes a shared database to foster fast data exchange and better organization of multimodal transport chains. Driven by ocean carriers, Kolar et al. [179] take a look at the central and eastern landlocked hinterland for container repositioning. Based on a literature review and semi-structured interviews with actors from the ocean carrier, reveal needed adjustments to deal with the peculiarities of landlocked hinterlands. Developing a performance indicator for ports based on hinterland connectivity, de Langen and Sharypova [71] indicate an increase in hinterland connectivity and importance over the last years. The dry-port concept tries to alleviate pressure from ports' land use. As Lättilä et al. [195] revealed in their study within Finnland, significant potential reductions of emissions using the dry port concept could be achieved. Veenstra et al. [365] introduce the concept of an extended gate, expanding the dry-port concept. With a high-capacity transport connection to hinterland terminals, customers would be able to collect transport units as if they were collected directly at the port. Aside from these operational aspects, the set-up and governance of intermodal transport chains are of focus. Talley and Ng [336] determine a behavioral model for the selection of hinterland transport chains. Murillo and Liedtke [262] take a look at colloidal structures, agglomerations of logistical actors, and develop a market model for hinterland terminals in Germany. Van den Berg et al. [357] analyze the role of port authorities in establishing new intermodal services as intermodal operators might be reluctant due to investment and complexity risks. In their case study for the Port of Barcelona, they look at the establishment of a shuttle service to Lyon. van der Horst and van der Lugt [359] take a look at the case of the Port of Rotterdam and analyze the complexity of the coordination of transport chains in a post-liberalized environment. With data from the Port of Rotterdam, they conclude that while new entrants have established railway connections, the management of these connections and the actors have become more complex and led to a non-ideal allocation of resources from a port perspective.

Resilience and Safety Combined transport can be susceptible to disorders due to the involvement of multiple actors and transport systems. Cigolini et al. [61] have investigated supply chain security mechanisms. Their multi company analysis of mechanisms on how to avoid issues like theft, damages and terrorism, reveal common reliance on internal mechanisms. A further cooperation between actors in the transport chain could improve supply chain security. Looking at the potential to handle disruptions, Lordieck and Corman [213] reveal constraints and requirements for intermodal transport with their expert survey.

(h) Enable new business models in Combined Transport

New business models in combined transport can be assessed from various viewpoints. Articles found deal with viability, the analysis of potential market segments and new possibilities through the concept of synchromodality.

Business Model Analysis Proper business models are vital for viable combined transport and can take various forms and focus on different actors. For shippers, the own-account model, with full control over used transport modes, has been investigated by Flodén and Sorkina [121]. This model emphasizes control at the risk of higher prices and less flexibility. When looking at how to integrate intermodal transport and logistics, Islam [161] has investigated door-to-door services within the rail freight sector. His first investigation looks at barriers that full integration of door-to-door intermodal transport services. In his subsequent work, Islam [162] addresses these barriers by looking at potential enablers for this kind of service. Another logistics focused business model's assessment is conducted by Lehtinen and Bask [196] who analyze possibilities for an operator to use a transport corridor in southeastern Europe. Based on interviews with potential buyers and suppliers for transport services, four potential business models have crystalized. Kreutzberger and Konings [185] investigate business models for operators in port related hub-and-spoke networks. Based on the analysis of studies and practitioners' statements, they describe reasons for the slow adoption of hub-and-spoke networks in the hinterland of ports. The competitive situation of the market after liberalization, a lack of understanding of the concept and holistic investment strategies have an influence. Aside from these shipper / operator views, business models for terminals are investigated by Van den Berg and De Langen [356] who investigate the potential of inland terminal centered business models. Aside from classical port-to-port and door-to-door offers, a third possibility to organize intermodal transport services is proposed. Another terminal focused investigation by Michalk [239] looks at the boundaries of sales areas for intermodal services with a model to calculate the corresponding areas.

Market Segment Analysis Combined transport can potentially satisfy different market segments. The potential for Italian dairy producers and supermarkets has been investigated by Cannas et al. [45], who have analyzed multiple case studies. The discussion of technical and organizational aspects leads to various recommendations regarding equipment, reorganization of logistics and a different business model for distribution. Looking at low density high value goods, which are predominantly transported via road, Islam and Zunder [166] investigate how intermodal transport could be facilitated for these kinds of goods. For a mode change, appropriate transport containers like temperature controlled wagons, increased reliability, consolidation enabled terminals and proper distribution networks need to be in place. Similarly, for the UK retail sector, Monios [248] is looking at the relationship between shippers, in this case retailers, logistics service providers and operators to enable intermodal transport chains. Here also the consolidation of shipments, multi-user platforms and the integration with other logistics services are a major part in enabling intermodal transport. Finally, Mommens et al. [246] look at different cargo types and their potential for intermodal transport. Their assessment for the case of Belgium shows that bulk and containerized goods have the best intermodal fit and that the type of transport container is a major choice in this case.

Synchromodality Synchromodality as a concept aims at enabling a seamless switch between transport modes, avoiding disadvantages of flexibility in combined transport. Research regarding this concept has been given its own subcategory as it represents an extensive business model covering most aspects of intermodal transport. How to integrate the concept into supply chains has been assessed by Acero et al. [4] who looked at different aspects like visibility of transport modes, integration within logistics concepts and multi-modal transport concepts and quantified them using a survey among professionals. Similarly, Dong et al. [81] took a holistic supply chain view and assessed the impacts of synchromodal transport on environmental and logistics costs and service levels. Operative issues when implementing the synchromodal concept has been assessed by Šakalys et al. [311] investigating the case of the East-West corridor in the Baltic Sea region. Using a questionnaire, they looked at main criteria for successful implementation like service quality, infrastructure sufficiency, technical properties of terminals and interaction of technologies. A similar view for port hinterlands in the case of Rotterdam has been taken by Zhang and Pel [392]. In a comparison to traditional intermodal transport, they subsumed that synchromodal transport can potentially foster service level, capacity utilization and modal shift while having little influence on service costs. As the synchromodal concept requires further cross-actor interaction, Giusti et al. [135] propose the introduction of a new stakeholder called the orchestrator. This technology-based platform should be used for better coordination. A major success factor for synchromodality is commercial viability. Pfoser et al. [282] stress in their literature review that technical and organizational aspects have received a lot of attention, yet managerial problems and the development of business models should receive further attention. By developing a fare class system, van Riessen et al. [363] try to solve part of this problem. Addressing the pricing problem, they estimate an upper limit for each fare class to improve reliability. Similarly, Perboli et al. [280] state that pilot projects have failed economic viability and propose several measures to reduce costs like slow steaming and development of a platform for better coordination.

4.6 Conclusion & Recommendations

The study at hand comprises the synthesis of the results from two different methods to develop a practice-oriented research agenda. Firstly, a Delphi study was conducted with experts from the combined transport sector to identify practice-oriented measures for improving combined transport. A total of 27 measures were identified, covering aspects from favorable legislation, improving railway and transshipment infrastructure, mechanisms to increase utilization to digitization of combined transport processes. These concrete measures can be used by practitioners, legislators and researchers to deliberately improve existing combined transport systems. To determine starting points for investigation and implementation, the measures have been rated by the participants on the dimensions of effectiveness and difficulty of implementation. Secondly, a systematic literature review was conducted, comprising qualitative and analytical research in the intermodal rail sector. The literature was categorized according to categories determined by the practice-oriented results from the Delphi study. This literature overview allows for the assessment of past research efforts in the area. Furthermore, by synthesizing the results from both methodologies, a profound recommendation for a practice-oriented research agenda can be given.

4.6.1 Recommendation for a practice-oriented research agenda

Based on the indications from practice and the assessment of research from the past decade, relevant research topic areas have been derived through thorough discussion. Assembling the research agenda had two goals in mind. First, all practical measures should be addressed under several and clear headers. Additionally, the research found in the systematic literature review (SLR) should suggest gaps or absence of current research for these headers and was assessed in this way. This process has led to a total of 6 different research areas, of which an overview is depicted in figure 4.11. Their reasoning and proposed content is subsequently described.

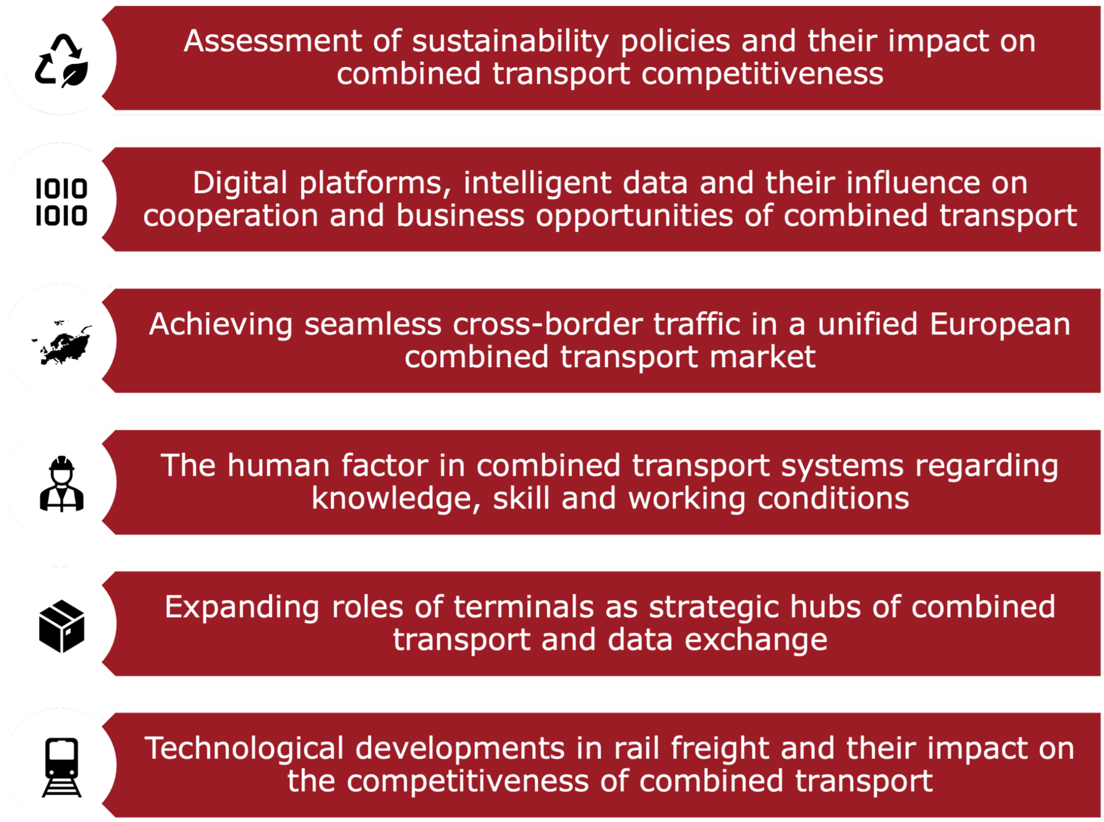


Figure 4.11: Overview of proposed research agenda
Source: Own design

Assessment of sustainability policies and their impact on combined transport competitiveness

Addressing several policy measures (P01, P03, P06, P07, P10, P11), making transport more sustainable not only has an effect on the desired outcome but also side-effects on the competitiveness of combined transport. As sustainable transport has been a major part of investigation from the literature review, especially research regarding these economic effects of sustainability policy on transport can be of interest. This could be done by modeling combined and unimodal transport chains (e.g., through a simulation) and apply various policies and analyze the effect they have on the economic situation of combined transport.

Digital platforms, intelligent data and their influence on cooperation and business opportunities of combined transport

Addressing several cooperation and technology measures (C02, C03, C04, T03), transport planning and coordination through digital platforms and data driven planning are a trend within the transport sector, that should find its way to combined transport as well. Research has addressed these issues in first studies, especially about the data that needs to be exchanged, yet as commercial platforms are not yet established various research opportunities arise. Next to having to build digital platforms, acceptance and positioning within combined transport systems can be of interest. Also issues of data availability and willingness for provision, in a highly interconnected system as combined transport, has not been thoroughly assessed and would be a prerequisite for the establishment of digitization in intermodal transport.

Achieving seamless cross-border traffic in a unified European combined transport market

In a unifying European market, cross-border traffic is increasing and as combined transport has its strengths in long distance transport, it is prone to profit from this. Taking into account measures from policy, infrastructure and cooperation (P02, P03, I04, C01), establishing such unified transport markets are a future goal. Research has focused in part on certain transport corridors and national policy analysis. How to achieve seamless cross-border traffic, how it should be organized, which entities are involved and their roles, how national agencies can cooperate to the benefit of a unified Europe, should be addressed in research. A potential starting point would be the analysis of existing transport corridors and how to improve throughput through policy and infrastructural measures.

The human factor in combined transport systems regarding knowledge, skill and working conditions

The human factor in combined transport is increasingly playing an important role due to the complexity of the transport system as addressed in various measures (I01, P05, P11). As challenges in combined transport systems, especially regarding digitization and advanced business models increases, proper education of actors within the system can lead to further success. A first step would be the analysis of requirements and potential gaps in current education systems, empirical analysis on how these gaps is relevant in the market and guidelines on how to improve. In literature this has been done for selected markets, a European perspective on this issue would be highly beneficial, also in order to achieve a unified transport market.

Expanding roles of terminals as strategic hubs of combined transport and data exchange

Terminals are at the center of combined transport chains and have been addressed by a lot of mentioned measures from various thematic areas (P04, P08, I02, I03, I05, I06, T01). Intermodal terminals have been researched plentiful, yet we expect a changing role of them and an increase in complexity of the services offered. Terminals as not just intermodal transshipment hubs but also as data hubs and potentially further service providers they would require a change in their strategic role in combined transport chains. Strategic management research for terminals should therefore be extended by a perspective of service provision.

Technological developments in rail freight and their impact on the competitiveness of combined transport

Finally, there are quite some technological advancements of rail transport, that can improve the competitiveness also of combined transport (T02, I07, T04). Potential automation and autonomous trains, faster provision of trains through digitized coupling or innovation in wagons can make combined transport more competitive. As these technologies, and further ones to come, are not yet addressed for combined transport, their implications on the competitiveness and integration within combined transport chains can be of research interest.

4.6.2 Limitations & Further Research

First and foremost it is important to mention that this paper focuses on combined transport, a subcategory of intermodal transport that encompasses rail-road transport. Inland waterway transport and other intermodal transport modes are therefore excluded in both methodologies applied. Looking at the results from the research methods, the developed research agenda is based on practical and scientific input, each with its own limitations. The practical input, as extensive as it is, represents a subset from the wide area of possibilities to improve combined transport systems. Exploring the different thematic areas in detail would likely extend the list of possibilities further and provide additional insight. The identified research in the systematic literature review has been restricted to the last decade and excluded quantitative approaches. It should be further assessed with the progress of research in the area. This research agenda is based on the current situation of combined transport in Europe and serves as a reference point, but it should be regularly reviewed and updated in a meaningful timespan to reflect changes in both practice and research.

4.6.3 Scientific & Managerial Contribution

Combined transport has established itself as both a relevant field for research and a sustainable transport option. By assessing this existing research and providing practice-oriented input, researchers in the field are provided with recent developments in the sector and guidance for conducting impactful research. For managers, this practice-oriented research agenda can serve as a guideline in assigning funds and as a strategic focus on improving their own combined transport capabilities. Same is true for policy-makers where the developed agenda can provide insights on which aspects of combined transport systems to prioritize and focus on.

4.7 Appendix

Id.	Short Title	Description
P01	Suspension of CO2 tax/toll for CT in the pre- and post-carriage	In the pre-carriage and on-carriage, the CT relies on truck transport. In particular on federal motorways, truck transport is subject to a toll and, more recently, a CO2 tax on fuel consumption. By suspending both charges for truck transports in the pre- and post-carriage of the CT, these can be offered more cheaply.
P02	Financial support for setting up new rail connections / increasing the frequency of existing rail connections	Promoting new relations or promoting the increase in the frequency of existing relations in the main rail route by setting financial incentives for the key players increases the offer and thus strengthens combined transport.
P03	Increase in route prioritization for rail freight traffic	Freight traffic is given lower priority in the current rail network. Increasing the prioritization (when allocating train paths) for freight traffic could lead to more attractive CT offers.
P04	Financial support for cranable equipment for transport companies / obligation to ensure cranability for new road registrations.	Transport companies can use financial incentives to make it easier to purchase crane-capable equipment for CT and thus create an incentive to use CT (e.g. promotion of crane-capable trailers) or stipulate a statutory requirement for crane-capability for new registrations.
P05	Focus training content in logistics and transport more on CT.	In training in the field of logistics and transport, focus more on CT / increase compulsory components.
P06	Compensation for the payload disadvantage of semi-trailers that can be craned by increasing the permissible weight (truck + trailer)	Increase in the permissible total weight by 1t to 41t for tractor and semi-trailer (even with continuous road transport) to compensate for the higher dead weight of the cranable semi-trailer while maintaining the regulation of the total weight of 44t in the pre- and post-carriage of the CT.

P07	Exempt pre-carriage and on-carriage from the cabotage regulation	In order to make it easier for foreign freight forwarders to transport goods before and after combined transport, they should be exempted from the cabotage regulations.
P08	Financial support for the maintenance costs of sidings	In the case of direct sidings, the maintenance costs should be subsidised. This reduces the costs for the respective shipper to use and maintain such a connection.
P09	Introduction of a nationwide concept for (handling) areas for combined transport	Introduction of a nationwide concept for the provision of areas for handling in combined transport, including semi-trailers that cannot be craned.
P10	Increase of the truck toll on actual and consequential costs	Adjustment of the truck toll to compensate for the actual costs of road use (full costs) as well as CO2 and particulate matter emissions and to make pure road transport less attractive.
P11	Enforcement of collective wages nationwide for all truck drivers	Truck drivers who are on the road in Germany should be legally entitled to the respective industry-wide collective wages.
I01	Alleviation of the shortage of truck drivers by increasing the attractiveness of work in the pre-carriage and on-carriage of CT	CT is dependent on the truck for the pre-carriage and on-carriage. For several years there has been a general lack of drivers, which is getting worse in the future. Targeted promotion of the job description, in particular for the pre-carriage and on-carriage of CT, could result in an advantage in the availability of drivers for this transport sector.
I02	Increasing the terminal density in high-demand regions by building new terminals	Build new terminals in high-volume regions to create new capacities and shorten CT pre-carriage and on-carriage.
I03	Increasing the capacity/productivity of existing terminals / automating terminals	Expand capacities of existing terminals or modernize outdated terminals in order to increase capacity and productivity.
I04	Expansion of the rail infrastructure with a view to freight transport.	The existing infrastructure is to be expanded at the appropriate points with regard to freight traffic. In addition, it should be discussed at which points pure freight routes can be built.

I05	Extension of storing areas of existing terminals.	Storage areas in existing terminals are to be enlarged/expanded in order to facilitate the handling of transports in combined transport.
I06	Expansion of terminals for 740m trains	Expand existing terminals for the use of 740m trains to increase capacities and enable shuttle traffic.
I07	Accelerated introduction of ETCS Level 3	The comprehensive introduction of the European Train Control System (ETCS) Level 3 enables driving with a relative braking distance, which increases the capacity per train path.
C01	Strengthening European cooperation in the rail sector	Promotion of cooperation in European cross-border rail traffic, in particular with regard to infrastructure, equipment and personnel.
C02	Establishment of digital platforms for data exchange in the field of CT	Numerous actors are involved in CT, most of whom interact bilaterally. Targeted support for central platforms can simplify the exchange of data between all actors, increase transparency and ensure targeted support for data-driven planning.
C03	Bilateral cooperation between terminals for the best possible utilization of trains	Enabling capacity shifts / diversions between geographically close terminals for the best possible utilization of trains, infrastructure and equipment.
C04	Creation of opportunities to consolidate LTL shipments in terminals.	Cooperation between the actors enables LTL shipments to be consolidated in the respective terminals.
T01	Promotion of innovative handling technologies	Simplification of handling in terminals by promoting innovative handling technologies to facilitate access to CT for non-cranable equipment.
T02	Expansion of the continuous tracking of modes of transport (lorry, train, inland waterway) and the containers located on them	Nowadays, modes of transport and containers can be tracked in many ways (e.g. via GPS). An expansion of the tracking options enables the individual players in CT to make more precise rescheduling in the event of delays in the operational process and to increase the service level for their customers.

T03	Establishment of central digital booking platforms in the area of CT	Promotion of the establishment of a multilateral digital booking platform for the transport chain in combined transport, analogous to a marketplace. In this way, pre-carriage, main carriage and post-carriage can be booked.
T04	Accelerated introduction of the central buffer coupling	Simplification of the coupling processes through the accelerated introduction of the central buffer coupling.
T05	Introduction of a 10-foot standard container	Allowing the loading of 10ft containers which can be coupled to an international 20ft container.

Table 4.6: Measures from Delphi study with full description

Author	Year	Title	Subcategory	Ref.
(a) Foster mode choice towards combined transport				
Ingrao et al.	2021	Freight transport in the context of industrial ecology and sustainability: evaluation of uni- and multi-modality scenarios via life cycle assessment	Sustainable Transport	[155]
Kos et al.	2017	Comparison of external costs in multimodal container transport chain	Sustainable Transport	[182]
Lammgard	2012	Intermodal train services: A business challenge and a measure for decarbonisation for logistics service providers	Sustainable Transport	[191]
Liljestrand	2016	Improvement actions for reducing transport's impact on climate: A shipper's perspective	Sustainable Transport	[205]
Mayer et al.	2012	Reducing the environmental impact of road and rail vehicles	Sustainable Transport	[230]
Mostert et al.	2017	Road and intermodal transport performance: the impact of operational costs and air pollution external costs	Sustainable Transport	[258]
Van den Berg	2017	Environmental sustainability in container transport: the attitudes of shippers and forwarders	Sustainable Transport	[355]
Zhang et al.	2014	The impact of CO2 pricing or biodiesel on container transport in and passing through the Netherlands	Sustainable Transport	[393]
Arencibia et al.	2015	Modelling mode choice for freight transport using advanced choice experiments	Mode Choice Analysis	[11]
Bask and Rajahonka	2017	The role of environmental sustainability in the freight transport mode choice A systematic literature review with focus on the EU	Mode Choice Analysis	[19]
Carboni and Dalla Chiara	2018	Range of technical-economic competitiveness of rail-road combined transport	Mode Choice Analysis	[47]

Cerna et al.	2017	The Methodology of Selecting the Transport Mode for Companies on the Slovak Transport Market	Mode Choice Analysis	[56]
Eng-Larsson and Kohn	2012	Modal shift for greener logistics - the shipper's perspective	Mode Choice Analysis	[92]
Eng-Larsson and Norrman	2014	Modal shift for greener logistics - exploring the role of the contract	Mode Choice Analysis	[93]
Khakdamen et al.	2020	Shippers' willingness to delegate modal control in freight transportation	Mode Choice Analysis	[175]
Meers et al.	2017	Modal choice preferences in short-distance hinterland container transport	Mode Choice Analysis	[233]
Reis	2014	Analysis of mode choice variables in short-distance intermodal freight transport using an agent-based model	Mode Choice Analysis	[293]
Roman et al.	2017	A latent class model with attribute cut-offs to analyze modal choice for freight transport	Mode Choice Analysis	[300]
Meers et al.	2018	Longer and heavier vehicles in Belgium: A threat for the intermodal sector?	High-capacity Vehicles	[231]
Palmer et al.	2018	A cost and CO2 comparison of using trains and higher capacity trucks when UK FMCG companies collaborate	High-capacity Vehicles	[272]
Palsson et Sternberg	2018	LRN 2016 SPECIAL - high capacity vehicles and modal shift from rail to road: combining macro and micro analyses	High-capacity Vehicles	[273]
(b) Increase capacity/efficiency of rail transport				
Carydi	2019	Integrated Railway Planning in the North West Peloponnese A Service Ecologies Perspective	Railway Infrastructure	[52]
Clausen and Voll	2013	A comparison of North American and European railway systems	Railway Infrastructure	[64]

Marzano et al.	2018	Incentives to freight railway undertakings compensating for infrastructural gaps: Methodology and practical application to Italy	Railway Infrastructure	[228]
Mortimer and Islam	2014	A comparison of North American and European railway systems - a critique and riposte	Railway Infrastructure	[257]
Vaiciunas	2018	Assessment of railway lines: An efficiency rating analysis for baltic countries	Railway Infrastructure	[352]
Vleugel and Bal	2012	Some approaches to reduce transport time of intermodal services: Smart rail investments	Railway Infrastructure	[367]
Woodburn	2013	Effects of rail network enhancement on port hinterland container activity: a United Kingdom case study	Railway Infrastructure	[383]
Dimitriou and Sartzetaki	2020	Assessment framework to develop and manage regional intermodal transport networks	Intermodal Rail Connectivity and Corridors	[80]
Islam and Eidhammer	2016	Advances in the competitiveness of pan-European rail freight services: findings from a case study	Intermodal Rail Connectivity and Corridors	[164]
Langen et al.	2017	Intermodal connectivity in Europe, an empirical exploration	Intermodal Rail Connectivity and Corridors	[194]
Pelevic	2021	Development of Logistics Routes of Intermodal Transport in the Eastern Adriatic	Intermodal Rail Connectivity and Corridors	[278]
Popa and Schmidt	2013	On the rail-based freight corridor between CE and SEE regions and the main obstacles on Romanian territory	Intermodal Rail Connectivity and Corridors	[285]
Saenger et al.	2021	Capabilities of a periodic containerized railfreight system in Germany	Intermodal Rail Connectivity and Corridors	[310]

Stoilova et al.	2020	Multi-Criteria Evaluation of Railway Network Performance in Countries of the TEN-T Orient-East Med Corridor	Intermodal Rail Connectivity and Corridors	[330]
Tadic et al.	2021	The Selection of Intermodal Transport System Scenarios in the Function of Southeastern Europe Regional Development	Intermodal Rail Connectivity and Corridors	[333]
Wagener	2017	Intermodal logistics centres and freight corridors concepts and trends	Intermodal Rail Connectivity and Corridors	[370]
Witte et al.	2012	Chokepoints in corridors: Perspectives on bottlenecks in the European transport network	Intermodal Rail Connectivity and Corridors	[382]
Bruckmann et al.	2016	Swiss Split-a holistic approach to the distribution of containers to private sidings	Sidings	[38]
(c) Increase capacity/efficiency of transshipment				
Cavallaro et al.	2021	Appropriateness of the 'small-scale corridor terminals' scheme for rail-road combined transport: Evidence from the Brenner axis	Location Assessment	[53]
Lizbetin	2019	Methodology for Determining the Location of Intermodal Transport Terminals for the Development of Sustainable Transport Systems: A Case Study from Slovakia	Location Assessment	[208]
Meers and Macharis	2014	Are additional intermodal terminals still desirable ? An analysis for Belgium	Location Assessment	[232]
Murillo and Liedtke	2015	Where Supply Meets Demand The Spatial Location of Inland Terminals	Location Assessment	[261]
Pamucar et al.	2018	New hybrid multi-criteria decision-making DEMATEL-MAIRCA model: sustainable selection of a location for the development of multimodal logistics centre	Location Assessment	[274]

Pekin et al.	2013	Location Analysis Model for Belgian Intermodal Terminals: Importance of the value of time in the intermodal transport chain	Location Assessment	[277]
Roso et al.	2015	Inland Intermodal Terminals Location Criteria Evaluation: The Case of Croatia	Location Assessment	[301]
Wisnicki et al.	2017	The Concept of the Development of Intermodal Transport Network Illustrated by Polish Market	Location Assessment	[381]
Abramovic et al.	2012	Analysis of intermodal terminals service quality in the Republic of Croatia	Operation and Automation	[2]
Carboni and Deflorio	2018	Performance indicators and automatic identification systems in inland freight terminals for intermodal transport	Operation and Automation	[48]
Carboni et al.	2020	Monitoring truck's operations at freight intermodal terminals: traffic observation by scanning on-board devices	Operation and Automation	[49]
Kostrzewski and Kostrzewski	2019	Analysis of Operations upon Entry into Intermodal Freight Terminals	Operation and Automation	[183]
Tadic et al.	2019	Selection of efficient types of inland intermodal terminals	Operation and Automation	[335]
Tadic et al.	2019	Planning an Intermodal Terminal for the Sustainable Transport Networks	Operation and Automation	[334]
Filina-Dawidovicz and Kostrzewski	2022	The Complexity of Logistics Services at Transshipment Terminals	Strategic Management	[118]
Liedtke et Murillo	2012	Assessment of policy strategies to develop intermodal services: The case of inland terminals in Germany	Strategic Management	[204]
Monios	2015	Identifying Governance Relationships Between Intermodal Terminals and Logistics Platforms	Strategic Management	[255]
Monios and Bergqvist	2015	Intermodal terminal concessions: Lessons from the port sector	Strategic Management	[255]

Monios and Bergqvist	2017	Identifying competitive strategies for each phase of the intermodal terminal life cycle	Strategic Management	[252]
Russo and Gronalt	2021	Value added services at intermodal inland terminals and the importance of choosing a moderate innovation path	Strategic Management	[304]
Illes et al.	2020	New ideas for inland intermodal transport	Innovative Handling	[154]
Truschkin and Elbert	2013	Horizontal transshipment technologies as enablers of combined transport: Impact of transport policies on the modal split	Innovative Handling	[344]
van Binsbergen et al.	2013	Mega-projects in intermodal freight transport: innovation adoption	Innovative Handling	[354]
(d) Increase knowledge and skills of combined transport				
Kourounioti et al.	2018	Simulation Games to Study Transportation Issues and Solutions: Studies on Synchromodality	Education and Knowledge	[184]
Kurapati et al.	2018	Fostering Sustainable Transportation Operations through Corridor Management: A Simulation Gaming Approach	Education and Knowledge	[188]
Macharis et al.	2012	Bringing intermodal transport to the potential customers: An interactive modal shift website tool	Education and Knowledge	[222]
Mitropoulos et al.	2017	Building on European scientific excellence to develop an educational program on intermodal connections for Latvia and the region	Education and Knowledge	[243]
Palacin et al.	2016	Evaluating the impact of rail research: Principles to maximise innovation uptake	Education and Knowledge	[271]
(e) Increase efficiency of transport markets through European and national cooperation and regulation				
Abbott and Cohen	2017	Vertical integration, separation in the rail industry: a survey of empirical studies on efficiency	European and Transnational	[1]

Beskovnik	2012	Green logistics strategy for south east Europe: To improve intermodality and establish green transport corridors	European and Transnational	[27]
Cantos et al.	2012	Evaluating European railway deregulation using different approaches	European and Transnational	[46]
Gharehgozli et al.	2019	The role of standardisation in European intermodal transportation	European and Transnational	[133]
Islam	2018	Prospects for European sustainable rail freight transport during economic austerity	European and Transnational	[163]
Islam et al.	2016	How to make modal shift from road to rail possible in the European transport market, as aspired to in the EU Transport White Paper 2011	European and Transnational	[165]
Marshall	2014	The European Union and Major Infrastructure Policies: The Reforms of the Trans-European Networks Programmes and the Implications for Spatial Planning	European and Transnational	[227]
Saeedi et al.	2017	European intermodal freight transport network: Market structure analysis	European and Transnational	[309]
Saeedi et al.	2021	Measuring concentration in transhipment markets: methodologies and application to a European case	European and Transnational	[306]
Stephenson	2022	The physical completion of the EU's single market: trans-European networks as experimentalist governance?	European and Transnational	[328]
Wagener	2014	Intermodal transport in Europe - Opportunities through innovation	European and Transnational	[371]
Wisnicki and Dyrda	2016	Analysis of the Intermodal Transport Efficiency in the Central and Eastern Europe	European and Transnational	[380]
Cowie	2015	Does rail freight market liberalisation lead to market entry? A case study of the British privatisation experience	National	[65]

Emberger	2017	National transport policy in Austria - from its beginning till today	National	[91]
Floden and Woxenius	2017	Agility in the Swedish intermodal freight market - The effects of the withdrawal of the main provider	National	[122]
Foltynski	2014	Barriers limiting the development of intermodal transport in Poland - The perspective of businesses and public administration	National	[123]
Kapfenberger-Poindl	2018	Analysis of Austria's land and multimodal transportation	National	[173]
Mindur and Paweska	2019	Methods of promoting intermodal transport development in the Federal Republic of Germany, France and Italy in years 1990-2016 - Conclusions for Poland	National	[241]
Ozster	2017	Transport policies in Hungary - historical background and current practice for national and regional level	National	[270]
Riha and Dockalikova	2021	Economic aspect of combined transport	National	[298]
Santos et al.	2015	The impact of transport policies on railroad intermodal freight competitiveness - The case of Belgium	National	[312]
Woodburn	2012	Intermodal rail freight activity in Britain: Where has the growth come from?	National	[384]
Behrends	2017	Burden or opportunity for modal shift? - Embracing the urban dimension of intermodal road-rail transport	Regional	[23]
Cavallaro	2020	Combined transport in the Alps: Reasons behind a difficult acceptance and possible solutions	Regional	[54]
Monios	2015	Intermodal Transport as a Regional Development Strategy: The Case of Italian Freight Villages	Regional	[250]

van den Heuvel et al.	2013	Spatial concentration and location dynamics in logistics: the case of a Dutch province	Regional	[358]
(f) Establish fully digital processes and transport chain visibility				
Bohacs et al.	2013	Intermodal logistics processes supported by electronic freight and warehouse exchanges	Process Digitization	[33]
Harris et al.	2015	ICT in multimodal transport and technological trends: Unleashing potential for the future	Process Digitization	[145]
Islam and Zunder	2013	Issues of eLogistics applications for varying stakeholders: findings from an online survey	Process Digitization	[167]
Jacobsson et al.	2017	Access management in intermodal freight transportation: An explorative study of information attributes, actors, resources and activities	Process Digitization	[168]
Marchet et al.	2012	Modelling the impacts of ICT adoption for intermodal transportation	Process Digitization	[226]
Milenkovic et al.	2021	Evaluation of the innovative value proposition for the rail freight transport: an integrated DEMATEL-ANP approach	Process Digitization	[240]
Vural et al.	2020	Can digitalization mitigate barriers to intermodal transport? An exploratory study	Process Digitization	[368]
Islam et al.	2013	Performance evaluation of an online benchmarking tool for European freight transport chains	Benchmarking and Performance Assessment	[78]
Paraskevadakis et al.	2021	A services operations performance measurement framework for multimodal logistics gateways in emerging megaregions	Benchmarking and Performance Assessment	[275]
Saeedi et al.	2019	Assessing the technical efficiency of intermodal freight transport chains using a modified network DEA approach	Benchmarking and Performance Assessment	[305]

Ambra et al.	2019	Towards freight transport system unification: reviewing and combining the advancements in the physical internet and synchromodal transport research	Tracking and Physical Internet	[7]
Lemmens et al.	2019	Synchromodality in the Physical Internet - dual sourcing and real-time switching between transport modes	Tracking and Physical Internet	[197]
Munuzuri et al.	2020	Using IoT data and applications to improve port-based intermodal supply chains	Tracking and Physical Internet	[260]
(g) Foster cross-actor cooperation for increased utilization and efficiency				
Monios and Bergqvist	2015	Using a ”virtual joint venture” to facilitate the adoption of intermodal transport	Intermodal Integration	[255]
Monios and Bergqvist	2016	Drivers for vertical integration in the rail sector - using wagons as ’relationship specific assets’	Intermodal Integration	[251]
Reis	2019	A new theoretical framework for integration in freight transport chains	Intermodal Integration	[292]
Saeedi et al.	2017	Analyzing competition in intermodal freight transport networks: The market implication of business consolidation strategies	Intermodal Integration	[308]
Jarasuniene and Ciziuniene	2021	Ensuring Sustainable Freight Carriage through Interoperability between Maritime and Rail Transport	Rail-bound Port Hinterland Coordination	[169]
Kolar et al.	2018	Intermodal transport and repositioning of empty containers in Central and Eastern Europe hinterland	Rail-bound Port Hinterland Coordination	[179]
Langen and Sharypova	2013	Intermodal connectivity as a port performance indicator	Rail-bound Port Hinterland Coordination	[71]

Lattila et al.	2013	Hinterland operations of sea ports do matter: Dry port usage effects on transportation costs and CO2 emissions	Rail-bound Port Hinterland Coordination	[195]
Murillo and Liedtke	2013	A model for the formation of colloidal structures in freight transportation: The case of hinterland terminals	Rail-bound Port Hinterland Coordination	[262]
Talley and Ng	2018	Hinterland transport chains: A behavioral examination approach	Rail-bound Port Hinterland Coordination	[336]
van der Horst and van der Lugt	2014	An Institutional Analysis of Coordination in Liberalized Port-related Railway Chains: An Application to the Port of Rotterdam	Rail-bound Port Hinterland Coordination	[359]
van den Berg et al.	2012	The role of port authorities in new intermodal service development; the case of Barcelona Port Authority	Rail-bound Port Hinterland Coordination	[357]
Veenstra et al.	2012	The extended gate concept for container terminals: Expanding the notion of dry ports	Rail-bound Port Hinterland Coordination	[365]
Cigolini et al.	2016	Reinforcing supply chain security through organizational and cultural tools within the intermodal rail and road industry	Resilience and Safety	[61]
Lordieck and Corman	2021	Infrastructural, Decisional and Organizational Aspects to Use Mode Shift to Handle Disruptions in Freight Transport: Literature and Expert Survey	Resilience and Safety	[213]
(h) Enable new business models in combined transport				
Floden and Sorkina	2014	Business models for shipper-operated intermodal transport solutions	Business Model Analysis	[121]

Islam	2014	Barriers to and enables for European rail freight transport for integrated door-to-door logistics service. Part 1: Barriers to multimodal rail freight transport	Business Model Analysis	[161]
Islam	2014	Barriers to and enables for European rail freight transport for integrated door-to-door logistics service. Part 2: Enablers for multimodal rail freight transport	Business Model Analysis	[162]
Kreutzberger and Konigs	2016	The challenge of appropriate hub terminal and hub-and-spoke network development for seaports and intermodal rail transport in Europe	Business Model Analysis	[185]
Lehtinen and Bask	2012	Analysis of business models for potential 3Mode transport corridor	Business Model Analysis	[196]
Michalk	2013	Optimizing sales areas of combined transport chains	Business Model Analysis	[239]
van den Berg et Langen	2015	Towards an 'inland terminal centred' value proposition	Business Model Analysis	[356]
Cannas et al.	2020	Sustainable innovation in the dairy supply chain: enabling factors for intermodal transportation	Market Segment Analysis	[45]
Islam and Zunder	2018	Experiences of rail intermodal freight transport for low-density high value (LDHV) goods in Europe	Market Segment Analysis	[163]
Mommens et al.	2020	Multimodal choice possibilities for different cargo types: Application to Belgium	Market Segment Analysis	[246]
Monios	2015	Integrating intermodal transport with logistics: a case study of the UK retail sector	Market Segment Analysis	[248]
Acero et al.	2022	Introducing synchromodality: One missing link between transportation and supply chain management	Synchromodality	[4]
Dong et al.	2018	Investigating synchromodality from a supply chain perspective	Synchromodality	[81]

Giusti et al.	2019	Synchromodal logistics: An overview of critical success factors, enabling technologies, and open research issues	Synchromodality	[135]
Sakalys et al.	2019	Investigation and evaluation of main indicators impacting synchromodality using ARTIW and AHP methods	Synchromodality	[311]
Perboli et al.	2017	Synchro-Modality and Slow Steaming: New Business Perspectives in Freight Transportation	Synchromodality	[280]
Pfoser et al.	2022	Antecedents, mechanisms and effects of synchromodal freight transport: a conceptual framework from a systematic literature review	Synchromodality	[282]
van Riessen et al.	2017	The Cargo Fare Class Mix problem for an intermodal corridor: revenue management in synchromodal container transportation	Synchromodality	[363]
Zhang and Pel	2016	Synchromodal hinterland freight transport: Model study for the port of Rotterdam	Synchromodality	[392]

Table 4.7: Results from systematic literature review

5 Port Competition through Hinterland Connectivity—A Case Study for Potential Hinterland Scope in North Rhine-Westphalia (NRW) regarding an Environmental Policy Measure

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5.1 Abstract

Comparable port efficiency among ports of the European northern range leads to a competitive shift toward hinterland connectivity. North Rhine-Westphalia (NRW), having a high population and industry density and an extensive road, rail and waterway network, is prone to such inter port competition due to its proximity. Using a simulation model, the potential hinterland scope by each port and mode in NRW is depicted and a sensitivity analysis with increasing carbon tax rates is conducted. With an increasing tax rate, the scope for central areas of NRW, prone to a shift to rail transport, expands and become heavily contested among multiple ports. A major profiteer of an increase is projected to be the Port of Rotterdam due to its good connectivity at the cost of Antwerp. The market share of German ports is likely to stay the same with a mode shift occurring. Policy measures like a carbon tax not only have an effect on environmentally friendly mode shift but can severely impact the competitive situation of infrastructure components. While

achieving the primary goal of transport sustainability, national interests might mandate the economical existence of a functioning maritime port, which leads to the consideration of additional measures when increasing carbon tax rates.

5.2 Introduction

5.2.1 Port Competition and Hinterland Transport Chains

Ports are countries' gateways to international trade. Due to the unification of Europe, market liberalizations and the unique composition of countries and geographies in central Europe, the ports of the northern range especially compete for transport capacity, essentially forming multiport gateway regions [266]. As internal port operations have reached a comparable efficiency level, port competition shifts towards hinterland connectivity as Acciaro et al. have shown for the Adriatic seaports [3], Kolar and Rodrigue [178] for the case of Czech Republic and van der Horst and van der Lugt [360] in a case study for the Port of Rotterdam. Hinterland connectivity also increases competition between transport chains as investigated by Li et al. [198]. Nonetheless, with overlapping hinterlands, port competition might not necessarily benefit overall welfare as economies of scale might not be reached [58]. With growing distance of the hinterland from the port, competition becomes more fierce as intermodal services become more and more feasible as Garcia-Alonso et al. have shown for the Spanish market [130]. Investments on hinterland connectivity, therefore, especially regarding intermodal connectivity, have both the chance to increase competition between ports and have a positive impact on environmental goals as shown by Guihery and Laroche for the Betuwe-Line connecting the Netherlands and Germany [140]. Increased port competition does have concentration effects, which in return lead to measure to relocate port functions in the proximate hinterland [149] or developing dry port facilities to increase hinterland scope [170]. Benefits of cooperation between ports to foster environmentally beneficial mode choice and economies of scale have been conceptualized by Hintjens [150]. Langen and Sharypova have developed a port performance indicator based on intermodal connectivity [71]. When assessing the hinterland of a port, it is important to distinguish the real hinterland, which is represented by real cargo flows including political and social factors and the potential hinterland, which is determined by economic factors, geography and infrastructure of the region under study as pointed out by Santos and Soares [314]. The study at hand therefore investigates the potential hinterland. As the hinterland consists of vertically integrated transport chains, their functioning and structure play an important role to welfare created through port choice [35]. The integration and relationships with actors from a port's side in the transport chain come to increased importance as the study of Caliskan and Esmer have shown for container terminals connecting ports [44] or Franc and van der Horst for the Hamburg-Le Havre Range [124]. Due to the number of actors involved, intense cooperation is necessary and competition shifts toward transport chains [321]. Nonetheless, interests and incentives might play a role in achieving this cooperation which might be mitigated through ICT systems [193]. Frequencies of intermodal connections are of high importance for port competitiveness [194]. Ports can play an important role in developing their hinterland logistics chains, although this is not traditionally their role [223].

As this recap of research shows, port competition is heavily influenced by hinterland connectivity. Hinterland transport in return contributes heavily to carbon emissions, which has led to modeling hinterland transport chains [143] and developing frameworks for its estimated contribution [337]. To mitigate climate change and to combat excessive resource consumption, policy makers in Europe, both on a national and a transnational level, have put in measures to reduce the exhaustion of carbon dioxide. Two major ways are usually discussed to achieve this goal. Within a cap-and-trade policy, emitters need to buy certificates that allow them to emit a certain amount of carbon dioxide. Unneeded certificates can be traded on the market to allow other emitters to use them. A reduction in carbon emissions is achieved by reducing the amount of certificates in the market over time, setting a limit on potential emissions, which various ways on how to govern such a mechanism [28]. Within a carbon dioxide pigovian style tax, social and environmental external costs of emissions are priced into the production of goods. This form of tax is especially useful when trying to reduce global carbon emissions, as the harm caused by them does not distinguish between its sources [120]. This style of tax may, aside from its positive environmental impacts, help fund governments efficiently [127] while being socially balanced [329]. These measures can have an impact on port competition as Gan et al. [129] have shown for a no tax, carbon emission tax and cap-and-trade policy for Chinese ports with regard to port service prices and profits, demand for goods and social welfare. For the European market, this has been investigated by van Hassel et al. by looking at the change in port choice between northern and southern ports depending on two environmental policies, the internalization of external costs and the establishment of the Sulphur Emission Control Area (SECA) in the North Sea region [362], although they have not found a significant shift between the ports of the northern and Mediterranean range due to these environmental measures.

5.2.2 Research Question and Design

Environmental measures might have side effects when implemented as shown by Raadschelders et al. for production processes [287]. When looking at the transportation sector, these side effects, e.g., shifting production to countries without implementation to avoid the restrictions, might decrease transport demand. In the study at hand, the side effect on the competitive situation of infrastructure components is investigated. As can be expected, a carbon dioxide tax will cause a shift to more environmentally friendly modes of transport like rail or barge as they emit less carbon dioxide [379]. Interesting is, whether this will also change the competitive situation between ports. The research question of the study is therefore:

> RQ: How does the competitive situation between ports regarding their potential hinterland scope change, when changes in the rate of a carbon tax occur?

In order to answer this question, the state of North Rhine-Westphalia as a hinterland can serve as a good case to study port competition through potential hinterland scope as several ports and several modes with different carbon emission footprint compete for transport capacity within it. Modeling the competitive situation of the ports in proximity to NRW by looking at their potential hinterland scope, several conclusions can be drawn on the effects the introduction and rate setting of carbon tax will have on their competition. For this, we use a transport chain for international transport, from NRW to Shanghai (P.R. China), and depict the hinterland situation for this transport chain. This transport chain is chosen, as the Port of Shanghai represents the largest port worldwide [385], and the P.R. China is the largest trading partner of Germany regarding imports and the second largest for German exports [76], which leads to high volume shipments and represents a typical export oriented transport chain. Additionally, all ports investigated have several shipping connections to the Port of Shanghai, which allows for a comparison of the different transport chains.

Finally, after establishing this transport chain in a model, different carbon tax rates can be simulated, and their impact on the potential hinterland scope of competing ports within NRW can be analyzed. This analysis can both take place from a port as well as a mode perspective. Using sensitivity analysis regarding their market shares, conclusions for the impact of different rates of carbon tax can be drawn. We hypothesize a shift towards rail transport, especially at the fringes of NRW with ports declining in market share that are currently served mostly via trucking. There will be a major profiteer from a tax rate increase with the port with the best intermodal connections to the most populous areas of NRW, the Port of Rotterdam. With these results, conclusions for political and business managers can be drawn. A contribution toward political insight is within the design and implementation of environmental policies, which are expected to have certain economic side effects. For business managers, changes in the strategic position of transport chains, modes and locations can lead to the possibility for an early adoption to these upcoming changes.

In the remainder of this paper, an introduction to the state of North Rhine-Westphalia and its unique location within the European hinterlands is given. Then, the modeling of hinterland port competition used in this paper is explained and its different components are described. After an analysis of the experiment results by port and mode, the paper concludes with a discussion of the results, implications for business, policy and research and an outlook for further investigation.

5.3 North Rhine-Westphalia—A State Susceptible to Port Competition

5.3.1 Background, Administrative Division, Population and Economy

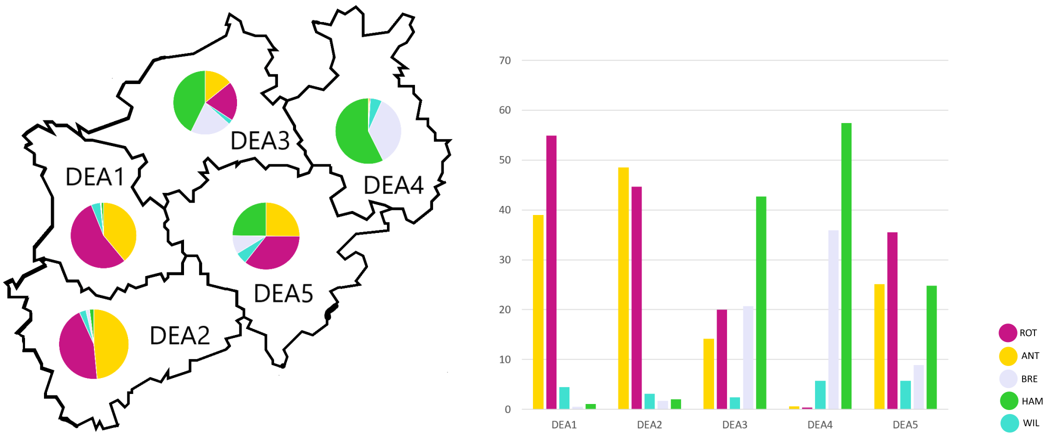
North Rhine-Westphalia (NRW) is a western state within the Federal Republic of Germany. Due to its location, it is interesting for many different modes (barge, rail and truck) and ports (Hamburg-Le Havre range) and competition between them. Roughly half of its area is located more than 300 km away to at least one port, which is usually regarded as the distance assumed beneficial for intermodal transport, yet this assumption has been challenged in the past especially for barge transport [234]. Therefore, competition in NRW is both interesting from a port as well as a mode competition's side. This is also shown in the market shares distributed by ports and modes. Due to its close proximity to several ports of the northern range, the area of NRW is roughly split among the ports of Antwerp, Rotterdam, Wilhelmshaven, Bremerhaven and Hamburg. While the western part mostly ships via Antwerp and Rotterdam, heavily utilizing barge transport on the Rhine river, the eastern part focuses on Hamburg and Bremerhaven, using trucking and railway connections. Due to these factors, the state of NRW is interesting to investigate inter port competition through hinterland connectivity.

NRW leads several metrics among the German states. It borders both Belgium and the Netherlands and possesses one of the most dense motorway, barge and railway network. It has the highest regional GDP of all German states, a strong industrial base that produce a lot of goods for export [242] and the highest population of all German states [324], which leads to having the second highest level of exports [74] and the highest level of imports [75]. NRW consists of 5 NUTS-2 level governorates (Regierungsbezirke), which are further subdivided into 53 NUTS-3 districts (Land-/Stadtkreis). Table 5.1 shows economic data on the NUTS-2 level. The strongest governorates economically are Düsseldorf and Köln, which are located in the west and southwest of NRW and both flowed through by the river Rhine. The northeast of NRW, with the governorates Münster and Detmold, have less population density and economic activity. This distribution also shows in the numbers for

Name	NUTS-2	Population	GDP total (mio. €)	GDP per Capita (€)
Düsseldorf	DEA1	5,202,817	211,611	40,680
Köln	DEA2	4,469,420	187,100	41,862
Münster	DEA3	2,624,201	86,691	33,035
Detmold	DEA4	2,055,812	76,775	37,345
Arnsberg	DEA5	3,582,225	122,959	34,324
NRW	-	17,934,475	985,136	39,678

Table 5.1: Economic statistics of NUTS-2 administrative areas of NRW (2018)
Source: Statistisches Landesamt Nordrhein-Westfalen [325]

containerized volumes. Data from ISL Bremen on the NUTS-2 level provides an overview for all relevant ports. The governorates differ hereby in the volume which is highest in the southwest and west and in the distribution among the ports. As can be seen in Figure 5.1,



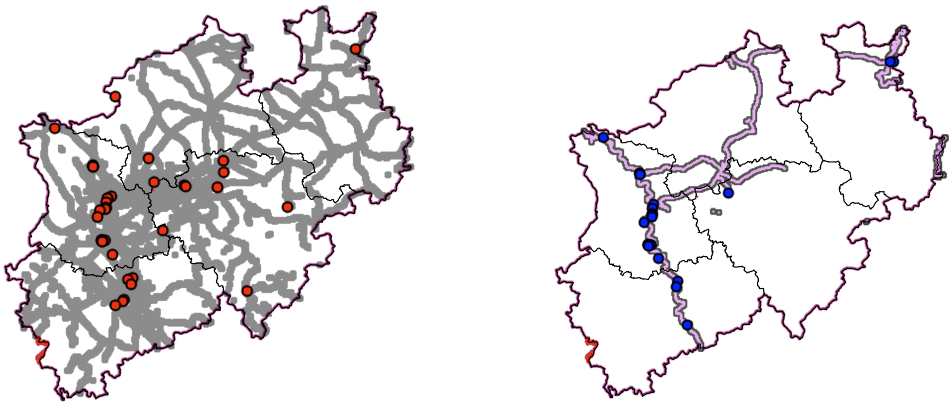
(a) Map **(b)** Statistics

Figure 5.1: Market Share of Ports in NRW (2018)
Source: Own design based on data from ISL Bremen [160]

the ports of Rotterdam and Antwerp are strong in the western, southern and central areas while the German ports are strong in the eastern and northern areas.

5.3.2 Transport Infrastructure

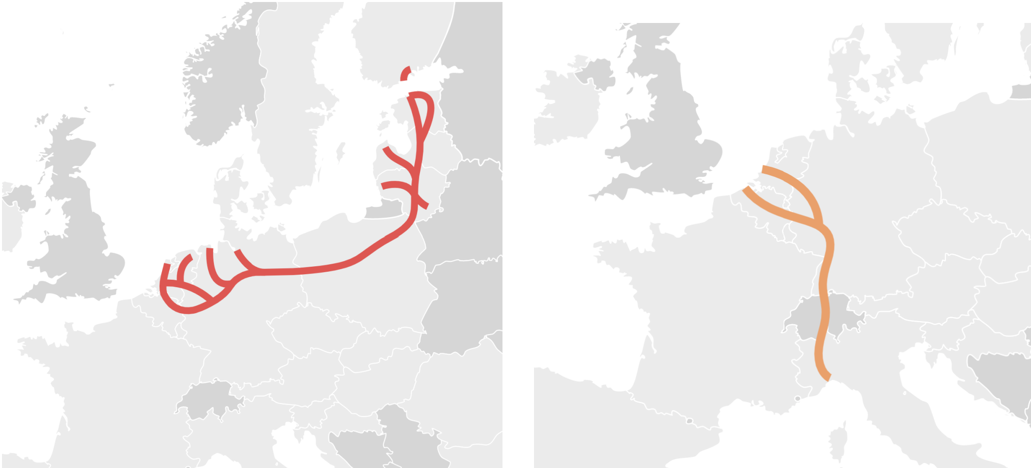
NRW is well connected to rail- and waterways through a multitude of terminals. There are basically three kinds of terminals in NRW: dedicated barge terminals, which are located at the two major rivers Rhein and Ruhr, dedicated rail terminals mostly located in high industrial and population density areas and so-called trimodal terminals that serve both barge and rail connections. According to www.intermodal-map.com, there are 20 trimodal (both barge and rail), 3 barge and 17 rail terminals in NRW, distributed over the whole state. Figure 5.2 shows relevant terminals in the area of NRW with the respective rail- and waterways. NRW is also part of two major TEN-T corridors [105]. The North Sea-Baltic



(a) Rail terminals and railways **(b)** Barge terminals and waterways

Figure 5.2: Intermodal Terminals in NRW
Source: Own design based on data from Intermodal Map [156] and Bezirksregierung Köln - GEObasis.nrw [29]

corridor (No.2) connects the western ports through NRW eastward to most major ports and the whole Baltic region. The Rhine-Alpine corridor (No.6) connects NRW to the western ports of Antwerp and Rotterdam and runs all the way down, mostly parallel to the Rhine river, to northern Italy and the Port of Genoa. Being part of these corridors further highlights the strategic position of NRW and its divide in competition of both port regions. Figure 5.3 depicts both corridors.



(a) Corridor 2—North-Sea-Baltic **(b)** Corridor 6—Rhine-Alpine

Figure 5.3: TEN-T corridors through NRW

5.4 Modeling hinterland competition of northern range ports

Modeling port hinterlands using containerized data in combination with hinterland connectivity and GIS data has been shown as a valid approach by Macharis and Pekin for the Antwerp hinterland as they investigated subsidies for different transport modes [220]. Modeling port competition has been a field of wide application. Zondag et al. have modeled port competition using a maritime, port and hinterland component [396]. In the study at hand, the ideas of both approaches are combined to investigate the impact of measures on port competition through potential hinterland scope.
The use of simulation modeling, as done in this study, allows to assess different properties of shippers, changes in infrastructure and the effect of policies dynamically in one experiment. The stochastic component of the simulation allows to assess dynamic components like schedules and capacity, where precise data for these model components is not available.

This is done by depicting port competition through hinterland connectivity in a stochastic model. The model simulates a transport chain from NRW to the Port of Shanghai. This relation was chosen, as China is the largest overall trading partner with high frequency and volume of containers and ships and all ports close to NRW have connections to Shanghai. Shanghai has also the largest port worldwide. On the European side, the model incorporates major relevant ports for NRW in the northern range (Antwerp, Rotterdam, Bremerhaven, Wilhelmshaven and Hamburg), their hinterland connectivity for intermodal rail and barge services and a road network based on actual map data to allow for a proper assessment of different transport distances, especially for intermodal precarriage and unimodal transport via truck. For deciding among transport alternatives, a cost function for shippers has been implemented that incorporates transport, handling and transport time costs. Additionally, the cost function holds a parameter for a carbon tax rate that, multiplied with the specific emissions of each transport mode, allows for an assessment of the additional costs incurred by it. Looking at these additional costs, the impact of different rates of a carbon tax on hinterland scope for different ports can be assessed. As frequency of intermodal hinterland connections is a relevant component in mode choice [194], it is modeled stochastically. Finally, as we assume that shippers usually cannot fully determine the exact price of a transport relation and hinterland scope usually is not drawn by clear lines, a cost tolerance component for the hinterland component is added. All components of the model are subsequently described in detail.

5.4.1 Model Structure & Content

The model depicts a typical transport chain from NRW to Shanghai. This transport chain consists of a hinterland component, from a location in NRW to a maritime port and then from this port on to the Port of Shanghai. Within the hinterland component, the intermodal terminal structure and the road network are incorporated to allow for a detailed assessment of this leg. Figure 5.4 shows the transport chain depicted in the model. For modeling, AnyLogic, a tool for a wide range of simulation applications, has been used. Within the model, administrative areas, the relevant ports and terminals, the road and intermodal network have been depicted. Figure 5.4 shows the visual representation of the model in AnyLogic Professional 8.7.

Geographical Coverage and Shippers

NRW is divided into 5 NUTS-2 level governorates, which are further divided into 53 NUTS-3 districts. The areas on the NUTS-3 level are incorporated into the model with the borders taken from the AnyLogic GIS map function. Within these areas a parameterized number of random shippers are placed. By default the number of shippers is set to 100 per NUTS-3 area and are distributed randomly over the whole area which, with 53 NUTS-3 regions, sums up to a total of 5300 simulated shippers in the model. Each shipper is assigned a weight depending on the area it is located in. This weight should represent

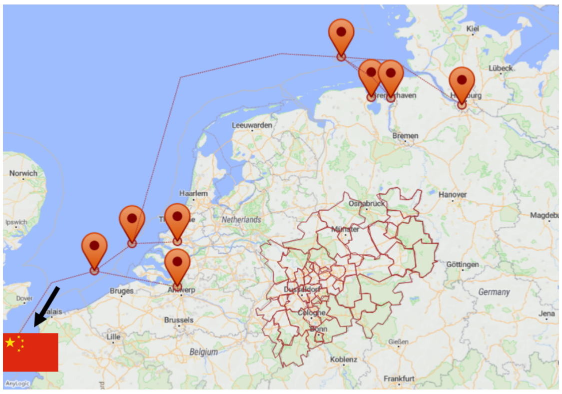


Figure 5.4: Transport Chain of Model from NRW to Shanghai (P.R. China)
Source: Screenshot from simulation model

differences in economic power and amount of containerized transports. To calculate this weight, the historic numbers from containerized transports on the NUTS-2 level are taken and distributed by regional GDP per capita on the NUTS-3 level regions. The table with these calculations can be found in the Appendix Table 5.4.

Ports and Maritime Component

Within the model, the five relevant ports of Antwerp, Rotterdam, Bremerhaven, Wilhelmshaven and Hamburg are included. They are represented by their GIS coordinates. As the model includes the maritime connectivity, frequency and transport time for the considered maritime connection to Shanghai, are averaged over the 5 fastest connections to the destination. Table 5.2 shows the used data. This way, the advantage of port of call position of the western ports in the model can be accounted for which brings an advantage in transport time. For the study at hand, it is assumed that both port handling and maritime transport are having the same cost across all ports. This enables a focus on the hinterland component of transport. Yet there is still a distinction between the ports, with the maritime transport leg taking different time and the ports having varying frequency for maritime connections to Shanghai.

Road and Intermodal Network

For a proper representation of the intermodal network, and possibility to compare with other modes, accurate road network and the corresponding intermodal terminals, both

Port	Frequency per Month	Transport Time (d)
Antwerp	30	30
Bremerhaven	5	31
Hamburg	21	32
Rotterdam	34	30
Wilhelmshaven	2	31

Table 5.2: Maritime Frequency and Transport Time to Shanghai per Port
Source: Estimations by port representative

barge and rail are incorporated into the model. The road network, relevant for unimodal transport as well as pre- and on-carriage, is depicted using data from Open Street Map (OSM) [132]. For practicability, the road networks from Germany, Netherlands and Belgium, relevant for the connections to the relevant ports, have been joined together for further use in the AnyLogic simulation model using the Osmosis Tool [269]. With this map data, a routing graph is created within AnyLogic using the highest accuracy setting. Intermodal connectivity for hinterland chains can be viable from as low as 100 km [194], especially for port hinterland chains, in contrast to the often propagated 300 km minimum distance for continental intermodal transport, which has been challenged by Meers et al. [234]. Therefore, for inclusion of the relevant terminals, distance plays only a minor role to be included in the model. The main criteria is a direct connection to the respective ports. The rail and barge terminals were identified through the port websites, including the distance and frequency of the connection. Additionally, terminals in 50 km proximity of NRW are considered as well. Just like the ports, the location of the terminals are set by GIS coordinates. Each terminal is defined by its main carriage distance to the ports and the frequency of the connection, which are obtained through the port websites or through estimation by Google Maps and Web search. The used distances and frequencies for the intermodal connections can be found in the Appendix Table5.5.

5.4.2 Cost Function

To determine a shipper's choice for a transport mode and port, a stochastic cost function is built. This cost function incorporates the actual transport and transshipment costs for uni- and intermodal transport, costs for the transportation time which is influenced by the intermodal and maritime transport frequency and the costs of carbon dioxide emissions for the different transport modes. Finally, as we assume that shippers' information regarding cost is usually not perfectly accurate, a fuzziness component for shippers' decisions has been implemented. The costs at the ports are assumed as equal, same with the cost for transshipment at all terminals involved.

Transport Costs

The transport costs consist of a hinterland component (uni- or intermodal), their respective carbon tax costs and a port and maritime component. To understand the assumptions of the model, all components are explained in detail.

Uni- and Intermodal Transport Costs The cost for unimodal transport is the distance traveled determined by the routing graph multiplied with a fixed cost function per kilometer. For intermodal transport, the cost for trucking in the precarriage is determined like this as well. Additionally, the main-carriage cost is determined by the distance of the intermodal leg multiplied by a cost factor per kilometer. This cost factor is different for barge and rail and within rail transport, cross-border transport is given an additional penalty as regulations increase costs. The cost of the transshipment itself is priced in with 60€ per operation.

Carbon Dioxide Emissions and Tax The carbon dioxide emissions per mode of transport, which are subsumed by the German Federal Environment Agency (Umweltbundesamt), have been estimated in several studies. For this study, we rely on the values per mode, publicized on their website [348], which per ton-kilometer are 113 g for trucking, 17 g for electrified rail at the average German electricity mix and 30 g for barge transport.

Summary of Assumptions Table 5.3 sums up the assumed transport costs, speed and carbon emissions per mode. We assume a weight per TEU of 24to, the maximum permissible weight, as in this case intermodal transport benefits the most and the potential hinterland for intermodal transport shows an upper boundary. Alternatively, and for further studies, a weight average or distribution of some sort could be used. This way, total carbon emissions per kilometer of transport and an estimation of the change in transport price can be calculated. For simplification reasons, a unified carbon tax for all countries involved is assumed.

Mode	Cost per TEU km	Speed	CO2 per tkm	CO2 per km (24to/TEU)
Truck	2€	80 km/h	113g	2.712g
Train (Germany)	1.3€	50 km/h	17g	408g
Train (cross-border)	1.4€	50 km/h	17g	408g
Barge	1.1€	20 km/h	30g	720g

Table 5.3: Cost and Carbon Dioxide Emissions per Mode and TEU
Source: Cost and speed estimated by port representative, carbon emissions by Umweltbundesamt [348]

Final Cost Function

The final cost function for the transport chain comes out as follows:

(1) $c_{total} = c_{transport} + c_{time}$

(2) $c_{transport} = d_{pre} * (c_{truck} + e_{truck} * tax_{carb}) + d_{main} * (c_{im} + e_{im} * tax_{carb}) + c_{transship}$

(3) $c_{time} = (d_{pre}/s_{truck} + w_{terminal} + d_{main}/s_{im} + w_{port} + t_{maritime}) * c_{capital}$

The main function (1) consists of two parts, a transport cost and a time cost component. The transport cost component (2) is determined by a pre- and main-carriage leg with the cost of transshipment in case of intermodal transport. The costs for precarriage are calculated by distance to terminal multiplied by the cost of trucking per km. In case of unimodal trucking, this represents the whole journey to the port. With intermodal transport, the cost for main-carriage is calculated by the distance to the relevant port multiplied by the mode-specific cost. The transshipment costs are added flatly. The carbon tax component is added at the transport cost per km with each mode by multiplying its emissions per km with the carbon tax rate. The cost for transport time (3) consists of the time used for precarriage, depending on the speed of mode, the potential waiting time at the terminal in case no immediate departure is possible, the transport time by the main-carriage depending on the distance and speed of the mode. At the port, depending on the maritime frequency, a waiting time occurs as well. Finally, the time for the maritime transport is included in the equation. The time component is then multiplied by a capital cost factor representing an average container value. This value is set to 12€ per day as advised by a professional from a major port. Yet, the value of time can be assessed more thoroughly as done by Santos et al. [313] in their study regarding short sea shipping in Europe and take much higher values, depending on the value of goods shipped in a TEU.

Validation and Verification

The cost function and the costs for the different transport modes, time and transshipment costs, have been discussed in workshops with a port representative. While the absolute rate of costs should give a good first indication of potential hinterland scope, the variable component of carbon tax will enable the analysis of the shift in potential hinterland scope as the conditions for all ports are, aside from the distance and connectivity to NRW, the same. Nonetheless, even when the verification attempts to create potential hinterland scope as close to reality as possible, results should be verified further with actual port hinterland data, yet data availability and detail play a crucial role in this case and were not available for the study at hand. More localized investigations could solve this issue, yet it would require adjusted research design.

5.4.3 Stochastic Components

Intermodal and Maritime Connectivity

The frequency of intermodal connections is taken into account through stochastic probability. Langen et al. [194] stated in their empirical assessment of intermodal connectivity in Europe, that the probability to choose intermodal transport is highest with at least 4 trains/barges per week. Additionally, with greater distance from the port, the frequency of intermodal connections matters less in mode choice. As no proper stochastic function for empirical frequency assessment has yet been determined, for practicability reasons, the frequency in our model determines the potential waiting time for an intermodal connection. Meaning that a connection running once weekly can potentially lead to a hypothetical waiting time of 7 days until the intermodal connection is reached. This rewards intermodal connections with high frequency, yet allows shippers to choose less frequent terminals at a lower probability as well. Information about intermodal and maritime connections can be obtained through different information systems, yet their precise schedules are not widely available. To still account for the frequency of intermodal connections and to honor higher frequencies as being beneficial to shippers, the frequency of these connections is part of the cost function. After determining the frequency of a connection, it is spread out evenly over the course of a week. For each shipper, a randomized waiting time for the next intermodal or maritime connection, based on the frequency, is drawn. This essentially means, that for a connection running every day of the week, the potential waiting time at a terminal or port is a maximum of one day, while a connection running twice a week it becomes a maximum of 3.5 days. This component essentially says, that a higher frequency leads to a smoother transport experience while still keeping the chance for lower frequency connections to be utilized stochastically.

Fuzziness of Shippers' Cost Determination

As an assumption, shippers usually do not have completely perfect information regarding the price of transport alternatives which results in the choice of assumed equivalent alternatives. Following this assumption, potential hinterland scope is not drawn by clear lines between ports anymore but is represented by a fuzzy area of influence, which we assume comes more close to reality. Therefore, a tolerance function has been incorporated to account for this. The tolerance function for price essentially takes the transport costs for the hinterland component of the transport chain's best option and adds a tolerance factor to it. Any transport alternative that is within this range becomes a valid transport option. For each mode/port combination only one alternative is added to the options. Among these possible transport options, a random function chooses any of the available. The tolerance function can be adjusted between 0% and 20%. For the simulation runs, a cost tolerance of 5% is assumed, which means that a transport option costing 100€ and an alternative costing 105€ will be treated as having the same utility. This essentially blurs the lines of potential hinterland scope to a more realistic level, as large areas are narrowly contested by different ports by cost.

5.4.4 Model Logic

For initialization, the preset number shippers are randomly placed within each NUTS3 region and assigned a weight for their economic relevance from a database. Intermodal terminals are placed according to their GPS coordinates and parameters regarding frequency and distance to each port are loaded. The road network is loaded from the previously calculated routing graph. To determine the best shipping options, each shipper evaluates the distance to the nearest terminals. Among the terminals, for barge and rail each, a preset number is kept for further evaluation, five in the standard setting. For each possible transport alternative, with different mode and port/terminal combinations, a shipping option is calculated which leads to one unimodal and up to eleven intermodal connections. In the presetting, a maximum of 55 shipping options are evaluated for each shipper. The costs of all shipping options are determined and sorted. Among the cheapest options, if within the cost tolerance, a list of potential shipping options is determined. Here, every mode/port combination can only be added once to the result set as otherwise intermodal connections would be at an additional advantage as there are potentially multiple connections within the tolerance range, skewing their chances to get chosen.

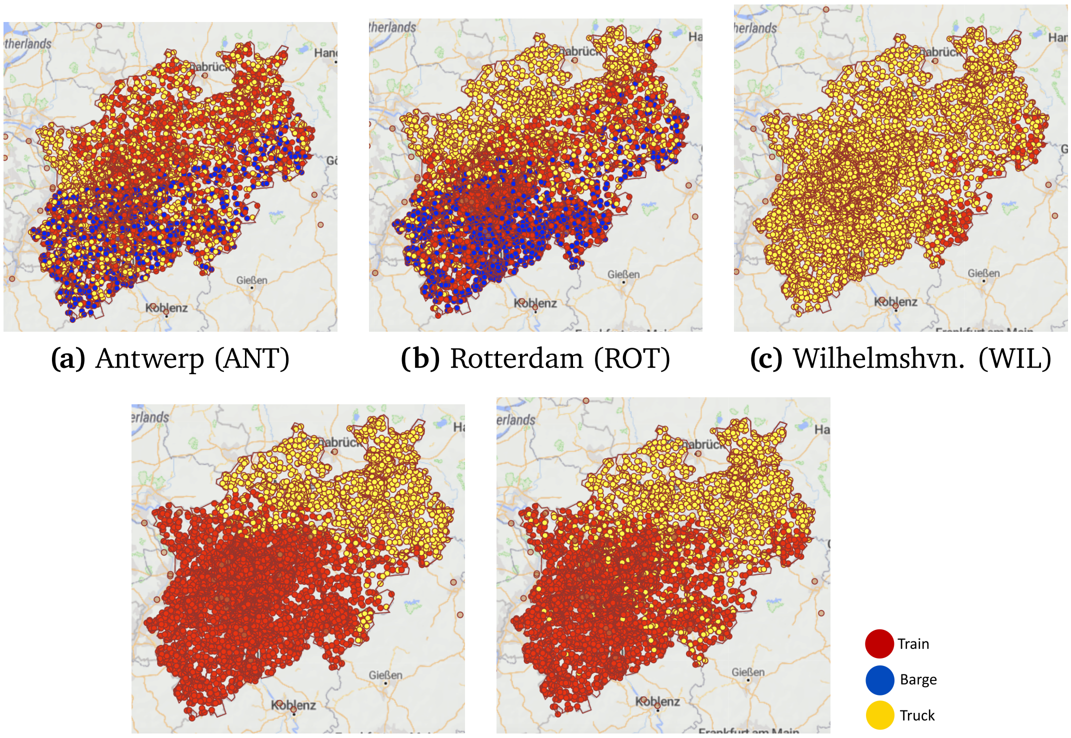
Within this result set, a random function chooses an alternative and sets it as the best option. Finally, the best shipping option, with their economic weight, is added to statistics variables to allow for an assessment of port and mode shares. As the model incorporates stochastic components, a number of reruns can be set. This repeats the determination of the best shipping options and averages out differences in results due to the influence of randomization. For the experiments, we made 10 reruns for each simulation and averaged the results. A higher number of reruns did not change the results further but increased runtime, which is why we opted for this setting.

5.5 Results

The model allows for the investigation of two different perspectives. First of all, it allows to assess the mode shift per port. Here, the scope of each port, depending on different carbon tax levels, can be displayed. By combining the mode scopes of all ports, the port competition in NRW and the implications of a carbon tax for it, can be analyzed.

5.5.1 Initial Port Potential Hinterland Scope

When looking at the base scenario, a carbon tax of zero, the investigated ports differ by their mode scope. This can be analyzed for each port individually and subsequently for the combination of all ports. Figure 5.5 shows the initial potential hinterland scope of each investigated port by their modes in a no carbon tax scenario. The western ports of Antwerp and Rotterdam have three different modes to choose from. In the south of NRW, barge transport is the most advantageous mode. This is due to the Rhine river, which flows through its center. In central NRW, the most populous area, rail transport is most advantageous. At the fringes of the state, at the western border for Antwerp and in the northern border of NRW for Rotterdam, trucking has an advantage. For the German ports, the situation looks different. As there are no direct barge connections from NRW to these ports, the mode competition is between truck and rail transport. The scope of Hamburg and Bremerhaven looks similar, differing by their distance to NRW. The western and central parts of NRW, with their high density of population and terminals, is attractive for rail transport. The eastern part of NRW, due to its close proximity to the German ports and lack of good terminal connections, is best reached via trucking. The situation of Wilhelmshaven is different. Due to its currently poor intermodal and maritime connectivity, its modal scope is currently mostly trucking. As terminals near the southeastern border of NRW serve Wilhelmshaven via rail, small parts of this area are attractive for rail transport.

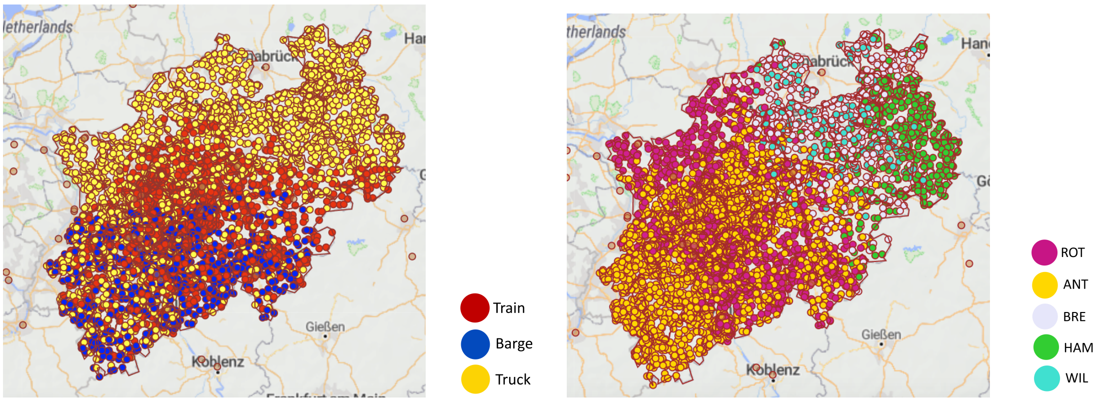


(a) Antwerp (ANT) **(b)** Rotterdam (ROT) **(c)** Wilhelmshvn. (WIL)

(d) Hamburg (HAM) **(e)** Bremen (BRE)

Figure 5.5: Potential hinterland scope per mode for selected ports in a no carbon tax scenario
Source: Simulation model output

When overlaying the potential hinterland scopes of the different ports, the competitive situation between them can be compared. The map of this overlay is shown in Figure 5.6. As expected, the western part of NRW is best reached by Antwerp and Rotterdam while the eastern part is divided between the German ports of Wilhelmshaven, Bremerhaven and Hamburg. In the eastern part of NRW, Hamburg and Bremerhaven compete roughly for the same areas as both ports have a similar distance and intermodal connectivity to them. Due to its proximity, Wilhelmshaven is mostly competitive in the northern part of NRW via trucking. This is due to its lack of good hinterland and maritime connections. In the western part, Rotterdam and Antwerp compete for rail transport in central locations. The south and southwest of NRW has a strong scope for barge, which is both utilized by Rotterdam and Antwerp. The most southwestern part of NRW is dominated by Antwerp



(a) Scope by mode

(b) Scope by port

Figure 5.6: Overlay of potential hinterland scope of all ports with no carbon tax scenario
Source: Simulation model output

via barge and truck.

5.5.2 Sensitivity analysis for carbon tax rates

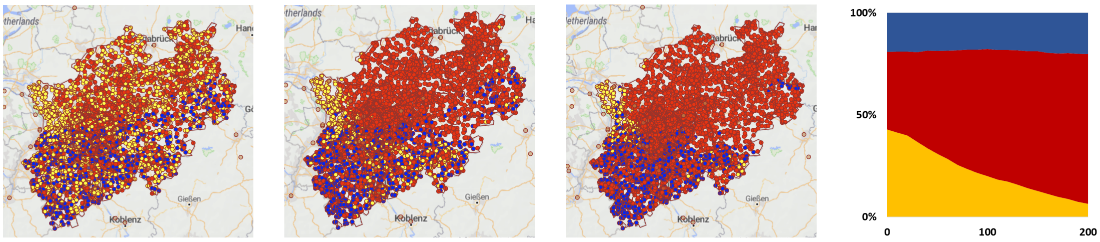
With the model at hand, different rates of carbon tax can be analyzed. This can be done with a parameter variation experiment. Sensitivity analysis, both on a port and a mode basis, can provide interesting insights. For all cases, the carbon tax rate is set between 0€ and 200€, varied in 10€ steps. The different potential hinterland scope for modes per port are displayed for the 0€, 100€ and 200€ scenario. Additionally, a mode graph is displayed that shows the mode share for all carbon tax rates from 0€ to 200€.

Belgian/Dutch Port Analysis

The Belgian/Dutch ports have the possibility to be reached by all three modes with good connections via the rivers of Rhine and Maas and extensive connections via rail to the industrial center of NRW.

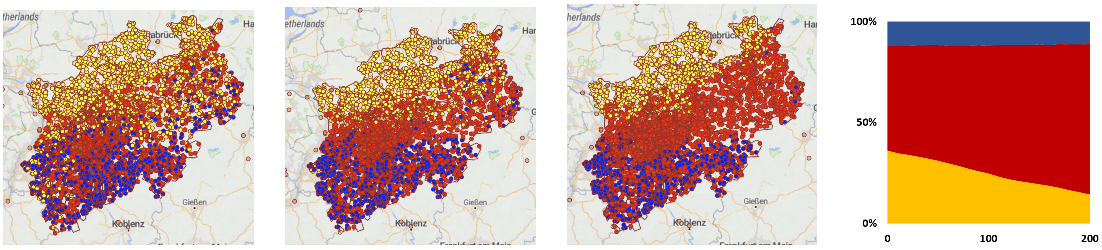
Figure 5.7 shows the potential hinterland scope for Antwerp and Rotterdam at different carbon tax rates. Initially at the zero tax scenario, Antwerp has a strong scope via barge in the southwest, rail in the center and parts of the west in trucking. The situation for Rotterdam is similar, yet the parts for trucking extend more to the northern part of NRW.

Antwerp (ANT)



(a) 0€ **(b)** 100€ **(c)** 200€ **(d)** Mode Graph

Rotterdam (ROT)



(e) 0€ **(f)** 100€ **(g)** 200€ **(h)** Mode Graph

Figure 5.7: Potential hinterland scope per Belgian/Dutch port with different carbon tax levels

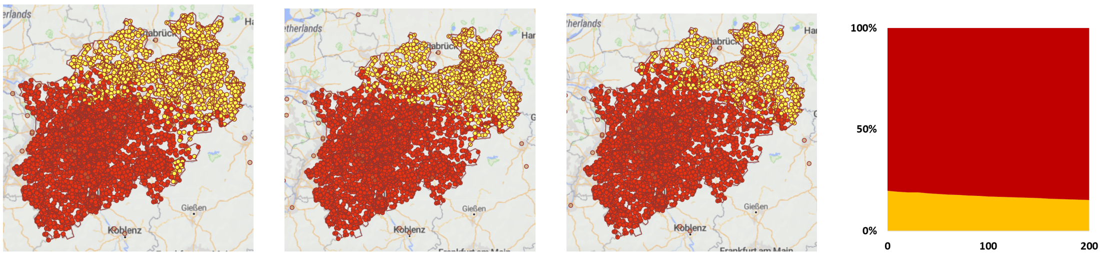
Source: Simulation model output

With an increase in the carbon tax rate, the borders for each transport mode scope become more pronounced. For Antwerp, this leads to the south being ideally served via barge while the area from the center to the east is best served via rail. Even if this trend can be observed for Rotterdam as well, the distinction is not as strongly pronounced.

German Port Analysis

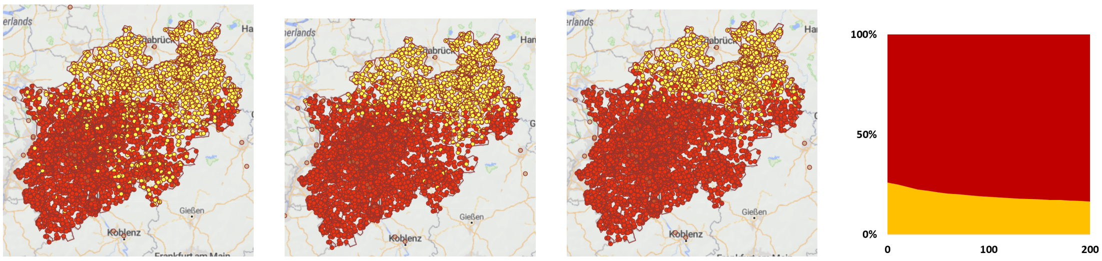
For the German ports, as they are not reachable via barge transport, mode competition is held between trucking and rail. Therefore, with an increase of the carbon tax rate, the area of rail transport expands toward the port. This is especially relevant for shippers that currently reside at the border of the modes' scope. Figure 5.8 shows the potential hinterland scope for the German ports for different carbon tax rates. The scope of Bremerhaven and Hamburg seem to be quite similar, with both ports having a similar

Hamburg (HAM)



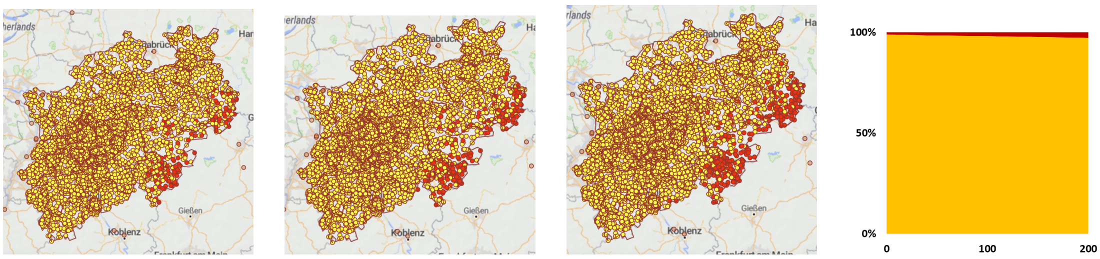
(a) 0€ (b) 100€ (c) 200€ (d) Mode Graph

Bremen (BRE)



(e) 0€ (f) 100€ (g) 200€ (h) Mode Graph

Wilhelmshaven (WIL)



(i) 0€ (j) 100€ (k) 200€ (l) Mode Graph

Figure 5.8: Potential hinterland scope per German ports with different carbon tax levels
Source: Simulation model output

good connection via rail and being located in quite close proximity. Port of Wilhelmshaven's scope is mostly trucking as the port has only intermodal connections at terminals east of NRW. With an increase of the carbon tax rate, both Hamburg and Bremerhaven extend their intermodal train scope as the border for it moves eastwards. Most of the industrial and population dense areas are best reached via intermodal transport with an increase in carbon tax rate. For Wilhelmshaven, an increase in carbon tax rate leads to rail prone areas in the southeast of NRW. Most of the scope, and the relevant scope in competition with the other ports, stays to be trucking predominantly.

Overall Port Analysis

When merging the different potential hinterland scopes of the ports for different rates of carbon tax, an overall analysis of NRW can be conducted. This analysis is both interesting from a mode and a port point of view, as there are areas both contested by port and by mode. As most population and industry is located in central NRW, obtaining a beneficial position compared to the other ports for this area heavily benefits the strength of a port's scope. Figure 5.9 shows this merge of the scopes of ports and modes with different carbon tax rates. In the zero carbon tax scenario, a divide between eastern and western NRW clearly shows. While the western part is ideally served via Rotterdam and Antwerp, the eastern part is dominated by the German ports. Mode wise, the north is ideally served via trucking, because of its proximity to the ports. The central and southern part is contested by train and barge transport. An interesting point to note is that Antwerp and Rotterdam have a way stronger position than the German ports, as they occupy the central areas of NRW with their scope, which are having dense population and industry.

By an increase in the carbon tax rate, areas best served via trucking are expected to remain in the northern and northwestern parts NRW, while more central parts shift to intermodal transport. The center of NRW, also its most populous area, will be best served via rail and an increase in carbon tax rate pronounces this even further. The rail transport scope is expected to extend from the central areas, as precarriage and transshipment becomes more feasible. Interesting to see is, that the rail transport also extends into the area previously dominated by barge transport. This is further fueled by the existence of trimodal terminals at the Rhine. Yet in the south of NRW, barge is expected to still dominate, even with an increasing carbon tax rate.

When looking at port competition, Rotterdam seems to increase their scope with an increase in tax rate. Mode wise, there is a shift from trucking to rail for Rotterdam. Antwerp looses some scope via barge to rail and to Rotterdam. The German ports experience an extension of their intermodal scope with trucking becoming increasingly unattractive. An interesting point to see is that for Rotterdam the competitive situation improves, especially competing with Antwerp. The situation between the western and eastern ports does not seem to change much though, with the east west divide still clearly showing even at the highest tax rate. Most of the shifts occur in the scope of ports between their modes. This largely explains the increase in the rail transport scope as shown by the mode graph. Especially trucking and barge transport are at a disadvantage, which also explains the loss of scope for the Port of Antwerp. The competitive situation of the German ports does not seem to change much though.

5.6 Discussion

With an increase of the carbon tax rate, a shift towards rail transport can be expected. The scope of rail transport is strongest in the highly populated areas in central NRW. With an increase the area extends toward the south into the barge scope and into the north into the trucking scope. Between ports, the Port of Rotterdam is expected to improve its

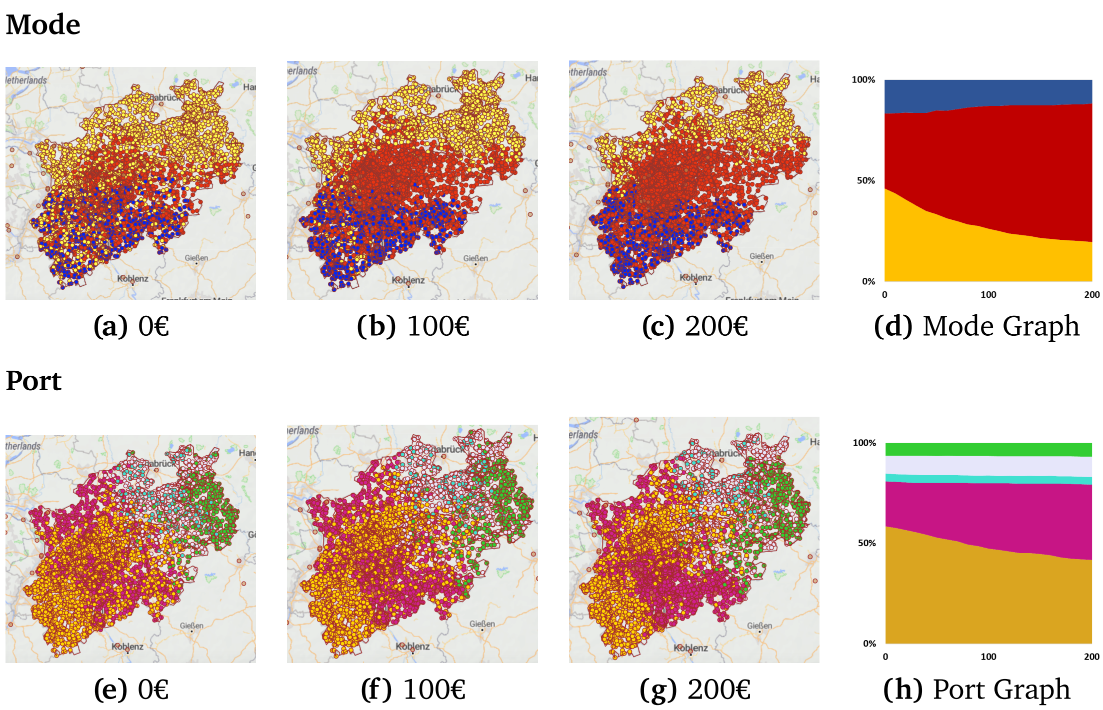


Figure 5.9: Overall potential hinterland scope per mode/port with different carbon tax levels
Source: Simulation model output

potential hinterland scope due to its good position with rail transport to central areas of NRW. As barge transport becomes less attractive with a higher carbon tax rate, the Port of Antwerp is expected to loose hinterland scope and market share in consequence. The German ports, in this model having a favourable scope mostly via trucking, seem to keep their hinterland scope as this area is neither densely populated, nor has a high density in intermodal terminals, yet their previously occupied scope shifts towards rail transport. For the highly attractive area for transport demand in central NRW, the German ports are generally in a less favorable position compared to the western ports, as they are further away from it. Competition between the German ports occurs in the eastern and southeastern part, where the Port of Hamburg is expected to improve its intermodal scope.

Business implications can be drawn for various participants. The involved ports need to reconsider which intermodal connections to foster and which terminals to include in their hinterland network. This is especially interesting for the Port of Antwerp, as barge transport despite its higher capacity might become less competitive. For intermodal operators, the interesting areas for business opportunities change as well. Areas that have not been interesting for intermodal connections become so through a rising tax rate, especially in the eastern and northern part of NRW. Therefore, the implementation of additional intermodal connections for areas that are feasible for intermodal transport can attract additional cargoes. For shippers and forwarders, which transport modes in contested areas and which ports to use for their exports, should be reconsidered as well. The already densely populated area of central NRW is expected to see more fierce competition between the ports involved. To relieve this area from transport demands, building of additional terminal locations, especially at the fringes of NRW, can become viable. Especially locations for intermodal terminals and connections to the German ports, still attractive to be served via truck, should be assessed with an increase of carbon tax rate.

Politically, an increase in the carbon tax rate nationally might lead to a weakening of national ports, especially in Germany, although a shift away from the Port of Antwerp might be more significant. Considering national interests aside from most efficient transport routes, the rise in carbon tax rates would need to be accompanied by other measures like subsidies for intermodal rail connections or the building of new terminals in closer proximity to the German ports. If following a transnational strategy, cooperation between the countries involved to improve the efficiency of cross-border transport need to be fostered.

From a research point of view, the analysis of further environmental measures and their implications on the competitive situation of actors involved is interesting. An aspect especially interesting are side effects on economic variables of environmental measures, especially when considering long grown infrastructure components and locations. This means, that aside from the directly intended effect environmental measures might have, their side effects on other areas, especially the competitive situation of actors involved, becomes highly interesting and offers plenty of research opportunities. With climate change advancing, additional policy measures are likely to be implemented, which allows for various forms of research regarding their effects. In this way, research can lead to more sound decisions and mitigation of the impact of environmental policy measures.

5.7 Conclusions

The article has investigated a case study of the hinterland scope of ports in the European northern range for NRW in the light of an environmental measure. A model regarding mode choice, expanded by carbon dioxide emissions and intermodal frequencies, has been created. The model has been applied to the case of NRW and changes in the potential hinterland scope of each port have been estimated. The shift has been analyzed for different carbon tax rates. The results show that the central and most populous parts of NRW become heavily contested between multiple ports with intermodal rail becoming the dominant mode. Therefore, the optimal intermodal connection to this area becomes crucial to compete with other ports. As intermodal rail emits less carbon dioxide than barge transport, a shift in areas previously dominated by barge can be expected. These shifts in transport and mode demands will have impacts on economic circumstances of intermodal actors like intermodal operators and terminals, port terminals and port authorities, shippers and forwarders. The novelty of this research is the assessment of environmental policy on port competition in a heavily contested region. The created model, due to the flexibility of the simulation method, allows for further assessments of different policies and changes in parameters for further studies. An important limitation of the study is the focus on potential hinterland scope. Even though the input parameters have been validated, there is no validation of the results with actual data due to data availability. This could be up for further investigation, yet would probably require a more detailed research approach. The focus on transport time and costs for determining the best transport option is a limitation as well as not incorporating capacity availability for choosing the best option, which would favor truck transport. Another limitation is the focus of the study on the region of NRW and the assumption of uniform policies across the involved countries. As this neglects differences in policies for simplicity reasons, it could impact meaningfulness.

Further research regarding the situation in NRW should investigate how and where to establish new intermodal connections to cope with a rising carbon tax rate. Within this investigation, the location and size of additional terminals should be investigated. This analysis should not only include the level of detail in the study at hand but investigate local implications of environmental policy change. A rising carbon tax rate might increase stress on local transport capacities and lead to the need for additional provision of capacity. As NRW is a special region, prone to port competition as shown, the applicability and extension of the model towards further multi-port regions, would be an interesting addition. As additional environmental policies can be expected to be implemented in Europe, their effect on the port competition by altering the model, should be investigated. The occurring side effects on economic variables through environmental policy provides a wide and interesting field of research.

5.8 Appendix

Name	NUTS	Population	GDP per Employee	TEU by Pop.	TEU by GDP
Düsseldorf (RegB)	**DEA1**	**5202817**	**74896**	**567741**	**567741**
Düsseldorf	DEA11	619631	91568	67615	130631
Duisburg	DEA12	498572	77215	54405	47565
Essen	DEA13	583123	74404	63631	66111
Krefeld	DEA14	226967	74066	24767	24270
Mönchengladbach	DEA15	261430	65135	28528	23733
Mülheim an der Ruhr	DEA16	170858	73178	18644	15960
Oberhausen	DEA17	210772	60008	23000	15099
Remscheid	DEA18	111038	65376	12117	10466
Solingen	DEA19	159400	68595	17394	13430
Wuppertal	DEA1A	354248	74314	38656	34717
Kleve	DEA1B	311177	62800	33956	25139
Mettmann	DEA1C	485624	78364	52992	53298
Rhein-Kreis Neuss	DEA1D	451170	89661	49233	49483
Viersen	DEA1E	298907	65150	32617	22762
Wesel	DEA1F	459900	65268	50185	35079
Köln (RegB)	**DEA2**	**4469420**	**76025**	**191219**	**191219**
Bonn	DEA22	327462	94325	14010	23812
Köln	DEA23	1085767	84530	46453	65825
Leverkusen	DEA24	163912	100105	7013	8423
Düren	DEA26	263956	62699	11293	7733
Rhein-Erft-Kreis	DEA27	470307	85095	20122	17397
Euskirchen	DEA28	193026	62816	8258	5376
Heinsberg	DEA29	254165	60351	10874	6567
Oberbergischer Kreis	DEA2A	272402	67841	11654	9987
Rheinisch-Bergischer Kreis	DEA2B	283441	65081	12127	7583

Rhein-Sieg-Kreis	DEA2C	599717	70201	25658	17347
Städteregion Aachen	DEA2D	555265	67807	23756	21170
Münster (RegB)	**DEA3**	**2624201**	**66019**	**95916**	**95916**
Bottrop	DEA31	117423	53825	4292	2874
Gelsenkirchen	DEA32	260655	68200	9527	8575
Münster	DEA33	314213	78383	11485	19674
Borken	DEA34	370784	65264	13552	15045
Coesfeld	DEA35	220064	63773	8043	7000
Recklinghausen	DEA36	615269	64053	22488	17298
Steinfurt	DEA37	448008	63641	16375	15801
Warendorf	DEA38	277785	66123	10153	9650
Detmold (RegB)	**DEA4**	**2055812**	**68665**	**158435**	**158435**
Bielefeld	DEA41	333838	63487	25728	26949
Gütersloh	DEA42	364499	75924	28091	35022
Herford	DEA43	250719	67135	19322	17584
Höxter	DEA44	140645	61465	10839	8195
Lippe	DEA45	348442	65522	26853	21588
Minden-Lübbecke	DEA46	310711	75210	23946	26386
Paderborn	DEA47	306958	67171	23656	22712
Arnsberg (RegB)	**DEA5**	**3582225**	**66909**	**153833**	**153833**
Bochum	DEA51	364731	63703	15663	14820
Dortmund	DEA52	586863	68403	25202	27451
Hagen	DEA53	188822	64951	8109	7989
Hamm	DEA54	179161	61724	7694	6368
Herne	DEA55	156353	58505	6714	4560
Ennepe-Ruhr-Kreis	DEA56	324263	67500	13925	12535
Hochsauerlandkreis	DEA57	260366	63521	11181	11790
Märkischer Kreis	DEA58	412198	70626	17701	19276
Olpe	DEA59	134773	70185	5788	6901

Siegen-Wittgenstein	DEA5A	278041	71248	11940	13987
Soest	DEA5B	301781	68624	12960	13149
Unna	DEA5C	394873	66649	16957	15006

Table 5.4: Containerized Data (Export) and Adjustment by Population and GDP per Employed Person after ISL Bremen [160] and Statistisches Landesamt Nordrhein-Westfalen [325]

Terminal	Mode	ANT	ROT	WIL	BRE	HAM
Andernach	barge	-	380km|2x	-	-	-
Bonn	barge	300km|5x	335km|14x	-	-	-
Cujik	barge	160km|5x	140km|5x	-	-	-
Dormagen	barge	200km|2x	-	-	-	-
Dortmund	barge	330km|2x	-	-	-	-
Düsseldorf	barge	315km|2x	255km|3x	-	-	-
Duisburg	barge	275km|13x	215km|20x	-	-	-
Emmelsum	barge	-	220km|5x	-	-	-
Emmerich	barge	205km|3x	145km|15x	-	-	-
Genk	barge	90km|5x	-	-	-	-
Koblenz	barge	395km|2x	455km|3x	-	-	-
Köln	barge	360km|5x	300km|6x	-	-	-
Krefeld	barge	210km|5x	210km|6x	-	-	-
Liege	barge	140km|5x	-	-	-	-
Neuss	barge	320km|7x	260km|7x	-	-	-
Oss	barge	160km|4x	-	-	-	-
Roermond	barge	-	215km|3x	-	-	-
Venlo	barge	250km|4x	190km|5x	-	-	-
Venray	barge	230km|11x	170km|6x	-	-	-
Voerde	barge	240km|5x	-	-	-	-
Beiseförth	train	-	-	375km|3x	340km|3x	350km|3x
Bönen	train	-	-	-	-	315km|2x
Coeverden	train	-	215km|3x	-	-	-
Dortmund	train	-	-	-	280km|1x	325km|5x
Düsseldorf	train	-	225km|5x	-	-	-
Duisburg	train	260km|3x	240km|33x	-	335km|1x	380km|7x
Emmerich	train	-	160km|8x	-	-	-
Genk	train	-	90km|3x	-	-	-

Göttingen	train	-	-	-	-	250km|1x
Kassel	train	-	-	320km|8x	290km|8x	290km|8x
Köln	train	-	275km|6x	-	400km|2x	440km|14x
Minden	train	-	-	-	200km|1x	225km|4x
Neuss	train	260km|5x	225km|9x	-	-	-
Osnabrück	train	-	-	-	-	230km|7x
Veghel	train	-	130km|3x	-	-	-
Venlo	train	-	185km|6x	-	-	-
Warstein	train	-	-	-	-	375km|2x

Table 5.5: Intermodal Terminal Distance and Frequency to Ports based on DB Netz AG [70]

6 Central European Perspective on the New Silk Road - Transport Opportunities for Hessian Exporters

6.1 Abstract

A major aspect of the Chinese driven Belt-and-Road-Initiative (BRI) is the promotion of rail-based transport between China and Europe. Its flagship service, the China Railway Express (CRE), offers superior transport speed over current maritime transport options while incurring similarly higher costs. While westbound traffic is heavily promoted and has been partly subsidized by the Chinese government, the eastbound counterpart lacks behind. The occurring imparity can negatively impact utilization and profitability and presents an interesting, subsidy free, assessment of the potential for transports from central Europe to China. Hesse, a state in central Germany and Europe, has been investigated as a case for export opportunities utilizing the CRE. Using a cost-based GIS model, rail and maritime transport options are compared to each other. Analysis is hereby done two-fold. First, the scope of rail and maritime transport is visualized for different cargo values. It shows that rail transport can potentially out-compete maritime transport for western China, which lacks access to sea ports, and parts of central Chinese provinces. Second, by assuming a global carbon tax on all transport options as proposed on the Africa climate summit [21], change in scope is visualized and analyzed. Such a global environmental policy can impact the competitive position of trans-continental rail transport by pushing its potential scope eastwards towards densely populated areas in China. Additionally, at significant tax rates, regions in northeastern China become viable for rail transport from Hessian exporters. It shows, that the regional economic and population setup of China limits potential of the CRE. For transports to central China, the transport option should be considered.

6.2 Introduction

6.2.1 The One-Belt-One-Road Initiative

The so-called Silk Road, a name given to it by the geographer Ferdinand von Richthofen in the 1860s due to silk being its main trade, was a trade lane that stretched from ancient China through central Asia and Persia all the way to Europe [131]. Building upon the historic idea of this land bridge, the One-Belt-One-Road (OBOR) or Belt-and-Road Initiative (BRI) was announced in 2013 by the Chinese president Xi Jinping and flanked by the establishment of the Asian Infrastructure Investment Bank (AIIB) [17]. The initiative encompasses investments in large infrastructure project to foster cross-border Eurasian trade. Its major aim is to interconnect China, central Asia and Europe by establishing high-speed railroads, pipelines and electricity links, alongside a maritime network of ports [153]. Due to better connectivity, especially of land-locked countries, the BRI is expected to benefit eastern European and central Asian countries economically through trade gains [148]. Additionally, due to vastly faster transportation speed of the rail connection compared to maritime transport, a new segment of transport options for Europe-Asia trades arises [394] and indications show that especially time-sensitive exporters make use of and benefit from it [229]. Aside from economic advantages, the Chinese initiative has geopolitical implications increasing the geopolitical influence of China especially in developing countries [9] although indications show no institutional changes in these countries [391]. The BRI also fosters Chinese outward foreign direct investments in countries participating in the BRI [389] and potentially has an effect on environmentally friendly investments and policy [206]. It also leads to a closer integration of participating countries by having trade agreements with China [279]. For the EU, the growing influence of China through the BRI is seen sceptical, although opinions on it vary regionally [238] alongside different levels of involvement [318]. This also shows in the diversity of research regarding the BRI and Europe. Different geographic focus and analysis has been conducted on the national level for Italy [115], or Poland [60], which is seen as a key transit hub for transport to western Europe [18] alongside the Rail Baltica project aiming to connect the Baltic states through Poland with western Europe [24]. Other important regions for BRI research are the eastern Mediterranean where China sees strategical importance especially for Greece [172] and has taken influence due to its investment in the Port of Piraeus [20]. Another important format is the CEE-16+1 group, which consists of eastern and central European countries and China to foster involvement and investment in the BRI [30]. Despite its economic weight and potential for the transport option [215], analysis especially for western Europe seems scarce and provide the motivation for the case study investigated.

6.2.2 Research Question and Design

The BRI is partly driven by subsidies from the Chinese government for westbound transport from China to Europe [187, 199]. This has led to an imparity of exports to imports on the China Railway Express (CRE) with underutilized trains on their eastbound travel [372]. This imparity seems to have further increased with western shippers opting out of the use due to the Russian aggression on Ukraine [319]. As imparity of transports can lead to higher transport costs, the potential of eastbound transports from western Europe should be investigated to close the gap. The main competitor of intercontinental rail transport is maritime transport, which at roughly half the cost, and speed, offers large capacity on well established shipping routes. A comparison of both transport modes can estimate the potential for the fairly new rail transport option. The CRE offers various routes between China and Germany, with Duisburg and Hamburg being two major start and end nodes. In order to assess the transport opportunities eastbound from Germany, the state of Hesse has been chosen as a case for investigation. The reasons for this choice are its central location in Germany and Europe and its role as a transport hub with good infrastructure and connections to the CRE nodes. Also Hesse is an economic powerhouse with an export oriented economy and a major logistics node. An assumption in the choice of Hesse is, depending on their connectivity to CRE hubs, that locations east of Hesse are more favorable for using the CRE and locations west are less favorable. From a Hessian perspective, it is interesting which parts of China are best reached by which mode, especially for its developed coastal provinces and its upcoming central and western provinces. Additionally, the effect of a global carbon tax as recently proposed on the Africa climate summit [21] and its impact on the competitive situation on the CRE yield interesting insights of changes in transport lanes due to environmental policy measures. Two research questions guide this study:

- RQ1: Which parts of China are favorable for Hessian exporters utilizing rail transport provided by the CRE over maritime transport?
- RQ2: How does an (assumed) global carbon tax change the competitive situation of rail transport for Hessian exporters to China?

The remainder of this article is structured as follows. First, an introduction to the CRE and the state of Hesse is given. This is followed by a description of the GIS model, its implementation, logic and cost function. Based on simulation runs of the model, analysis regarding different cargo values and different rates of an assumed global carbon tax are discussed. Finally, a conclusion of the research conducted and an outlook on further research needs for the perspective of central European shippers utilizing the trans-Eurasian corridor is given.

6.3 Scope of the China Railway Express (CRE)

The China Railway Express (CRE) is a key component of the BRI for rail transports between China and Europe [59]. Its southern route runs through the Balkans, Turkey, Iran and central Asia to western China. Its northern and trans-Siberian route runs through eastern Europe, Russia, Kazakhstan and Mongolia. For entry to China multiple border stations exist. For the major German port of Duisburg the main transport legs are depicted in figure 6.1. For both major German nodes of the CRE, the Port of Duisburg and the Port of

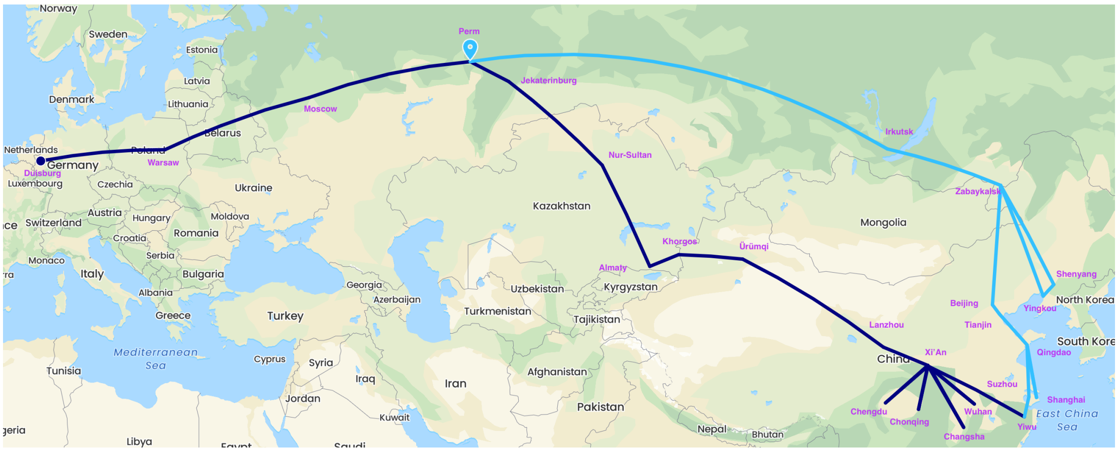
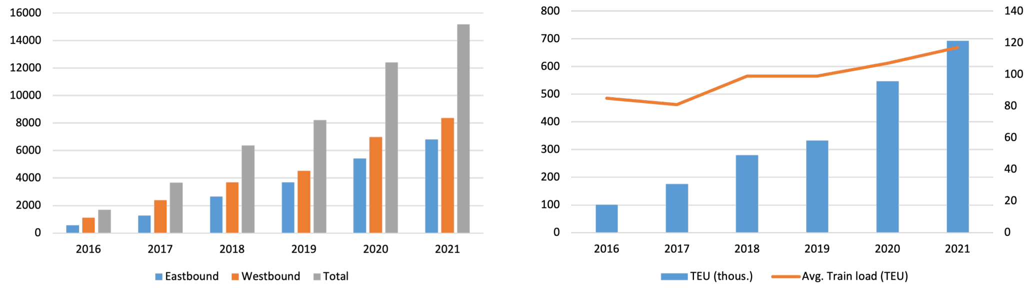


Figure 6.1: CRE connections from Duisport in Duisburg

Source: Own design based on Duisburger Hafen AG [84]

Hamburg, several connections to China exist. Starting from both nodes, transports need to reach the eastern European border station of Malaszewice/Brest, where a gauge change from standard to wide gauge needs to occur. After gauge change the train runs through Minsk, Moscow, Perm. At Perm existing tracks allow for two options. By going south through the so-called northern route, the train runs through Jekaterinburg and several cities of Kazakhstan until it reaches the border station of Druzhba/Alashankou. The other option is utilizing the trans-siberian railways all the way to Irkutsk and Ulan-Ude. Here either the Mongolian route to the border station of Zamiin-Uud/Erenhot or the Russian route to Zabaikalsk/Manzhouli can be taken. After a final gauge change at the respective Chinese border station to standard gauge, the trains continue on their inner Chinese travel

to their respective inland terminals.
Transported capacities and number of trains have severely increased on the CRE since its inception. Figure 6.2 shows both the total of trains run, containers transported and average load factor. While load factor and total capacity have increased manifold over the years, the gap between westbound and eastbound traffic persists. There have been



(a) Trains **(b) TEU and avg. load factor**

Figure 6.2: Trains conducted and cargo transported between China and Europe 2016-2021

Source: Own design based on (a) National Development and Reform Commission (PRC) [265, p.15] (b) Eurasian Rail Alliance Index (ERAI) [96, p.9]

several investigations regarding the CRE. Wang et al. [374] attempt to estimate the market share of each CRE relation. Sun et al. [331] have looked at the optimal placement of consolidation centers of the CRE in China similarly Zhao et al. [395] have done so for Europe. Jiang et al. [171] look at which cities may ideally become major transport hubs and Cheng et al. [57] on how to optimize transport hub locations for greenhouse gas emission reduction. Feng et al. [117] investigated the subsidy schemes of the CRE to find an optimal regime and Lian et al. [201] took a look at the competitive situation of the CRE because of the sulphur control act of maritime shipping.

6.4 Hesse - A state in the heart of Europe

With its central position as a state in federal Germany and its major urban center of Frankfurt being located approximately in the heart of Europe[1], Hesse is an economic powerhouse in Germany. It hosts an export-oriented industry, and with Frankfurt one of

[1]As sung in the anthem of the hessian UEFA Europe League 2021/2022 winner Eintracht Frankfurt [126]

Europe's major financial center with several national and international banks and home to the European Central Bank. Due to its location Hesse it is a major transport hub with important infrastructure running through it. Aside from calling home the largest airport in Germany by passengers and largest in Europe by cargo [128, p.43], it hosts major highways like the A5 and A67 in north-south and the A3 and A66 in east-west directions that intersect in Frankfurt. Its central railway station is among the most busy nodes in Germany [77]. Its central location ensures proper connectivity to major transport nodes like the maritime Port of Hamburg and the river Port of Duisburg. It is connected to the Rhine-Alpine [101], the Rhine-Danube [102] and the Scandinavian–Mediterranean [103] corridor of the TEN-T networks. Aside from these favorable infrastructure location, Hesse presents an interesting case for the investigation of transports using the CRE. It is deemed to be at the competitive zone for rail transport [215]. Additionally there have been first, although temporary, attempts of establishing direct CRE connections to the terminal of Frankfurt-Höchst [110] which shows interested in China bound transports. As geographical situations of other locations have their unique peculiarities, the case of Hesse can be seen as a good proxy for central Europe regarding favorable transport choice. While eastern European locations have a more clear outlook on using the CRE, as analysis for transports to Moscow from China show [372], in the case of Hesse this advantage is not as clear as its location is comparably less favorable. Nonetheless, due to the economic importance of Hesse, an investigation as a proxy for western Europe can yield interesting insight regarding the potential scope of the CRE.

6.5 Mode competition on Hesse-China trade

Cargo transport from Hesse to China can make use of several well connected transport modes. High value and time critical goods usually make use of air freight opportunities from Frankfurt airport. General cargo is shipped via maritime transport whereas multiple ports in the northern range are potential gateways. With the CRE a third option has come into existence. Just like for the ports, pre-carriage can be conducted either by truck on one of the well connected highways to the respective ports or by utilizing the extensive rail network in Germany. When utilizing the CRE, the Port of Duisburg is the closest option although connections from the Port of Hamburg exist as well. Focusing on the comparison of rail and maritime transport to China, connection to the transport hubs in Duisburg and Hamburg are important. Duisburg, which houses the largest inland terminal in Europe named Duisport [85], is a major node of the CRE and offers direct connections to several Chinese cities. The maritime Port of Hamburg, Germany's largest sea port [210], offers maritime connections to several Chinese destinations and additionally is included into the CRE network as an end node as well. For Hesse, both ports offer relevant connections for transport to and from China. In order to compare the transport options a GIS model is developed that depicts pre-carriage and on-carriage and the different nodes and tracks of the CRE and maritime transport. This GIS model is then used to compare origin-destination pairs on a cost basis. The structure and logic of the model alongside the cost function and parameters are explained subsequently.

6.5.1 Model Structure & Logic

The GIS model, implemented in AnyLogic Researcher Version 8.8.4, consists of three transport legs. The state of Hesse and each Chinese province is depicted. GIS data for the road network, to allow for proper routing within Germany and China, is derived from OpenMaps [268]. Additionally, relevant nodes within Germany, the ports of Duisburg and Hamburg, within the trans-Siberian with stations for gauge change and border crossing, and Chinese maritime ports and CRE terminals are set. The pre-carriage in Germany to the ports and the on-carriage in China from the terminals/ports is assumed to occur via trucking, the rail and maritime distances are set by fixed distances and loaded from a data table.

The logic of the model initially generates 100 random points in Hesse and for each Chinese province. These points serve as the start and destination nodes and for each point in Hesse and every Chinese province origin-destination pairs are created. For the Chinese destination point, the nearest CRE terminal and maritime port is determined by available CRE and maritime services. Then, from the Hessian start point, truck transport is conducted based on GIS routing to the German terminals in Duisburg or Hamburg. For maritime transport, after a transshipment, the vessel is sent to the selected Chinese port, transshipped and carried via truck to its final Chinese destination. For rail transport, the train runs inner-EU to the border node of Malaszewice/Brest where a gauge change occurs. Then the train continues to run through Belarus, Russia and Kazakhstan/Mongolia, depending on the route taken, to the respective Chinese border node. After an additional gauge change the train runs on Chinese tracks to its destination terminal, gets transshipped and reaches its final destination via trucking. For all parts of the transport, distance and time data is collected. By applying a cost function, the best transport alternative is chosen and the destination point in China is colored respectively red for rail and blue for maritime transport. For evaluation purposes, and because most Chinese economic power is concentrated in the eastern coastal region, each Chinese destination point is weighted with the province's economic power to allow for a market potential analysis.

6.5.2 Cost Function

In order to compare rail and maritime transport to China from Hesse, a cost function is developed. The function basically consists of two components, a transport cost and a time cost component. Regarding the transport costs, a fixed cost per TEU and km for each leg is assumed, whereas costs for pre-carriage and on-carriage trucking differ between Germany and China, as well as the different rail legs have different costs associated with them. The gauge change that needs to occur twice is assumed to fixed cost of 30€ per process and transshipment at the origin and destination rail terminal is assumed to cost a fixed 60€ per transshipment and maritime port transshipment at 120€ per transshipment. The same is done for time costs which are depending on transportation speed, where an interest rate of 5% is assumed. Here as well, transportation speed depends on the mode of transport and the country the transport is conducted in. For gauge change, including waiting time, a fixed time of 8h is assumed as well as for transshipment a fixed time of 12h. Table 6.1 shows the assumed transport costs and speeds based on the work of Zhang and Schramm [394] and the carbon emissions per TEU km as estimated by the Eurasian Rail Alliance Index [95]. The final cost function combines therefore the transportation

Component	Costs per TEU km	Avg. speed	Carbon emissions per TEU km
Truck EU	3 €	50 km/h	2440g
Truck CN	2 €	50 km/h	2440g
Train EU	1.2 €	40 km/h	27g
Train Sib.	0.6 €	40 km/h	27g
Train CN	0.6 €	35 km/h	27g
Maritime	0.15 €	27.5 km/h	131g

Table 6.1: Cost, speed and emissions of different transport modes (2022)
Source: Zhang and Schramm [394] and Eurasian Rail Alliance Index [95]

and time costs. Additionally, a hypothetical carbon tax can be added. By setting the value of the transported container, the time cost can be quantified by using a fixed capital cost per year that is broken down to the actual time in transit at an assumed interest rate of 5%. By incorporating this time costs, the advantage of faster rail transport might offset slower but cheaper maritime transport. The final cost function comes down to:

(1) $c_{total} = c_{transport} + c_{time} + c_{carbon}$

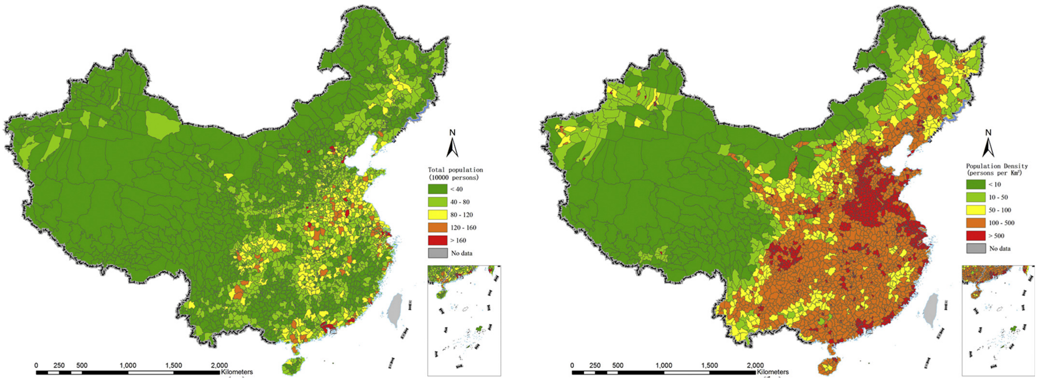
(2) $c_{transport} = d_{pre} * c_{truckDE} + c_{transship} + d_{main} * c_{im} + c_{transship} + d_{on} * c_{truckCN}$

(3) $c_{time} = (d_{pre}/s_{truckDE} + t_{transship} + d_{main}/s_{im} + t_{transship} + d_{on}/s_{truckCN}) * c_{capital}$

(4) $c_{carbon} = d_{pre} * e_{pre} * t_{carbon} + d_{main} * e_{main} * t_{carbon} + d_{on} * e_{on} * t_{carbon}$

6.6 Results & Discussion

The simulation model allows for different assessments of potential geographic scope for exports from Hesse to China on various transport and cargo parameters. Two specific assessments were chosen for the study at hand. The first assessment looks at different cargo values for general cargo that is transported on the route. An increase in cargo value leads to higher capital costs for longer transport times as more capital is bound in the transport. An increase in cargo value therefore benefits the faster transport mode, in our case rail transport. The second assessment is that of a global (hypothetical) carbon tax. Such a tax has not yet been implemented, due to a lack of international agreements. Yet, first calls by nation groups for such a tax exist [21]. Such a carbon tax benefits rail transport as well due to the electrification of large parts of the transport leg. With the help of the simulation model, both geographic maps colored by the potential transport mode scope and statistical estimates of mode share can be obtained, of which the following analysis is based on. For a better understanding of the geography and distribution of population in China, Wang et al. [373] have estimated both the absolute and density of population for the year 2010 in the different Chinese regions depicted in figure 6.3. As can be seen, most population is concentrated around the coastline, in and around the major cities and notably within the Sichuan province and around Chongqing city in central China.

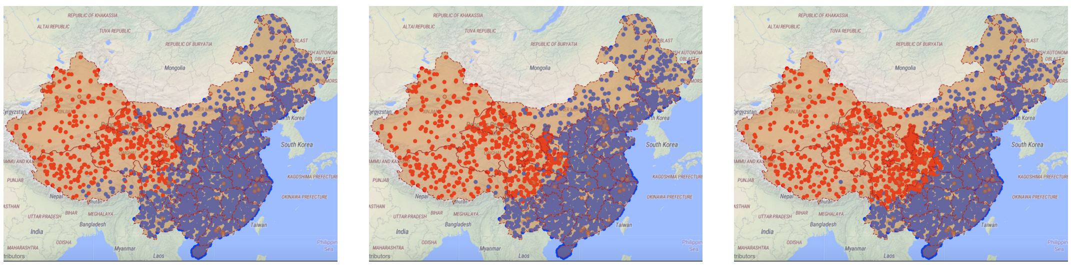


(a) Absolute population (b) Population density

Figure 6.3: Estimated absolute and density of population for areas in China for 2010
Source: Wang et al. [373] **License:** No. 5785350894322159 - see chapter 'Copyright Licences & Notices' for further information

6.6.1 By cargo value

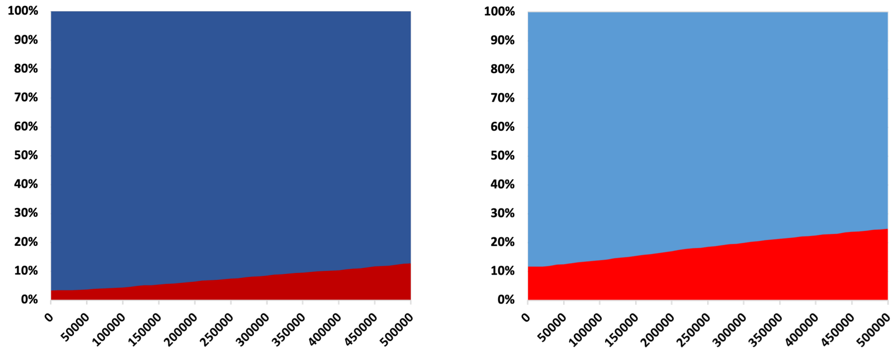
Assessment by cargo value is conducted specifically for the values of 100k€, 300k€ and 500k€. Additionally, a graph is created in 10k€ steps. Figure 6.4 depicts the geographical scope for the three different cargo values in a no carbon tax scenario and the graphs for the range. As the initial 100k€ scenario shows, the use of rail transport is definitely



(a) 100k € (b) 300k € (c) 500k €

Figure 6.4: Base scenario scope for exports from Hesse to China by cargo value
Source: Simulation model output

interesting for western and partially for central Chinese provinces. Yet, for these lower value goods, the scope within in China doesn't cover major urban centers aside from Ürümqi in Xinjiang. The higher valued cargo at 300k€ and 500k€ extend the potential scope of rail transport into the province of Sichuan, which has two major urban centers with Chengdu and Chongqing. As most economic power is located in the coastal regions



(d) Econon. share **(e) Area share**

Figure 6.5: Economic and area share in base scenario by cargo value
Source: Own design

in eastern and southern China, this scope of rail transport is not clearly competitive and might not attract much capacity. This also shows when comparing the share of potential rail transport by economic power of the respective provinces and by their land area as can be seen in figure 6.5. As can be seen, the economic power of the coastal provinces in China boost the economic share of maritime transport, whereas rail transport is attractive for less developed central and western provinces of China.

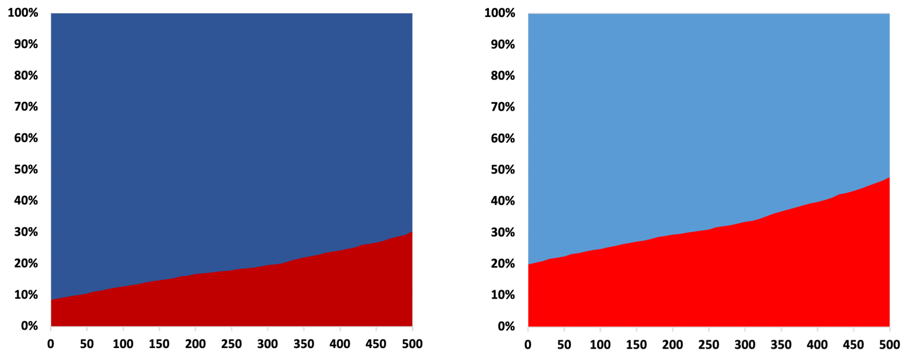
6.6.2 By (hypothetical) global carbon tax

When looking at different hypothetical global carbon tax rates, three significant tax rates are investigated. A tax rate of 50€ per emitted tonne revolves around the rate of this tax in Germany. Additionally, a rate of 200€ per tonne is investigated as a challenging rate. Finally, the rate of 500€ per tonne is investigated as an extreme scenario and to illustrate the difference to the other two scenarios. Figure 6.6 shows the different geographic scopes for the three carbon tax rates and economic and area share in a graph for 10€ steps of carbon tax rate. For all analysis a cargo value of 300k€ is assumed. A (hypothetical) global carbon tax would have a severe impact on the potential scope of rail transport from Europe to China. At rates of 50€/to the effects of such a tax slowly start to push the rail scope into densely populated areas of central China. When increasing the tax to rates

(a) 50€/to (b) 200€/to (c) 500€/to

Figure 6.6: Carbon tax scenario scope for exports from Hesse to China by different carbon tax rates at cargo value 300k€
Source: Simulation model output

of 200€/to, that effect is even more pronounced, doubling the expected scope. At the extreme scenario of 500€/to, the potential scope of rail transport is roughly quadrupled to a no-tax scenario Figure 6.7 shows economic and area share for the carbon tax scenario.



(d) Econ. share (e) Area share

Figure 6.7: Economic and area share in carbon tax scenario for different carbon tax rates at cargo value 300k€
Source: Own design

Effects are more pronounced in this scenario as also northeastern and large parts of central China become part of the potential scope for rail transport. While with a European carbon tax rate in the low to mid 2-digit range [338] an increase in the attractiveness of the CRE can be expected, for a noticeable change a much higher tax rate would need to be considered.

6.7 Conclusion & Outlook

This study contributes in two ways. First of all it presents a way to visualize the CRE scope using a GIS model. This visual representation helps in assessing its potential and to determine further focus points for investigation. Second, it provides analysis regarding the CRE for transport from central Germany to China. When compared to maritime transport, indications show attractiveness of the transport option for western and (depending on cargo value) central provinces of China. As these provinces are both landlocked and not yet as developed as the eastern coastal regions, capacity potential for rail transport seems limited. Important to keep in mind is, that pre-carriage and on-carriage are assumed to be conducted via trucking, which favors terminals in proximity to destination, giving rail transport over CRE even further advantage. The results therefore can be seen as the outer most scope. If maritime transports would utilize multi-modal inner Chinese transports, they would likely be at an even further advantage. Yet, the CRE is increasing in popularity nonetheless. Potential reasons for this can be the cargo value, specific needs for transport chains and certain constraints on the goods transported. Further investigations of customer structures, goods transported and mode choice characteristics is therefore needed to thoroughly understand the possibilities and usage of the CRE from a European perspective. Especially empirical investigations of customer mode choice for the CRE would be very interesting. As also a hypothetical carbon tax on all transport modes on low rates does not improve the competitive situation of the CRE by much. For a significant effect, such a tax would need to be raised to rates that likely causes additional economic side effects. As Hesse represents a rather well connected and located region in Germany and benefits of the CRE are not apparent for general cargo, shippers that utilize the transport mode could be investigated in in-depth interviews to gain inside.

For western Europe, the use of the CRE for transports to China has a limited target area and the case study at hand indicates, that for central German states the use of it only makes sense form transports to central Chinese provinces when comparing it to maritime transport. With further increases of transport speed, rail transport could be a potential rival to air freight transports, which is worthy of its own investigation. Additionally, the CRE offers connections aside from China. From Europe it would be interesting to reach the landlocked countries of central Asia. The potential of these connections and the implications for European trade and policy are worthy of further investigation from a European perspective as well. As the northern and trans-Siberian route as investigated in this paper have become part of political jeopardy, the southern route running through

Kazakhstan and Azerbaijan has sparked interest. Here also a European perspective on new possibilities of the route, its scope and a comparison to its northern counterpart would be worth to investigate. Finally, aspects of resilience for Europe-Asia trade have become a recent focus. The involuntary blockade of the Suez Canal through the Evergiven vessel, that led to a surge in additional costs for maritime shipping [176] and the lockdown on several Chinese ports due to COVID-19 restrictions had a significant impact on maritime shipping calls [15]. Also the land bridge is not free of disturbances as the Russian aggression on Ukraine from 2022 on has shown and impacted the rail connection tremendously [236]. Therefore, the usage of the CRE can also be seen from a resilience perspective, opening up its own set of research opportunities.

6.8 Appendix

Terminal	Route	CN entry	Dist. EU	Dist. BY|RU|KZ|MN	Dist. CN
Khorgos	Northern	Alashankou	1280 km	5310 km	200 km
Ürümqi	Northern	Alashankou	1280 km	5310 km	450 km
Lanzhou	Northern	Alashankou	1280 km	5310 km	2050 km
Xian	Northern	Alashankou	1280 km	5310 km	2700 km
Chengdu	Northern	Alashankou	1280 km	5310 km	3300 km
Chongqing	Northern	Alashankou	1280 km	5310 km	3400 km
Changsha	Northern	Alashankou	1280 km	5310 km	3550 km
Wuhan	Northern	Alashankou	1280 km	5310 km	3350 km
Yiwu	Northern	Alashankou	1280 km	5310 km	4000 km
Beijing	Trans-Siberian	Manzhouli	1280 km	6970 km	1750 km
Tianjin	Trans-Siberian	Manzhouli	1280 km	6970 km	1850 km
Qingdao	Trans-Siberian	Manzhouli	1280 km	6970 km	2300 km
Suzhou	Trans-Siberian	Manzhouli	1280 km	6970 km	2900 km
Shengzhou	Trans-Siberian	Manzhouli	1280 km	6970 km	3050 km
Shanghai	Trans-Siberian	Manzhouli	1280 km	6970 km	2950 km
Shenyang	Trans-Siberian	Manzhouli	1280 km	6970 km	1220 km
Yingkou	Trans-Siberian	Manzhouli	1280 km	6970 km	1380 km
Hongkong	Maritime	19200km			
Yantian	Maritime	19200km			
Xiamen	Maritime	19650km			
Shanghai	Maritime	20700km			
Qingdao	Maritime	21200km			
Dalian	Maritime	21500km			
Tianjin	Maritime	21500km			

Table 6.2: Distances for rail/maritime transport from Duisport/Hamburg estimated after Duisport [86] and Li et al. [200]

Name	GDP (Bn. CNY)	GDP (Bn. USD)	Share of GDP
Anhui	3868.06	560.80	3.81%
Beijing	3610.26	523.42	3.55%
Chongqing	2500.28	362.50	2.46%
Fujian	4390.39	636.53	4.32%
Gansu	901.67	130.73	0.89%
Guangdong	11076.09	1605.84	11.25%
Guangxi	2215.67	321.23	2.18%
Guizhou	1782.66	258.45	1.75%
Hainan	553.24	80.21	0.54%
Hebei	3620.69	524.94	3.56%
Heilongjiang	1369.85	198.60	1.35%
Henan	5499.71	797.36	5.41%
Hubei	4344.35	629.85	4.28%
Hunan	4178.15	605.76	4.11%
Inner Mongolia	1735.98	251.69	1.71%
Jiangsu	10271.90	1489.24	10.11%
Jiangxi	2569.15	372.48	2.53%
Jilin	1231.13	178.49	1.21%
Liaoning	2511.50	364.12	2.47%
Ningxia	392.06	56.84	0.36%
Qinghai	300.59	43.58	0.19%
Shaanxi	2618.19	379.59	2.58%
Shandong	7312.90	1060.24	7.2%
Shanghai	3870.06	561.09	3.81%
Shanxi	1765.19	255.92	1.74%
Sichuan	4859.88	704.60	4.78%

Tianjin	1408.37	204.19	1.39%
Tibet	190.27	27.59	0.19%
Xinjiang	1379.76	200.04	1.36%
Yunnan	2452.19	355.52	2.41%
Zhejiang	6461.33	936.78	6.36%

Table 6.3: Economic statistics for mainland Chinese provinces (excl. Hongkong and Macao) after National Bureau of Statistics in China [264]

7 Conclusion

Combined transport systems are complex ways to organize freight transportation. The increased need for coordination, their complex environment regarding policy, infrastructure and technology make improvements to combined transport systems challenging. Yet, the importance of sustainable transport options especially in Europe can't be underestimated, especially with self set climate goals. Additionally, combined transport systems provide extensive transport capacity and with expected continually growing transport demands the use of combined transport seems inevitable. Therefore, making these transport systems function properly and efficiently is important for the transport markets in Europe, yet a complex task, which does not have simple answers. A coordinated effort of multiple stakeholders to achieve these goals is inevitable. In order to improve combined transport systems, a practice-oriented view is helpful, yet research can contribute by providing analysis and guidance to effectively find effective ways on how to improve.
This dissertation contributes to European combined transport systems research two-fold. First, it provides a list of potential practical measures, a meaningful subset of all available options, and a synthesis of research of the past decade. The goal hereby was to provide guidance for practitioners and researchers alike. Aside from findings from primary practice-oriented input and secondary literature based data, the synthesis of both concludes in 6 research topic areas that give guidance on focus of future research efforts. Second, it provides analysis of two case studies in relation to intermodal transport systems and their current developments in and with regard to Europe. The first case study takes a look at the potential effect of a recently implemented sustainability policy on established intermodal transport networks regarding the hinterland of ports. With the help of a simulation model the potential hinterland of these ports can be analyzed and made visible for further assessment. The second case study takes a look at export opportunities for Hessian exporters utilizing the trans-Siberian railway connection to China. This case is especially interesting as it takes a look at a large infrastructure project where intermodal transport is a key component. The trans-Eurasian corridor's benefits are quite apparent for eastern European and land-locked central Asian countries. With Hesse as a centrally

located state in Europe, the apparent benefits don't show clearly. Hesse is at the fringe of economic viability for utilizing rail-bound transcontinental transport. It is a viable option for transports to western and parts of central Chinese provinces. Additionally the (hypothetical) implementation of a world-wide carbon tax was tested. The impact of such a tax does not severely impact the competitive situation of rail-bound transport when assuming reasonable tax rates. As the development of this corridor is on-going , it provides an on-going pool for interesting research opportunity.
Research in transportation, especially with a focus on combined transport, is inherently practice-oriented as research projects are usually driven by needs from practise. While operational improvements, especially through quantitative optimization research, can make transports more efficient, transport systems are still socio-economic systems with a multitude of variables difficult to map with quantitative approaches. Improving the understanding of intermodal transport systems, especially through qualitative and analytical research is therefore necessary for a thorough understanding of it. Strategic and long-term developments in the sector should be assessed and accompanied by meaningful research to reduce uncertainties of deciders in the sector. Sincere hopes are that this dissertation can contribute and interested readers find inspiration.

7.1 Recap

The dissertation at hand consists of three studies in total. The results of the studies built upon each other and provide consistency within this work. The first study creates a practice-oriented research agenda. It does so by utilizing the Delphi method to create a subset of potential measures on how to improve intermodal transport systems in Europe. A total of 27 measures, ranging from improving policy, infrastructure, coordination and technology, have been identified. The measures, as extensive as they are, only provide a subset of potential measures. For further assessment, and better comprehension, these measures have been grouped into a total of 8 generalized categories. In a second step, intermodal transport research for Europe of the last decade, regarding qualitative, analytical and empirical studies has been analyzed and categorized according to the previously determined generalized categories. By doing so, the research of the last decade on combined transport can be assessed with a practical view. With the results of the practice-oriented input and the scientific overview, a synthesis of the results of both methodologies was conducted. This has led to the development of 6 research topic areas for promising and impactful research. They provide inspiration and recommendations for practitioners, policy makers and researchers alike.
Focusing on the research topic area of sustainability policy assessment, a case study

investigating environmental policy changes has been conducted. As a carbon tax has recently been implemented in Germany, the effects of this policy on port hinterland scope is investigated. Hereby, a special focus is put on the situation of North Rhine-Westphalia, as it provides an interesting case in this regard. It is a state located in proximity to 5 major ports of the northern range, with a multitude of intermodal connections both for rail and barge and an extensive road network. It also ranks highest by population among all German states and has the highest import and export volumes. The proximity to the ports makes NRW an ideal case for investigating port hinterland competition as it is located within the economic range of intermodal transport and with a similar distance to all ports mentioned. The case of NRW as a contested port hinterland has been depicted in a GIS model with all relevant intermodal connections, terminals and road network. The simulation of this model allows for the assessment of different levels of carbon tax by both showing the percentage and geographic coverage for each port and more. The competitive situation of the ports and their potential hinterland scope was analysed in this regard. The analysis shows that a shift towards rail transport and the Port of Rotterdam is likely to occur, yet there are areas which likely stay uncontested both on mode and port base.

Finally, the third study takes a look at the new transport possibilities utilizing the rail connection between Europe and China. The transport option is propagated and partly subsidised by the Chinese government. This lead to the creation of an imparity, as exports from Europe lack behind. This imparity is leading to inefficiencies for the transport option and unnecessarily increases its costs. Yet, a growing number of cargo is transported using the route. To assess which scope the new transport option has for central Germany, the case of Hesse has been investigated. Hesse presents an interesting case in itself as it has an export oriented economy, is well connected both to maritime and rail-bound transport options and is located both in central Germany and Europe. By developing a cost-based GIS model, the Eurasian rail connection is depicting and the potential scope for Hessian exporters to China can be visually analyzed. It shows that the rail connection can be economically suitable for general cargo to destinations in western, central and north-eastern China depending on cargo value. Additionally, a (hypothetical) carbon tax (as proposed in 2023 collectively by various African leaders [21]) is investigated. As rail transport can potentially be run fully on renewable electricity, this would heavily benefit it. Yet, due to the distance and efficiency of maritime transport, no clear advantage for rail transport shows for meaningful carbon tax rates.

7.2 Contributions

The overall goal of this dissertation is to contribute to the understanding and strengthening of combined transport in Europe. Combined transport not only provides a meaningful and resource efficient way to move large quantities of freight. Due to its complexity it provides plenty of opportunities for research and optimization and additionally is a challenging field to work in. The studies conducted for this dissertation contribute overall to the body of knowledge on combined and intermodal transport. A main contribution is providing an up-to-date view on current issues within combined transport systems to help policy makers, practitioners and researchers on focusing resources and efforts. Additionally, the studies conducted have their distinct contributions.

The first study, the development of a practice-oriented research agenda on combined transport in Europe, has three major contributions. First and foremost, the research agenda developed can aid practitioners, researchers and policy makers alike on focusing resources and efforts. It presents six topic areas that are promising for upcoming investigations and investments in the sector. As the study consists of two distinct methodologies, linked through content assessment, the outcome of each methodology also stands on its own. The Delphi method conducted determined 27 measures on how to improve combined transport systems from the four thematic areas of policy, infrastructure, cooperation and technology. They alone are interesting insight into pressuring needs from practice and can be used to determine which problems to address in combined transport. Additionally, a systematic literature review has been conducted for qualitative, analytical and empirical research of the last decade regarding combined transport. Here, researchers can find guidance on which topics to work on further as it shows which broader thematic categories have been addressed. The second study developed a simulation model to assess port competition through hinterland accessibility. Looking at the ports in the northern range, the heavily contested state of North Rhine-Westphalia has been investigated as a case. While this case stands on its own as a unique case, it shows how environmental policies can have an impact on the competitive situation of infrastructure components. This is especially relevant for combined transport that heavily relies on infrastructure for its proper functioning. While this only represents one, yet rather unique, case of port hinterland competition, the methodology and ideas presented in the study can easily be transferred to other interesting regions. Also, due to the on-going climate crisis, environmental measures might rather increase than be cut back. Therefore the study at hand provides an approach on how to analyze their impact. Finally, the third study deals with transport opportunities for Hessian exporters utilizing the CRE to China. While the relation is heavily subsidized by the Chinese government for transports westwards to Europe, interest in utilization of this relation is not likewise on the European side. The study investigates for which relations this new opportunity makes sense based on a cost-based view. Especially for exporters in Hesse the study indicates that the relation is interesting for exports to western and parts of central China. As this relation is utilized, further investigations on current shippers and empirical investigations on mode choice should occur. Interestingly, a (hypothetical) global carbon tax has the potential to improve the competitive situation of the relation. Yet, the rate must reach levels currently unimaginable to be agreed on by several world leaders.

7.3 Limitations

The studies conducted for this dissertation have several limitations. Generally, as this dissertation has collected or utilized empirical data, the results are based on the validity of this data. Especially for exploratory input and qualitative analysis this presents a general limitation of the dissertation. With more extensive data collection validity can improve, yet data was collected and analyzed as objectively and transparently as possible. Also, as the results reflect the current situation of combined transport in Europe, they represent insight into the respective time span. Additionally, the studies in themselves have their own limitations which are introduced subsequently.

The first study generates a practice-oriented research agenda based on input from practitioners and research based on the last decade. While this synthesis provides an overview of both worlds and their distinct focus, it needs to be stated that especially the input from practice is limit by the selection of participants. As the aim was to obtain a rather broad approach to the topic, more specialized and operative participants would potentially yield more precise and diverse results. Also the obtained potential measures can just be seen as a subset of all potential measures. This was attempted to be mitigated through further analysis and grouping within generalized categories to increase general validity, yet additional measures might have provided potentially additional results. Also the final results, especially the practice-oriented research agenda, is based on the analysis and interpretation by the author. As thorough as it has been conducted and the objective reasoning laid out, a total elimination of personal bias is difficult to achieve. This is a distinct limitation of qualitative research in general, but it applies to this study explicitly.

The second study regarding the competition between ports through their hinterland connectivity employs a simulation model of intermodal transport. While the model utilized catches the main components of intermodal transport well, the complexity of such models can always be increased and made more precise. Especially the choice model for transport modes could incorporate additional stochastic functions and with the help of Monte-Carlo simulations validity can potentially be increased. Additionally, aspects of mode choice

beyond cost-based aspects of shipper, could be incorporated as well, while the cost-based view was regarded as sufficient for the study at hand. For further assessments, more complex mechanisms of mode choice could mitigate this, yet the advantage of the higher complexity needs to be further assessed. Also the study investigates just one specific state in Germany regarding the implementation of a carbon tax and should be read as the case study it is. Generalization of results need proper investigation of further cases, which can be achieved by transferring the methodology to other interesting regions.
Finally, the third study investigates new transport opportunities for Hessian exporters. Hesse, as a state in central Europe, represents an interesting case in this regard as it lies in the center of one of the most powerful economic areas in the world. Connecting the EU and China by rail, the CRE offers plentiful of interesting opportunities. Due to its young age, the transport option is constantly changing with different terminals used and changes in the political or economic climate. The study looks at a very limited case and how transports might make economic sense to China. The results are meant for general cargo in a limited value frame. A generalization that the relation is unattractive for use can only be drawn for the cargo and transport parameters set and keeping in mind the simplifications of the case study. Further cargo properties should be investigated as well, as current utilization of the route shows a practical need for it. Further investigations must therefore take place, even more so as this study is meant as a first glimpse from a European perspective on the issue.

7.4 Outlook

This dissertation has investigated various aspects of combined and intermodal transport. Aside from the overall assessment of potential it has investigated two specific case studies. All studies have the potential for further research. First and foremost, the aspects of the practice-oriented research agenda not investigated in the case studies at hand should receive attention. Especially the emerging field of digital platforms for the booking of services and exchange of data within intermodal transport systems is a promising field to foster the transport mode. As various platforms are currently establishing themselves on the market, investigations regarding their functioning and economic viability are promising. Same with technological developments in rail transport. DB Cargo has developed a modular and multi-functional wagon for rail transports, that aside from traditional heavy rail cargo like timber and metal coils can also be used for intermodal transport after modification. Also the developments of the implementation of ETCS will likely have an impact on the reliability and competitiveness of intermodal transport systems and should be accompanied through research. Aside from these technical aspects of intermodal transport, a deeper investigation of specific actors can yield interesting results. Especially the role of terminals, with their central location within the intermodal transport system, has the potential for expansion of their functionality and strategic role. Finally, a rather neglected area for research, is the role of humans within the system. Knowledge regarding the complexity of intermodal transport, how to use the system as a forwarder and for which forwarders it is useful, alignment of education needs and offerings, can all be promising investigations.

The investigated individual studies also have the potential for further assessment. The practice-oriented research agenda only presents a subset of potential measures to improve intermodal transport systems. For a thorough assessment, focus group investigations, e.g. with a specific group of intermodal actors, can provide more in-depth insights. Also a further confirmation of the results through surveys to derive statistically sound advice would be helpful. Finally, as intermodal transport systems are ever-changing, a re-investigation of the study in a meaningful time span can allow for both a chronological assessment and accompany the developments in the sector. The GIS model and simulation of the case study regarding port hinterland competition in the northern range in Europe can potentially be applied to other interesting areas, especially the Mediterranean range of European ports. The Port of Piraeus is especially interesting in this case as its capacity and hinterland networks are heavily expanding due to Chinese investments. Also the developments regarding the TEN-T corridors, especially the Rail Baltica that aims to connect Helsinki in Finland in a direct rail connection to Berlin in Germany will have positive effects on intermodal transport capacities and the impact of its completion can be estimated with a GIS model as well. Within the model itself, further policies can easily be implemented and their effect on the competitive situation within the hinterland assessed.

The third study dealing with Hessian exports to China leaves plenty of room for further investigation. First and foremost, the environment the CRE operates in is constantly changing. Being dependent on the cooperation of several countries, a thing not necessary for maritime transport due to the open seas, makes political assessments of developments of the route mandatory. Nonetheless, the CRE presents a way to mitigate transport risks as the blockade of the Suez Canal has shown. How this affects mode choice and utilization of the CRE, how it is marketed and who uses it are all valid further topics for further assessment. Especially empirical and qualitative assessments of shippers and intermodal operators might be very fruitful in this regard on how they utilize the transport corridor and which pitfalls it provides.

Railway systems have come a long way. First established in the industrial revolution they are still ever evolving. Combined transport systems are a fairly young phenomenon that likely increases in relevance. It is interesting to see not only how technology impacts combined transport, but also how the complexity of combined transport systems evolves.

A lot of unsolved problems are in dire need for investigation. The European economy requires combined transport for both economic and sustainability goals. Therefore, sincere hopes are that further impactful research contribute to the strengthening of the transport mode and that this work provides guidance and inspiration on how to achieve this impact.

Figure 7.1: Generated artificial picture from tags based on content of dissertation
Source: Generated with DeepAI [73]

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