Chair of Industrial Logistics

Doctoral Thesis

Decarbonization of Industrial Logistics: Understanding and Supporting Strategic and Operational Initiatives

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Dedicated to those for whom this thesis might be an inspiration for greening our planet Earth.

Abstract

According to the recent report by the Intergovernmental Panel on Climate Change, the decisions made about reducing greenhouse gas emissions during the next decade will have a definitive impact on how severe the consequences of climate change will become. As all corners of the world have agreed that the worst-case scenarios presented by the IPCC and other research institutions are not desirable for human well-being, all countries, regions, sectors, companies, and other economic and non-economic entities have been or will be required to meet stringent emission reduction targets in the coming decades. One sector that will be hit hard by such reduction targets or emission taxes is transportation, since avoiding transportation is associated with the undesirable concept of sufficiency, and technological advances are costly and tedious. Particularly challenging is the freight transport sector, which due to its complexity and cost pressures, presents significant obstacles to decarbonization. As sustainable innovations were discovered to diffuse downstream the supply chain, one of the most important actors in the decarbonization of transportation is the transportation principal and buyer – which is, for freight transportation, the freight owner. This entity determines the importance of logistics indicators such as costs, lead time, and emissions. It is exactly because of this reason that this thesis investigates the decarbonization of transportation from the industrial perspective which is commonly known as industrial logistics.

Therefore, the aim of this thesis is to close the gap between the well-researched field of Green Supply Chain Management and the under-researched field of industrial logistics decarbonization. Answering four overarching research questions that were delineated from existing research contributes to the scientific body of knowledge regarding strategic and operational perspectives and provides industrial logistics practitioners with effective decision-support. Throughout the publications that emerged from this thesis, various in-depth research questions were answered, providing nuanced insights in the decision-making process in industrial logistics, thereby enhancing the understanding of these processes. Subsequently, this increased understanding of strategic and operational decisions that have already been made by industry practitioners was utilized to develop several tools that effectively support future decisions on this field by practitioners. Conclusively, an approach on how to decarbonize industrial logistics most effectively was developed and based on the evidence gathered throughout this thesis. For the scientific community, the transdisciplinary studies conducted by the authors brought up research gaps and ideas for future directions.

In brief, this thesis yields scholarly contributions that enable researchers to understand how industrial freight owners comprehend and implement decarbonization in transportation. It also provides benchmark data from Austria and offers several tools for practitioners to assess decarbonization possibilities in their Scope 3 upstream and downstream transportation activities.

This thesis presents the research context and frame, delineates the overarching research questions, summarizes the scholarly publications and their contributions to answering the questions, and conclusively presents implications for practitioners and researchers.

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1. Introduction

With the summer of 2023 having ended, we can conclude on an outstanding period regarding climate change. On the one side, the impacts of climate change have become economically devastating. In 2022, severe floods in Pakistan are estimated to have caused $40 billion of losses (Mangi, 2022); draughts in America have reduced water levels on the Mississippi, a global bottleneck in food supply chains, costing the economy $20 billion (Balbi, 2022); and similar events in Europe caused shipping on the Rhine to almost standstill (Thomson, 2022). This trend continued in 2023, as for example hurricane-fueled wildfires devastatingly destroyed the Hawaiian city Lahaina (Fuller, 2023); heatwaves in Europe threatened economically important touristic activities (Wittels, 2023); or inadequate infrastructure combined with an unstable political situation and one night of record rainfall caused 15,000 Libyan people being dead or missing (Millan and El Wardany, 2023). All in all, the summer of 2023 was Earth's hottest since records began in 1880 (NASA, 2023). On the other side, positive news has been around regarding the mitigation of climate change. The US passed the Inflation Reduction Act – an economically motivated program including $370 billion of climate spending (Newburger, 2022). The EU reached a provisional political agreement on the Carbon Border Adjustment Mechanism, a tax designed to hit low-cost and carbon-intensive imports into the EU (Simões, 2022). Finally, in the last hours of the COP27 in Sharm el-Sheikh, the Conference of the Parties decided on a loss-and-damage fund that supports developing countries in fighting the impacts of climate change (UNFCCC, 2022).

Besides these catchy headlines, 2022 and 2023 brought ample scientific evidence for the impacts of climate change and possible actions. With the Intergovernmental Panel on Climate Change (IPCC) having published its Synthesis Report for the Sixth Assessment Report, about 15,000 pertinent studies on the physical science basis of climate change, its impact, and possible adaption and mitigation strategies have been collected, analyzed, and synthesized. To conclude on these reports – it is unequivocal that the frequency and severity of, e.g., extreme-weather events, rising sea levels, and forest fires have increased; that this development is connected to the earth's rising surface temperature; and that those rising temperatures correlate to anthropogenic greenhouse gas (GHG) emissions. In other words, humans have – with very high confidence – caused all the impacts they are suffering from right now and will have to deeply reduce emissions in the coming decade to prevent more serious damages (IPCC, 2021, 2022a, 2022b, 2023).

1.1. The Need to Reduce Industrial Logistics Emissions

1.1.1. From the Logistics Perspective

As rising GHG emissions were proven to correlate with the number and intensity of damages to human-built infrastructure (IPCC, 2021), emissions from transportation contribute to endangering global transport systems (Jaramillo *et al.*, 2022, p. 1057; Koetse and Rietveld, 2009). Evidence exists that all modes of transport have already been or will soon be affected by the impacts of climate change. Rising sea levels and flooding events, for example, threaten international shipping by increasing challenges for ports (Pérez-Morales *et al.*, 2019; Portillo Juan *et al.*, 2022). At the same time, heat-wave-induced low water levels and strong winds on inland waterways hinder efficient capacity utilization or navigation at all (Liu *et al.*, 2019). Railway tracks expand with high temperatures and cause delays or derailments – cumulated economic costs of which are estimated to be 25-60 billion US Dollars in the United States until 2100 (Chinowsky *et al.*, 2019). Similarly, volatile and extreme temperatures negatively affect the lifetime and quality of road pavements, which increases construction and maintenance costs as well as delays in the road transport network (Underwood *et al.*, 2017).

Nevertheless, some climate-change induced developments also bear potential for transportation. For example, decreasing ice levels in the Arctic enables shipping companies to route ships on polar shipping routes (Rodrigue, 2020). Conflicting scientific studies exist on its effects on the ecosystem – some report on the high sensitivity of Arctic climate on local emissions (Sand *et al.*, 2016), while others report temperature cooling effects due to the formation of liquid water clouds and increased albedo (Stephenson *et al.*, 2018). This already demonstrates the difficulty of assessing the impact of new practices and technologies on climate and highlights the importance of holistic and grounded considerations.

1.1.2. From the Global Perspective

In 2019, the sector emitting the highest emissions was the industry, accounting for 24% of direct global GHG emissions (Dhakal *et al.*, 2022, p. 237). Besides these direct production-based emissions, the importance of accounting for indirect consumption-based emissions is highlighted frequently, e.g., by the Greenhouse Gas Protocol. These days, reallocating emissions from heat and electricity is frequently done by practitioners (WBCSD and WRI, 2004) and researchers (Dhakal *et al.*, 2022, p. 237) in Scope 2 reporting. If these emissions are distributed among the other sectors, industry is responsible for 34% of GHG emissions (Dhakal *et al.*, 2022, p. 237). Furthermore, the consumption-based perspective suggests including Scope 3 emissions that cover the pollutants emitted in the corporate value chain, of which up- and downstream transportation and distribution are a core part (WBCSD and WRI, 2011, p. 33). Globally, the transport sector emits 15% of all GHGs, about one-third of which stems from freight transport. Further attributing these emissions to the industry raises the global share by another 5% to 39% (Dhakal *et al.*, 2022, p. 237; Ritchie and Roser, 2020), making the industry responsible for nearly 40% of global GHG emissions. This not only highlights the relevance of decarbonizing industrial transportation from the global perspective but also from the industries' perspective per se.

1.1.3. From the Industrial Perspective

Transport emissions begin to plateau in Europe, Australia, Japan and New Zealand (Jaramillo *et al.*, 2022, p. 1055), although transportation demand kept increasing over the last years (ITF, 2019; OECD/ITF, 2015). On the one side, these are good news from an environmental perspective – indicating that specific transport emissions are decreasing, at least in those regions. On the other side, this also implies that all efforts that are currently undertaken only make it for compensating economic growth – which is not enough for reducing emissions and reaching ambitious climate goals.

Furthermore, freight transportation demand is expected to double by 2050 from the 2019 level under current policies (ITF, 2021a, p. 61). This is supported by projections of the International Energy Agencies' World Energy Outlook – diving into which reveals an increase in global oil demand for freight transportation until 2030 in all scenarios (IEA, 2022b, p. 333). In this respect, it is not to be expected that major emission reductions will be achieved in freight transport soon. This is a worrying development as it contrasts with developments in passenger transport, the oil demand of which is estimated to remain constant at worst (IEA, 2022b, p. 332).

Especially in Europe, which is a region having one of the highest levels of awareness of climate change worldwide (Lee *et al.*, 2015), and, in general, rising awareness for environmental protection in the last years (Bacsi, 2020), this will put additional pressure on industrial freight transport due to changing institutional environments. Already in 2020, 80% of European citizens believed that "big companies and industry" were not doing enough to reduce their environmental impact (European Union, 2020). This results in environmentally conscious buying behavior, increased stakeholder pressure, and the prospect of new laws for environmental protection. To deal with those pressures, firms are predicted to adopt their processes towards more environmentally friendly operations (Latif *et al.*, 2020; Neri *et al.*, 2018; Collins *et al.*, 2010; Merli *et al.*, 2015). The urgency for those adoptions depends on the proximity of the firm to the end customer (Seles *et al.*, 2016), and thus the industrial sector (Maccarrone, 2009).

1.2. The Need to Foster Research on Industrial Logistics Decarbonization

Industrial firms impact the environment through a multitude of operations, often categorized into the three operations management practices "products", "processes", and "logistics". Understanding barriers, drivers, and mechanisms in those practices was shown to be a crucial step towards reducing GHG emissions from the industry (Seles *et al.*, 2016). While recent research finds current practices on the product and process level to already reduce GHG emissions, measures implemented in in- and outbound logistics do not yet reach their expected reduction potential (Lopes de Sousa Jabbour *et al.*, 2021), albeit those processes are primary activities for industrial firms (Porter, 1985). Scientific literature has been aware of this problem for more than 30 years – the earliest pertinent study found by the keywords "Transport" and "Carbon Emission" on SCOPUS dates to 1991 (Leach, 1991); and at least since the mid-2000s, the number of studies hit the roof, as visualized in Figure 1. Similarly, emissions from transportation did. The stacked area chart in Figure 1 further visualizes global GHG emissions from transportation, increasing steadily with two major exemptions – the economic crisis of 2009 and the pandemic of 2020. Although final datasets for 2021 and 2022 are not available by the time of writings, all evidence indicates that the rebound from the latest crisis will let emissions hit an all-time high, again (IEA, 2022a).

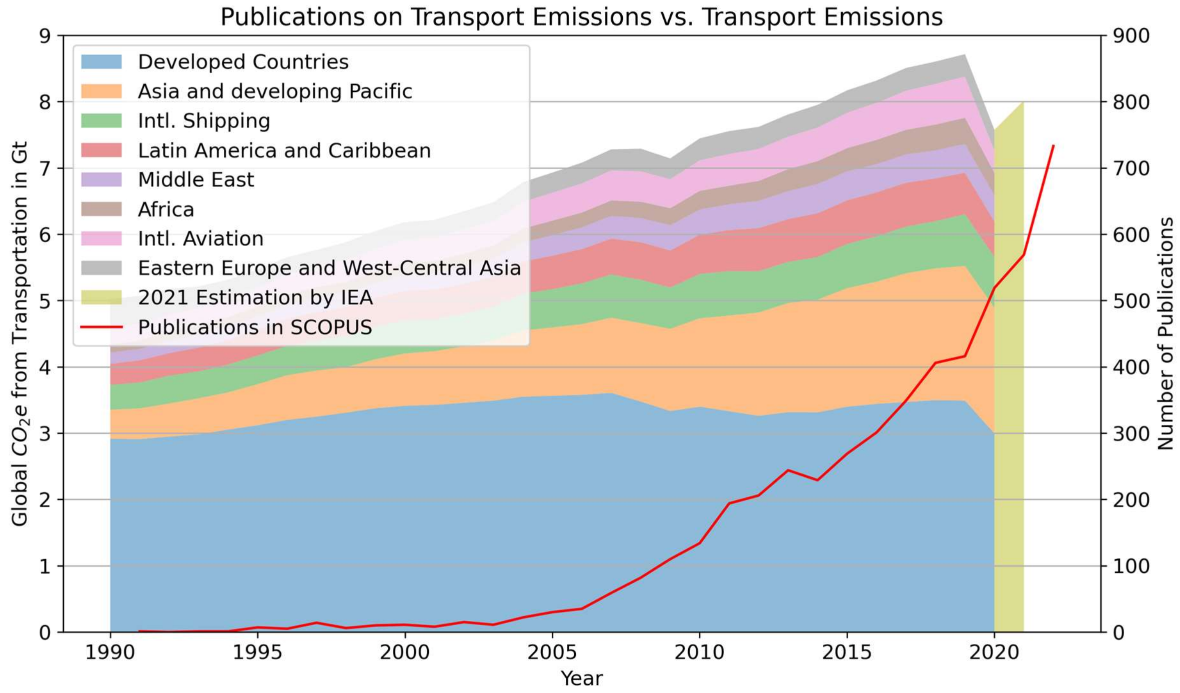

Figure 1. Historic transport emissions and publications on them (own illustration based on data from https://www.scopus.com, Minx et al., 2022, and IEA, 2022a)[1]

It seems that, in developed countries, research, awareness and incentives for lower-carbon technologies and practices in transportation have been high enough to at least offset economic growth in terms of emissions. In future, initiatives to reduce specific emissions will have to increase drastically to meet ambitious climate goals and withstand rising institutional pressures. Therefore, this thesis aims at supporting decision-makers in industrial logistics to make decisions that comply with future environmental awareness and regulations – by providing competitive operations at the same time.

1.3. The Research Exemplified by Austria

Historic data indicates Europe is slowly reaching a plateau in transport emissions (Jaramillo *et al.*, 2022, p. 10). On the one side, these are good news because transportation demand has increased over time (ITF, 2019), meaning that specific emissions per passenger and ton have started to decrease. On the other side, investigating this finding in more detail reveals another challenge: The low-hanging fruits in decarbonization, i.e., measures that are easy to find and implement, are already being implemented on a large scale (Mir *et al.*, 2021). Those measures are important, but still, only compensate for the rising demand for transportation. Further advancements in transport decarbonization request novel technologies and practices – which are often complex and costly and thus neglected by logistics companies due to the competitive nature of freight transportation (Rodrigue, 2020).

[1] Global transport emission values are calculated based on the finding of IEA (2022a) that in 2021, transportation-related emissions remained 8% below 2019 levels due to various lockdowns and supply chain disruptions.

While the largest long-term decarbonization potentials are seen in non-OECD countries (Taptich *et al.*, 2016), firms in Europe will be faced with higher degrees of awareness of climate change (Lee *et al.*, 2015). Thus, the implementation of more costly and complex measures in those firms will be necessary in the long-term – highlighting the need to investigate those countries in detail to guide practitioners in finding novel and competitive measures and practices to lower carbon emissions.

Regarding logistics, Austria is thereby an interesting case due to its challenges in freight transportation. Geographically, the country is a small land-locked territory in central Europe, having a well-developed and maintained land transport infrastructure (Schwab, 2019), a decreasing freight transport volume on inland waterways (ITF, 2021b) and no sea access. Regarding emission reduction measures, many low-hanging fruits are already in use. A fuel-efficient driving style for truck drivers has long been just as much a part of good manners as driving bans for trucks with low exhaust emission classes (WKO, 2022a, 2022b). Shifting transport to rail is, statistically, more common than in the European average, as the modal share of rail transport in Austria outstands other European countries (European Union, 2021). Regarding zero-emission vehicles, the future regulations and infrastructural development are still unclear. Although hydrogen-powered trucks are credited with overcoming some disadvantages of battery-electric trucks, a decision on the further roll-out of hydrogen for road transportation is postponed to 2024-2026 in the Austrian hydrogen strategy due to the alignment with other European countries (Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology, 2022a). Current fluctuations in electricity prices also increase uncertainties in the Total Cost of Ownership calculations of electric trucks (Müller, 2022). In addition, there is a sparse charging infrastructure for trucks (Schwendlinger, 2022), an elimination of which would be necessary for the efficient operation of trucks in heavy-duty long-distance transport (Unterlohner, 2022). Firms that are exposed to such uncertainties tend to mimic other firms (Zsidisin *et al.*, 2005) and thereby reduce financial risk rather than environmental risk (Zhu and Sarkis, 2007; Miemczyk, 2008), which hinders progress in reaching climate goals.

Furthermore, to the best of the authors' knowledge, no empirical evidence exists that sheds light on the measures and practices that are currently in practice among Austrian logistics practitioners, in comparison to other European countries, e.g., Germany (BVL, 2022), Lithuania (Vienažindienė *et al.*, 2021), Croatia (Petljak *et al.*, 2018), or Slovakia (Richnák and Gubová, 2021). This increases difficulties in conducting meaningful research and developing effective implications for further emission reductions in Austrian logistics.

In conclusion, several challenges exist in formulating actionable recommendations for Austrian companies, as it is unclear to what extent measures are already in use in Austria, which sectors should be prioritized initially, how to improve modal shift, and what regulations will be in law for alternative drives and fuels in the future.

1.4. The Structure of this Thesis

In order to meet the modern requirements of international research, especially in the field of Supply Chain Management, Industrial Engineering and Logistics, and to guarantee a high quality of studies and results, this thesis has been written cumulatively. Therefore, the main purpose of this dissertation is to define the framework of the individual publications and to work out their connection and contribution to the overarching question. To this end, the object of investigation is precisely defined at the beginning of Section 2. This is followed by a review of the current state of policy initiatives and scholarly work, from which the four overarching research questions are derived. Section 3 discusses the methodological approach of the dissertation, followed by the presentation of the nine academic contributions in Section 4. These are briefly summarized and their contributions to answering the research question are systematically presented. Section 5 describes how additional work beyond the publications has contributed to the achievement of the objectives, before section 6 concludes the thesis with a discussion and the derivation of recommendations for action. Figure 2 visualizes this structure.

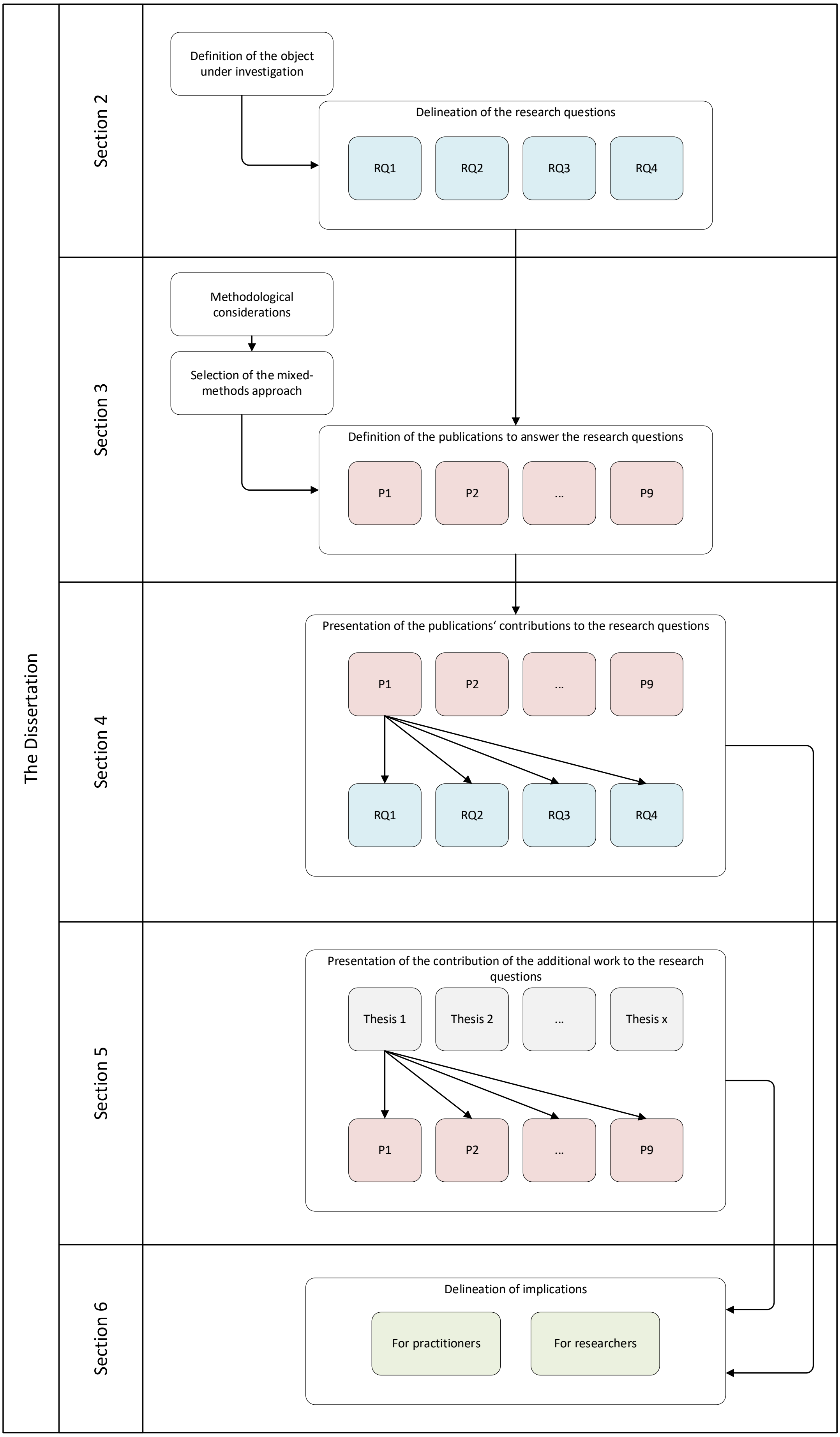

Figure 2. The thesis' structure (own illustration)

2. Background and Research Questions

2.1. Definitions and Theoretical Framework

2.1.1. Industrial Logistics

Following the definition of logistics made by the Council of Logistics Management (CLM), logistics is "that part of the supply chain process that plans, implements, and controls the efficient, effective forward and reverse flow and storage of goods, services, and related information between the point of origin and the point of consumption to meet customers' requirements." (Riopel *et al.*, 2005) Extending this definition by the industrial perspective, we understand industrial logistics as the logistics activities necessary for industrial firms to plan, implement, control, and continuously optimize "efficient material flows and the related information flows to satisfy customer requirements." (Woschank *et al.*, 2021) Different sub-systems of industrial logistics exist, thereby. One approach to distinguish those is having in mind the boundaries of the focal firm – i.e., separating inbound, inhouse, and outbound logistics (Zsifkovits, 2013). Another, cross-departmental approach to this is the division of industrial logistics into its functions, mainly described as transportation, warehousing, packaging, data management, and sometimes waste management (Vienažindienė *et al.*, 2021; Centobelli *et al.*, 2017).

2.1.2. Sustainable, Green, and Decarbonized Logistics

The topic of this thesis, decarbonization of logistics, can be subordinated to the much broader field of "sustainable" logistics. Although "sustainable", "green", and "decarbonized" logistics are often used as synonyms, "sustainable" logistics includes all aspects of sustainable development, i.e., environmental, economic, and human aspects (World Commission on Environment and Development, 1991). Operationalizing sustainability is a challenge in all disciplines, for which a lot of research under the umbrella term of "sustainability reporting" exists (Lenort *et al.*, 2022; Siew, 2015), and several reporting frameworks have been developed (e.g., UNCTAD, 2022; GRI, 2023). "Improving" sustainability thereby refers to improving individual metrics in the sustainability scorecard – which, in turn, often leads to the deterioration of other metrics. This difficulty of globally "optimizing sustainability" is why the research area of multi-criteria decision-making is very prominent in the sustainability debate (Lindfors, 2021; Buchert *et al.*, 2015; Ren, 2020).

"Green" logistics, in our understanding, thereby refers to the multiplicity of environmental impacts of logistics, by, first, consuming provisioning services from the ecosystem, i.e., using energy, raw materials, water, air and land, and, second, returning emissions in form of pollutants, greenhouse gases, waste and noise to the environment (Deckert, 2016).

Specializing this even further to the emission of GHG allows for the definition of decarbonizing logistics, i.e., lowering GHG emissions from logistics. Thus, "decarbonized" logistics is the vision of making logistics at least net-zero and refers to all initiatives reducing the use of fossil fuel in logistics. As elaborated in the introduction, GHG emissions from industrial logistics account for around 5% of global GHG emissions. One of the largest drivers are thereby international supply chains of industrial companies that are necessary to transport goods over long distances (McKinnon, 2018). Although logistics activities generate several environmental impacts, GHG emissions have become a universal metric in describing those impacts (Lohre and Gotthardt, 2016) and are seen as the most urgent one to deal with. The main emitter of those emissions in logistics are activities in the transport chain, so this thesis solely concentrates on those emissions. Besides emissions from transportation, other logistics activities for which green practices are researched are, for example, green warehousing, green packaging, green administration and logistics data management, and sustainable waste management (Vienažindienė *et al.*, 2021).

2.1.3. Transportation and its Emissions

In this subchapter, a brief and non-exhaustive overview of the freight transportation system and its GHG emissions is provided, focusing on Austria. Diving deeper into the characteristics and statistics of freight transportation would go beyond the scope of this thesis.

2.1.3.1. Modes of Transportation

Transportation, in general, can be described as the change of goods location with technical aids (Pfohl, 2018). Many different versions of such technical aids, commonly known as vehicles, exist – and can broadly be categorized according to the surfaces they use – Land, Water, or Air. The term mode of transport refers more specifically to the type of infrastructure required for the means of transport of that mode (Rodrigue, 2020). For example, trains are floor-bound means of transportation that require rails. Figure 3 provides an overview of modes of transport, types of means of transport, as well as most common transport products in global supply chains.

Mode choice, thereby, depends on the requirements of the transport service, as every mode encompasses its characteristics. Trucks, for example, are the most flexible means and usually the cheapest option for short to medium distances (Rodrigue, 2020). Trains are capable of cheap mass transportation and higher average speeds but need high mass or volumes and long distances to take advantages. Deep-sea ships have similar characteristics and need infrastructure to load and unload goods (Wehking and Hager, 2020; Rodrigue, 2020).

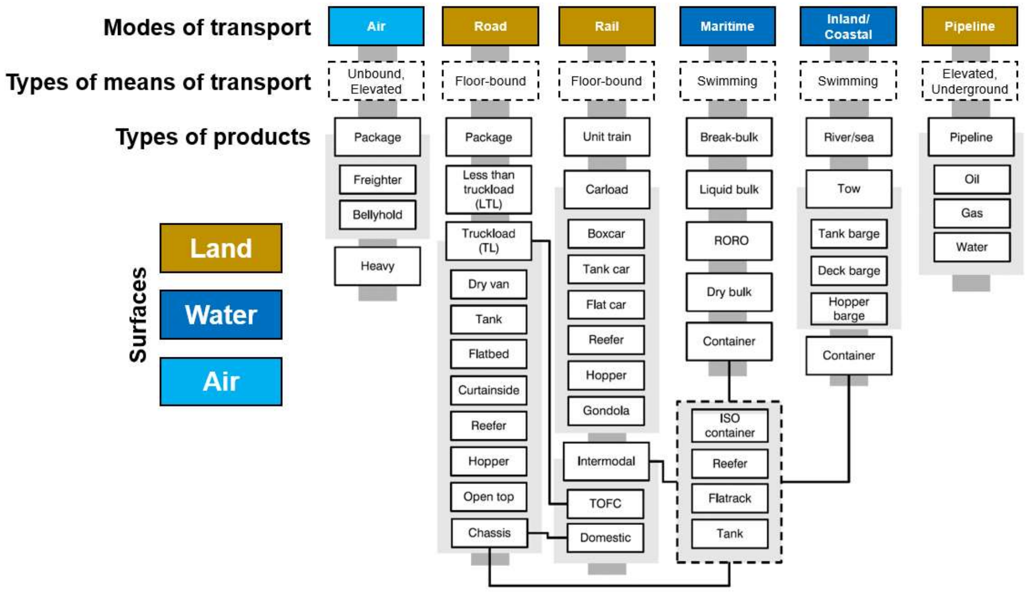

Figure 3. Surfaces, modes, types of means of freight transport (adapted from Rodrigue, 2020; Wehking and Hager, 2020)

In intercontinental traffic, different transport activities connected by hub operations are usually carried out one after the other – which together form a transport chain. If more than one mode is used in the transport chain, transport is referred to as intermodal transportation (Crainic and Kim, 2007). This is usually done to exploit the benefits of individual modes, e.g., to consolidate goods for overseas shipping while providing a flexible first- and last-mile by trucks.

Further specification of intermodal transportation exists – the European Union exemplarily defines 'combined transportation' as the combination of truck transportation on the initial or final leg with transportation by rail, inland waterways (IWW), or maritime services on the other leg. The peculiarity of this definition lies not only in the prohibition of air transport on the main leg, but also in the type of handling – the goods themselves may not be manipulated, but only the loading unit, for which only swap bodies, containers and semi-trailers are eligible (Council of European Union, 1992).

Combined transport can further be split up regarding the form of transport, which is unaccompanied or accompanied, the geographical scope, i.e., domestic, or international, and the focus of the transport chain, i.e., continental, or maritime (UIC, 2020). This highlights the vast number of possibilities to transport goods from an origin to a destination and, at the same time, the challenge to describe transportation on the conceptional level of transport modes – as many different transportation products exist for each mode.

2.1.3.2. Products of Transportation

Transportation products do not refer to products in a physical sense but rather define the characteristics of the transport service. For example, products in road haulage can be Less-than-Truckload (LTL) or Full-Truckload (FTL) shipments. LTL shipments are usually consolidated with LTL shipments from other freight owners to utilize the truck as much as possible. Usually, those consolidation tasks are done by the freight forwarder as the logistics service provider. When buying FTL shipments, the freight owner or shipper pays for the whole truck to drive from an origin to a destination. Thereby, the buyer of the transport service is left to decide how well he utilizes the truck within the legal and safety limits (Rodrigue, 2020). It is economically beneficial to utilize the vehicle as well as possible since transport costs usually do not depend on the transported quantity in FTL shipments. Similarly, unit trains and carloads in rail freight transportation can be distinguished as two possible products in rail transportation (Rodrigue, 2020).

2.1.3.3. Emissions from Transportation in Austria

In Figure 4, Austria's total GHG emissions in 2020 are visualized by sector in the pie chart on the left. Although mobility was limited during the Corona-related lockdowns, the transportation sector has been the largest contributor to greenhouse gases, followed by the industry and the energy sector.

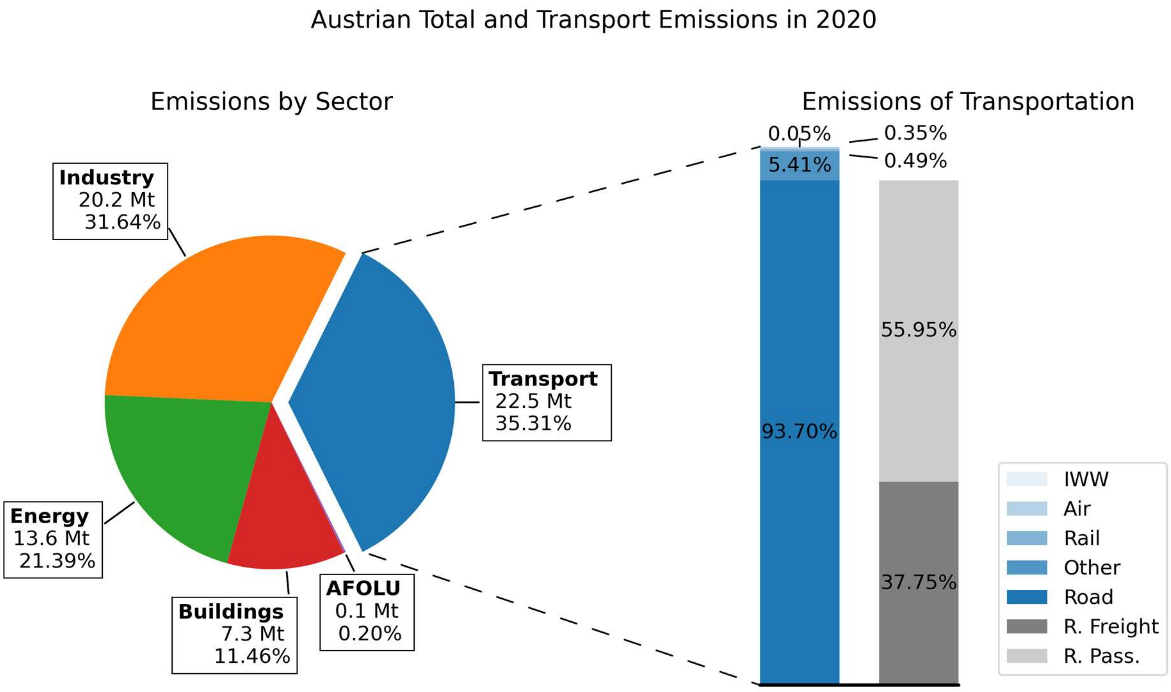

Figure 4. Austrian GHG emissions by sector and subsector of transport (own illustration based on data from Minx et al., 2022; BMK, 2022)

It is noteworthy that the absolute numbers of GHG emissions of transportation found in the international reference used by the IPCC (Minx *et al.*, 2022) are slightly higher than official national numbers released by the Austrian Ministry for Climate Action, Environment, Energy, Mobility, Innovation, and Technology (BMK, 2022). In this work, we used international numbers to investigate the sectoral and sub-sectoral emissions, and national numbers to elaborate on the share of freight transport. Regarding the latter, data availability is limited. Solely for road transportation numbers are available, as visualized in the rightmost bar chart in Figure 3. 40.28% of road emissions stem from freight transportation, while passenger transportation accounts for the rest. For other non-road, rail, and air transport, no split between the two functions was available, only transportation on IWW can be fully attributed to freight transport (0.05%). So, freight transport in Austria accounted for at least 37.8% of total transport emissions in 2020. Therefore, roughly speaking, we can approximate emissions from freight transport by a little more than 1/3 of 1/3 of Austria's total emissions.

Nevertheless, what is not considered in these figures are emissions from hub operations in intermodal transport chains. Hub operations emit pollutants when linking transport operations in a chain and possibly conducting additional services, e.g., storage of empty and full containers, or maintenance of transport means or load carriers (ISO, 2022). In this context, different hubs often show different specific emissions per handled good or load carrier – a fact that has not yet fully found its way into emission calculations (Dobers *et al.*, 2019) and therefore provides ground for further research and dissemination.

2.2. Political Initiatives

2.2.1. The US Inflation Reduction Act

In August 2022, US President Joe Biden signed the 2022 Inflation Reduction Act into law. The program encompasses an investment of $433 billion US Dollars, including $369 billion USD for “Energy Security and Climate Change”. Thereby, the Democrats created a climate funding instrument that shall help reduce climate emissions by 40% below 2005 levels by 2030, and, at the same time, push the economy to hinder a recession (The White House, 2023b). Regarding freight transportation, the act, e.g., supports the deployment of clean vehicle technologies by defraying up to 30% of the costs of cleaner trucks when replacing Diesel alternatives, granting funding for the development and deployment of cleaner transportation fuels like sustainable air fuel (SAF) or higher and advanced biofuel blends, green hydrogen, and a decarbonized electricity grid. Industrial decarbonization, in general, is pushed by incentivizing emission-intensive sectors to invest in new technologies, such as carbon capture and storage (CCS) (The White House, 2023a). At the time of writing this thesis, no statistics on how effective the law is existed, yet. Nevertheless, it is a well-operationalized climate funding program with a significant investment budget, challenging European supremacy in the field of climate technology.

The package intends to find a way out of the volatile economic situation caused by the pandemic, the US trade war with China, the tense situation in the energy market, and their subsequent supply chain disruptions. Similar programs were launched by the European Union, entitled “EU Next Generation” and the “Recovery and Resilience Facility” – forcing member states to develop plans how to sustainably escape an economic recession. According to recent studies, only the recovery plans of Belgium, Finland, Germany, and Hungary will not miss the 37% goal of green investments that the EU agreed upon. Anyways, regarding mobility, an 82% share of investments are considered “positive” or “very positive” for the green transition and aim at improving railway infrastructure or supporting the private sector in deploying electric vehicles. 9% have been assessed as critical due to funding of road networks, aviation, or combustion engines (Wuppertal Institute and E3G, 2021).

2.2.2. European Initiatives

This subchapter provides an overview of EU programs, initiatives, and legislation relevant to future transportation regarding climate change. Clarifying these programs highlights, again, the importance of considering the political factors on regional and nation-state levels.

In Figure 5, a non-exclusive list of EU initiatives and legislations regarding climate change is visualized. Its key elements, with a focus on transportation, will be presented in the following sections.

Figure 5. EU strategic initiatives (in grey) and legislative actions (in green) regarding climate change (own illustration based on the references in section 2.2.2)

2.2.2.1. The European Green Deal

By communicating its ambitious Green Deal in 2019, the European Union set sail to becoming "the first climate-neutral continent" by 2050 (European Commission). The deal thereby aims at transforming economic growth towards sustainable growth – by developing new technologies and business models that enable a net-zero economy, aligning those to the principles of circularity to decouple economic growth from resource use, and ensuring that every region and citizen is supported in this transition (European Commission, 2019).

Under the umbrella of the Green Deal, several sectoral and cross-sectoral initiatives have been launched that specify the Deal's mission to certain domains, and, together, form the building blocks of the Deal. For example, "The New European Bauhaus" aims at aligning building design and construction across all application areas, e.g., housing, industrial facilities, or transportation infrastructure, to environmentally friendly, aesthetic, and inclusive principles (European Commission, 2021b). The "Circular Economy Action Plan" (CEAP), on the other side, focuses on reducing environmental impacts from the resources' perspective and, thus, promotes the use of renewable and recycled materials, the reuse and repair of products, the reduction of waste and enhanced waste collection, as well as the development of circular supply chains. From the transportation perspective, the action plan mainly outlines future revisions of the Battery Directive and the rules on end-of-life vehicles (European Commission, 2020a). The EU "Clean Energy Package" is thereby a well-institutionalized set of four directives and four regulations, aiming at transforming the EU electricity market towards a more sustainable one in a fair way. It includes energy efficiency, renewables, biomass, as well as governance aspects – which are, especially regarding future electrified transportation, also of interest to the transport sector (Nouicer *et al.*, 2020).

A cross-sectoral initiative that aims at ensuring that "no one is left behind" during the green transformation is the "Just Transition Mechanism". It aims at the social aspect of the green transition by providing, e.g., support for regions that are most affected and supporting reskilling and retraining of workers that suffer from climate change-related impacts. A key element thereby is the "Just Transition Fund", which encompasses €19 billion of investments (European Commission, 2023b).

One initiative of special interest to this thesis is the “Sustainable and Smart Mobility Strategy”, which is discussed in a little more detail in the next paragraphs.

2.2.2.2. Sustainable and Smart Mobility Strategy

The Sustainable and Smart Mobility Strategy covers the transportation aspect of the Green Deal, aiming at an emission reduction of 90% compared to 2019 by 2050. It outlines three objectives, ten flagships, 14 milestones, and 82 initiatives that the Commission will follow in the years after its release.

One of the flagships aims specifically at freight transportation. Eight initiatives and five milestones thereby define the ground for future regulative proposals of the Commission.

Most initiatives aimed at freight transportation focus on modal shifts and making rail freight and IWW transportation more attractive to customers. Regarding rail freight, the Commission outlines the necessity to revise policy frameworks like the Combined Transport Directive, the regulations governing Rail Freight Corridors, TEN-T, and State aid rules. In combination with EU funding and R&D support, this should lead to increased use of combined transportation through better data sharing, more transparent information, closing the gap in intermodal terminals, and incentivizing sustainable modes of transport through internalizing external costs. After all, setting up economic incentives is key for the Commission to any changes. Regarding IWW, the Commission wants to put forward the NAIADES III program, which helps finance fleet renewal, information exchange, and compliant with environmental policies. By implementing these measures, the Commission aims at increasing rail freight by 50% and 100% by 2030 and 2050, respectively; as well as increasing IWW and short-sea shipping by 25% and 50%, respectively (European Commission, 2020b).

Critics of the strategy report mixed feelings - on the one hand, they concede it has some “useful and promising approaches”, but on the other hand, they address a lack of implementation strategies, insufficiently ambitious goals, and the absence of already known and promising measures (GIZ GmbH, 2021).

Some of the mentioned initiatives have, at the time of writing, already been discussed in trilogue negotiations, some have been proposed to the EU Council, and some are still just initiatives. Those that have already been communicated and targeted especially on freight transportation are presented in the next subchapter.

2.2.2.3. European Climate Law and Fit for 55

The European Climate Law, for the first time, puts the onus on EU members to meet their climate targets, contributing to the EU-wide goal of reducing GHG emissions by 55% compared to 2019 levels in 2030. To reach this goal, a set of revisions and updates of EU legislation was proposed by the EU Council, which are summarized under the umbrella term “Fit for 55”. Step by step, the packages’ proposals are discussed within the EU Council’s working packages, among EU ministers, and with the European Parliament (Council of the EU, 2023a). As the Fit for 55 package includes a variety of proposals for all sectors, the following paragraphs summarize the main impacts and proposals for the freight transport sector.

Road transport

By the end of 2022, the European Commission, the European Parliament, and the EU Council reached a provisional political agreement on the revision of the European Emission Trading Scheme (EU ETS). Before, included sectors have been power and heat generation, as well as energy-intensive industries. As of now, the current ETS is extended to cover emissions from offshore vessels larger than 5000 gross tons by 2024 – and a separate ETS will cover emissions from fuel use in road transportation and buildings from 2027. Furthermore, the emission cap will be lowered, free allowances will be phased out for certain sectors, and the Carbon Border Adjustment Mechanism (CBAM) will be phased in gradually to price embodied carbon emission in imports (European Commission, 2023c; Council of the EU, 2023b).

In 2022, the EU also strengthened targets for non-ETS sectors by the revision of the Effort Sharing Regulation (ESR) to a 40% EU-wide reduction compared to 2005 levels in 2030 (Council of the EU, 2022e). Until 2027, road transportation is among those sectors. As these savings are cumulative across the EU, countries are presented with different targets –for example, the proposed projected target for Austria tightens by 12 percentage points to a 48% reduction compared to 2005 levels in 2030 (Council of the EU, 2023e).

One piece of the puzzle to achieve these goals is to raise emissions standards of heavy-duty trucks, as recently proposed by the European Commission (European Commission, 2023a). The proposal includes the gradual reduction of specific emissions by 45% compared to 2019 from 2030, 65% from 2035 and 90% from 2040. Besides decarbonization, this should also lead to investment security for truck OEMs and infrastructure operators, as the deployment of electric and hydrogen-powered trucks will be forced.

In line with this, the proposed regulation on alternative fuels infrastructure (AFIR) aims to adapt the legislation from the infrastructure's perspective – and includes, for example, the installation of electric charging stations for trucks every 60 km and hydrogen filling stations every 200 km on the TEN-T core network. With the focus on road transportation, AFIR highlights EU intentions to supply mobility users with alternative fuels, where needed. Regarding freight transportation, the deployment of infrastructure for electric heavy-duty trucks is supposed to start in 2025 – whereby coverage of the TEN-T core corridors is scheduled for 2030. The deployment of gaseous hydrogen refilling infrastructure is planned similarly – but with regular assessments of the sectoral developments and needs (Council of the EU, 2022b). Negotiations with the Parliament are still pending, as EU member states and the EU Council agreed upon a common position on AFIR in June 2022 (Council of the EU, 2022c).

Maritime transport

Besides road transportation, AFIR also encompasses infrastructure deployment for the maritime and aviation sector, especially regarding the availability of on-shore power supply for deep-sea and inland ports, as well as airports (Council of the EU, 2022b, 2022c). In comparison to AFIR, the FuelEU Maritime legislation package shall ensure demand for alternative fuels in the maritime sector by introducing, e.g., the obligation for on-shore power supply by 2030, more robust calculations for GHG intensities, fuel certification mechanisms, and numerical targets for the reduction of carbon intensity in maritime transportation (Council of the EU, 2022b, 2022d).

Aviation

As of the most recent political agreement between the EU Council and the European Parliament, the EU ETS is aligned to the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), as flights arriving on or departing at a Union airport will fall under CORSIA, while emissions from intra-European flights are accounted to the emissions auctioned in the EU ETS. The effectiveness of CORSIA will thereby be monitored by the EU in the next years, and the free allocation of EU allowances will be reduced in 2024 and 2025 and eliminated as of 2026. Furthermore, stricter monitoring and reporting mechanisms of non-CO_2 GHGs will be proposed by the Commission. A package of measures to shift short flights spanning 1000km or less to alternative modes of transport will be discussed, as these contribute disproportionately to emissions from the transport sector (Council of the EU, 2023c, 2022a, 2023d).

A package like FuelEU Maritime to foster the supply and demand of sustainable aviation fuel (SAF) – named ReFuel EU Aviation – was proposed by the European Parliament and the Council in 2022. Aviation fuel suppliers are thereby obliged to blend minimum shares of SAF to aviation fuel, beginning with 2% in 2025 and gradually increasing to 63% in 2050. Aircraft operators will then be hindered from bunkering low-cost and possibly carbon-intensive fuel from non-EU airports in the aeroplane by restricting the annual quantity of aviation fuel uplifted at a Union airport to a minimum of 90% of the required fuel quantity. In line with this, stricter reporting obligations for aircraft operators and fuel suppliers are proposed. Union airports need to make sure that aviation fuel suppliers can access the airport and meet SAF demand – otherwise aircraft operators may report the unavailability of SAF blends to the competent authority of the Member State (Council of the EU, 2022a).

2.2.2.4. EU Strategy on Adaption to Climate Change

Away from all efforts to prevent the emission of new GHG emissions, climate science introduced the concept of climate change adaption – which aims at making societies, ecosystems, and economies resilient to the unavoidable and irreversible effects of climate change (IPCC, 2021).

Thus, in June 2021, the EU Council approved a Commission proposal to renew the EU's 2013 adaption strategy and form a new EU Strategy on Adaptation to Climate Change. The strategy includes several instruments to foster (European Commission, 2021a):

- "Smarter adoption", e.g., enhancing knowledge on adaption and climate risk assessment;
- "More systemic adoption", e.g., enhancing cooperations across all levels, regions and sectors to form new policies and guidelines, supporting ecosystem recovery and protection;
- "Faster adoption", e.g., setting up funding for adaption research through a Horizon Europe Mission (European Commission, 2021c) and reducing the share of non-insured economic losses from climate change; and
- International support and financing for adoption

From a transportation perspective, the strategy paper discusses the threat of droughts to inland waterways. The presented initiatives aim to create adaptation mechanisms in response (European Commission, 2021a).

2.2.3. Austrian Initiatives

In 2016, Austria ratified the Paris Climate Agreement (UNFCCC, 2023), committing to delineate its own National Determined Contribution (NDC) to mitigate climate change. The initial NDC was submitted to the European Union in 2016 and then revised and strengthened in 2020 to meet the EU's goal of reducing emissions by 55% (Meinshausen *et al.*, 2022). Policies to reach the NDC targets are developed and enacted frequently across the federal and provincial laws. Thus, it is hard to compile an up-to-date list of all policies affecting environmental impacts (Mayer and Wolf, 2023). In general, as a member state of the European Union, Austria's climate policies align with those of its European ancestors. The main green legislations affecting transportation from the European perspective have already been discussed in Section 2.2.2. Nevertheless, some Austrian transportation-related legislations that extend the European laws are worth mentioning. For instance, Austria introduced the National Emission Allowance Trading Act (NEHG) in 2022, which levies a tax on GHG for all sectors not obeying to the European ETS, the most affected of which is transportation. This law features a gradual increase in the allowance price for emitting one ton of GHG until 2025, beyond which the law introduces an emission trading market (Federal Ministry of Finance, 2022).

An amendment to the Austrian Waste Management Act introduced a gradual tightening of environmental requirements for waste transportation. Commencing in 2023, only means of transport with pollutant emissions comparable to those of rail transport may be used to transport waste exceeding 10 tons over a distance greater than 300 kilometres by road. Beginning in 2024, the distance is yearly reduced to 100km. Certain exemptions to the regulation are in place to preserve the competitiveness of the waste recycling sector (Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology, 2021b).

As of January 1, 2023, an amendment to the Austrian fuel ordinance increases the compensation amounts that distributors of fossil fuels must pay for each ton of CO2 placed on the market. These compensation payments can be reduced if renewable electricity or biogenic fuels are sold in the transportation sector. In sum, this amendment aims at increasing the price of fossil fuels and creating incentives to build infrastructure for alternative fuels (Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology, 2022b, 2022c).

Most of the initiatives implemented by the Austrian government in recent years are included in Austria's 2030 Mobility Master Plan. This 68-page document presents a strategic approach to reduce transportation-related greenhouse gas emissions and serves as a statement of intent at a high strategic level. In addition to the Avoid-Shift-Improve approach, the plan includes incentives for utilizing alternative transportation modes and creating citizen awareness. However, the measures within the plan are overly general and prioritize passenger transport over freight transport (Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology, 2021a).

Similarly, the Austrian hydrogen strategy puts more focus on the use of hydrogen in the energy, than in the transportation sector. Although hydrogen’s significant contribution to the emission-free freight transport system is acknowledged, it postpones more precise decisions on the use of hydrogen in trucks and buses until 2024-2026, justifying this with the need to expand the hydrogen infrastructure in Europe in a planned and strategic manner, especially for transit traffic. The strategy mentions the utilization of hydrogen in aviation and shipping in more detail. In these areas, the strategy foresees the creation of incentives for the construction of production facilities for the manufacture of SAF. By 2030, a cross-sectoral systemic approach should be in place - providing vehicles, infrastructure, green hydrogen and linking the energy and transport sectors (Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology, 2022a).

2.3. Scientific State of Research and the Derived Research Questions

2.3.1. Strategic Perspective

The management of greening in- and outbound logistics are often discussed in line with greening Supply Chain Management (SCM), as logistics is seen as one dimension of SCM (Sarkis *et al.*, 2011) that supports SCM effectiveness significantly (Khan *et al.*, 2022). Logistics and SCM are cross-sectional functions in manufacturing enterprises – multiple decision-makers on different hierarchical levels are involved in these domains. Typically, this is referred to as ‘Hierarchical Decision-Making’ in literature, comprising decision makers on the higher levels who decide first, have more power and information, and frame the decision-making space of decision makers on the lower levels, who have less power and information and decide afterwards (Liu, 2005). The most common framework in this area was presented by Anthony, 1981, encompassing three hierarchical levels, i.e., strategic planning, tactical planning, and operational control. Those differ in the frequency of the decision-making process and the time horizon affected by the decision. Elaborating this framework for SCM, Chopra and Meindl, 2016 assign high-level decisions affecting several years, e.g., product design, number of service providers, outsourcing strategies, or location selection, to the strategic planning level. These decisions thereby influence the opportunity space of the tactical planning level, where decisions on, e.g., the number of servers at each facility or the number of service tasks to be processed by each facility. Finally, decisions impacting the next few minutes up to the next week are assigned to the operational control level. Building on this well-known framework, Riopel *et al.*, 2005 elaborate on a multitude of decisions that have to be made in business logistics. All in all, they define 48 decisions and assign them to three levels, the Strategic Planning level, the Network level, and the Operations level. The operations level is further split up into nine key functions of business logistics, with one of them being transportation.

Although Riopel *et al.*, 2005 assign transportation to the operations level, there is a long-term perspective in transportation decisions. This is incorporated in a framework for decisions influencing emissions of road freight, which was initially created by McKinnon and Woodburn, 1993 and extended by Piecyk and McKinnon, 2010. It comprises six main decisive factors determining freight amount and freight emissions, which are the structural factor, the commercial factor, the operational factor, the functional factor, the product-related factor, as well as the external factor. Decisions on those factors determine the nodes of the transport network, the supplier, customer and service provider selection, transport order scheduling, and the vehicles used for transportation. Thereby, all those decisions together determine, first, the amount of freight transport that is necessary for the focal firm, second, the carbon intensity of those transports, and, thus, the carbon emissions resulting from freight transport. Usually, several parties contribute to those decisions in industrial logistics (Chopra and Meindl, 2016). Shippers, i.e., industrial firms, commission transports and define the basic structures of the supply chain, whereas logistics service providers conduct what the shippers stipulate them to (Pålsson and Kovács, 2014).

This highlights the importance of investigating the short-term, as well as the long-term perspective in logistics decision-making to adjust decisions on the operational and functional, as well as on the structural and commercial levels, respectively. Solely by including the contingency of GHG emissions into all decision-making levels, deep decarbonization will be possible in a sustainable way, i.e., economically viable for the firm.

To the best of the author's knowledge, a link between specific measures and the decision-making levels, i.e., the decision-making parties per se, is still missing in the literature. Whereas extant literature on the impacts of specific measures exists, we are not aware of research that connects those measures to the hierarchical levels discussed above. Thus, the first research question of this thesis can be defined as follows:

RQ1: Which parties involved in industrial freight transportation are capable of implement certain measures?

Besides this, we are further interested in the state of the art in practice, i.e., which measures are currently being adopted among Austrian logistics practitioners to effectively guide further decarbonization. Several studies already investigated practitioners across Europe and beyond. For example, evidence from Lithuania indicates that eco-driving and intelligent routing are frequently used (Vienažindienė *et al.*, 2021). Similarly, evidence from Sweden scores transport planning and eco-driving highest regarding their implementation (Pålsson and Johansson, 2016). The importance of eco-driving is underlined by similar research from Thailand (Sureeyatanapas *et al.*, 2018). Standing out in this study is the high score for alternative fuels – which is contrary to the findings of other studies (Martins *et al.*, 2019; Froio and Bezerra, 2021; Vienažindienė *et al.*, 2021). Modal choice scores are mediocre. A study from Brazil ranks it among the most frequently used measures, with only 27% of companies using it (Martins *et al.*, 2019). This discussion indicates that there is still a lot of potential for many measures – which depends on the degree of implementation in the respective country. To the best of our knowledge, there is yet no similar study for Austria, indicating that the potential to be exploited in Austria is uncertain. Thus, the second main question to be answered is:

RQ2: How widespread are decarbonization measures in the Austrian transport-intensive industrial sectors?

Having discussed the state of the art, we seek a deeper understanding of decarbonization decisions in practice. Thereby, a multitude of studies exist that explain organizational decision-making behavior by utilizing various organizational and behavioral theories (Sarkis *et al.*, 2011; Touboulic and Walker, 2015; Carter and Liane Easton, 2011). Some of which seem to be used more frequently, e.g., the institutional theory (Miemczyk, 2008; Zhu and Sarkis, 2007; Zsidisin *et al.*, 2005), the stakeholder theory (Busse *et al.*, 2017; Gooyert *et al.*, 2017; Siems and Seuring, 2021; Huge-Brodin *et al.*, 2020), or the resource-dependency theory (Hofer *et al.*, 2021; Schnittfeld and Busch, 2016; Trujillo-Gallego *et al.*, 2021); whilst others are "imported" from other fields of research and thereby less common in decarbonizing logistics, e.g., customer value theory (Wagner, 2008), network theory (Gulati *et al.*, 2000), or event system theory (Morgeson *et al.*, 2015).

To sum up, on those studies, we can conclude that not many firms are advanced in reducing industrial logistics' emissions. Although a certain movement towards environmentally friendly activities can be observed by bigger companies (e.g., Volkswagen AG, 2022; Brau Union Österreich AG, 2022), things are not getting too serious, yet; many endeavors never made it out of the pilot phase. One reason for this might be the absence of significant external pressures on decision-makers in logistics (Touratier-Muller and Ortas, 2021). Nevertheless, as elaborated on in Section 2.2, most political initiatives are in their infancy and will come into effect in the next few years. Furthermore, evidence shows a movement towards European citizens gaining a rising awareness for the environment in general (Bacsi, 2020), and for climate change in special (Lee *et al.*, 2015). Paired with the perception that "big companies and industry" are not doing enough to protect the environment, environmentally conscious buying behavior slowly starts to diffuse upstream in the supply chain, creating a "green bullwhip effect" that will hit more upstream industrial firms with a delayed, but stronger impact (Seles *et al.*, 2016).

Decision-makers in logistics, thereby, need to take action now, because changes in logistics systems may take a horizon of up to 15 years (Bretzke and Barkawi, 2013). Introducing changes when they are requested by stake- and shareholders might be too late, and companies closing themselves off to change might not exist in a changing institutional environment. Thus, decision-makers in industrial logistics need evidence on how to successfully and competitively adapt to new contingencies that arise through further dependence on carbon emissions. Whereas there is an extending amount of studies investigating the diffusion of green practices in the supply chain and how to support those (Seles *et al.*, 2016; Gulati *et al.*, 2000; Trujillo-Gallego *et al.*, 2021; Siems and Seuring, 2021), or why single firms act how they act (Busse *et al.*, 2017; Shin *et al.*, 2018); we could not find any studies investigating those companies that already successfully implement measures. There are indications that some exemplar firms do take decarbonization seriously and implement measures not solely as pilot projects or for marketing purposes. We are deeply interested in how those companies find consensus on greening their logistics processes and what differs from other firms. Simply put, to shed light on these industrial logistics decarbonization frontrunners and delineate implications for other industrial companies, we aim to investigate the following research question:

RQ3: What makes organizations, that have successfully implemented initiatives to decarbonize industrial logistics an example to follow?

Summing up the first three research questions we strive to answer in the managerial-oriented part of the thesis, we want to investigate how management principles in industrial logistics must change to be prepared for unavoidable long-term decarbonization. In this context, various sub-questions that arise when discussing the above-stated research questions are, for example: What are managerial success factors that ensure the future competitiveness of the logistics operations? Are there already Austrian firms that managed the transition exemplarily? If so, how did they adopt it? If not, why not? Answering those questions to gain a better understanding of the mechanisms in the Austrian context is the first main part of this thesis.

2.3.2. Operational Perspectives

Nevertheless, besides the long-term implications for management, the more pressing issue regarding the factor of time is how to promptly decarbonize the economy, as an American investor expresses that "the timeframes to get our act together on climate are starting to be incompatible with doing things that will take decades." (Bergen, 2023) Scientific evidence outlines that deep reductions in emissions will have to happen in the coming decade to prevent a climate disaster (IPCC, 2021). The managerial implications we aim for will probably not impact the carbon footprint of real-world processes soon enough to contribute to this urgent situation.

Nevertheless, much progress has been made on the technological and operational aspects of logistics decarbonization. In the following paragraphs, a non-exhaustive overview of measures to decarbonize transportation is presented according to the well-known "Avoid-Shift-Improve" (ASI) framework, which is used in recent literature (e.g., Dhawan *et al.*, 2022; Zhang and Hanaoka, 2022) and practice (e.g., Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology, 2021a). First introduced for public transportation (Dalkmann and Brannigan, 2007), references nowadays frequently cite it as a prioritization and categorization of decarbonization initiatives for freight transport, too (Jaramillo *et al.*, 2022).

2.3.2.1. Avoid

Avoiding unnecessary transportation while maintaining logistics service levels constitutes the first category of actions. This category thereby includes all measures related to minimizing total vehicle distance travelled – and thereby reducing emissions from fuel usage. Those measures thereby address either the distance between the origin and destination of goods or insufficient utilization of vehicles and load carriers – the potentials and barriers of both options are widely recognized. For example, industrial firms' supply networks often span globally and thereby include distances of several thousand kilometres (McKinnon, 2018). Restructuring the supply chain thereby bears the potential to avoid transports on a large scale through, e.g., the re-location of manufacturing plants. An example of shifting car manufacturing closer to the final customers reveals outbound reduction potentials of 80% to 90% (Nieuwenhuis *et al.*, 2012) – but cannot be implemented ad hoc due to its widespread effects and strategic character.

Regarding utilization, near-time potentials are still prevalent, as 20% of road freight journeys in the EU in 2021 were performed by empty vehicles (Eurostat, 2022). Measures in industrial logistics include, for example, the reduction of inbound Just-in-Time transports – or at least the abundance of time windows to increase supplier and carrier flexibility (Harris *et al.*, 2010; McKinnon *et al.*, 2010; Rogerson, 2017), optimization of packaging and load carriers, or backhauling (Kaack *et al.*, 2018; IEA, 2017). Increasing capacity utilization of trucks thereby reduces the necessary number of runs and thus costs and emissions, at the same time (Jaramillo *et al.*, 2022). Such changes can be hard to implement as larger transport volumes increase demand for on-site storage and its cost. At the same time, the reduction potential of such measures can be negligibly small in global supply chains with transport legs measuring thousands of kilometers (Lin, 2019).

2.3.2.2. Shift

Shifting transportation from carbon-intensive modes of transport to lower-carbon ones is the aim of the second category's actions. As the focus is shifting away from carbon-intense modes, research investigating continental transportation mainly addresses shifting road transportation to rail (Regmi and Hanaoka, 2015; Heinold and Meisel, 2018; Dioha and Kumar, 2020), inland waterways, or short-sea shipping (Harris *et al.*, 2018; Svindland and Hjelle, 2019). Regarding intercontinental transport, the credo is to avoid air freight and instead use the more environmentally friendly sea freight or, if possible, rail transport.

Investigating the emission intensities of different modes of transport in Figure 6 highlights that a clear gradation in the order air-road-inland waterway-sea-rail exists, albeit large spreads in the data indicate that mode choice is only one factor determining the emission intensity.

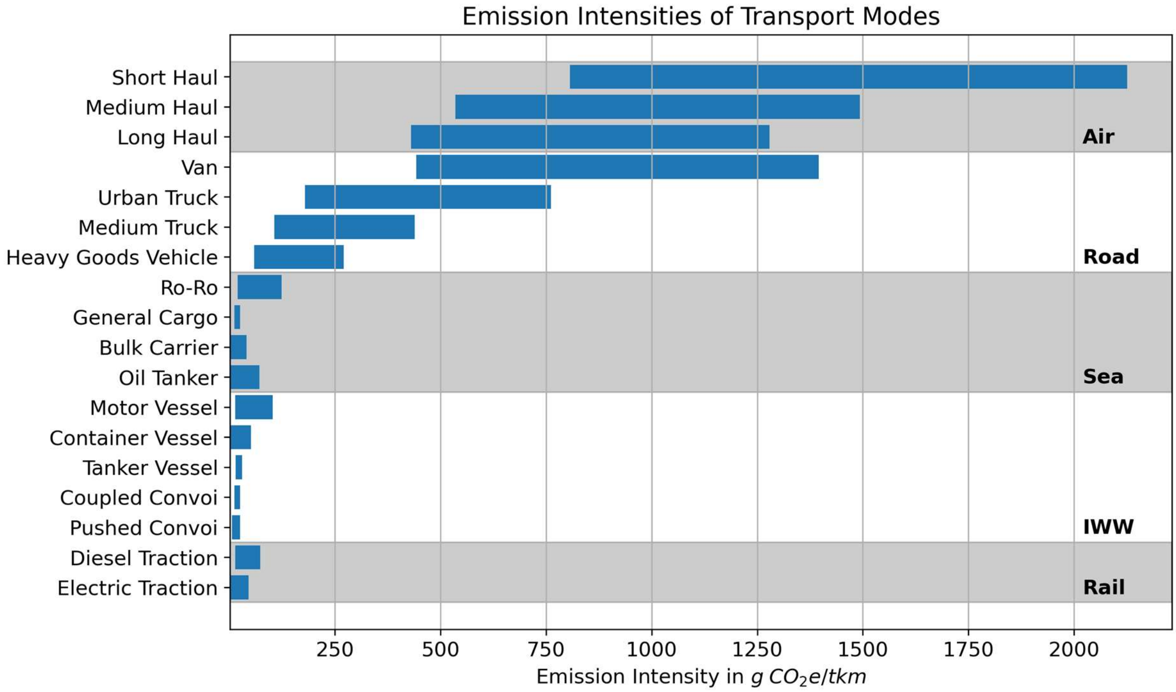

Figure 6. The transport modes' emission intensities (own illustration based on data from GLEC, 2022)

Besides the ecologic aspect, the shift to mass-capable means of transport – for example, from truck to train – usually brings economic benefits, as specific freight rates are 30% to 35% lower (Zgonc *et al.*, 2019; Müller *et al.*, 2021). Nevertheless, challenges arise regarding limited flexibility due to operational inefficiencies (Cichosz and Pluta-Zaremba, 2019; Colicchia *et al.*, 2017) or missing infrastructure (Regmi and Hanaoka, 2015). Furthermore, especially waterborne transport depends on geographic characteristics (Svindland and Hjelle, 2019).

Although in Europe modal shift was intensely promoted, researched, and incentivized in the last decades, the share of road transport has increased drastically in the Union, which is why literature calls for further research on intermodal transportation and the shift to rail (Kaack *et al.*, 2018). Recent articles thereby indicate one reason are soaring prices for rail electricity – which force railway operators either to use Diesel locomotives or lose competition with road transportation (van Leijen, 2022; Geerts, 2022; CER and ERFA, 2022).

2.3.2.3. Improve

Even if the first two principles become exhaustively utilized, transport emissions will still occur in burning fossil fuels in combustion engines. Therefore, is the measures in the last category aim to reduce and, at best, prevent these very emissions by changing vehicle properties and technologies. Perhaps the most frequently and intensively discussed action is the use of alternative drives and fuels, as several low-carbon transport technologies and related energy pathways exist (Jaramillo *et al.*, 2022, p. 1064; Breuer *et al.*, 2022). Options include the use of novel fuels in advanced combustion engine vehicles, e.g., DAC FT-Diesel, the use of battery electric vehicles, or low-carbon hydrogen generating electricity in fuel-cell powered vehicles (Jaramillo *et al.*, 2022, p. 1083).

The use of hydrogen as an energy carrier in fuel cell electric vehicles (FCEV) is a promising and prominently discussed solution as it can be used in many different applications – in transportation alone application scenarios for port assets, trucks, trains, ships, or airplanes exist – without direct emissions. Nevertheless, achieving emission reduction potentials is bound to the utilization of green hydrogen (Fritz *et al.*, 2022) – the availability of which is likely to be scarce by 2030 and uncertain in further future (Odenweller *et al.*, 2022). Thus, it will be deployed for applications where no other decarbonization options exist. It is questionable whether this will be transportation in the first or second place. The

Austrian hydrogen strategy, for example, prioritizes hydrogens' industrial use above the use in transportation (Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology, 2022a). Even if an application in transportation is favored, using it for decarbonizing trucks is unrealistic in the coming decade, as the demand in aviation and shipping is expected to be higher (Jaramillo *et al.*, 2022). Furthermore, hydrogen refueling infrastructure is costly – especially for open road networks. The construction of company-owned on-site hydrogen refueling stations may thereby be a technological option, but investments for each unit are estimated to be 0.6 – 2 million USD (ICCT, 2017). Comparing different technological hydrogen production, storage and transportation options for Germany reveals the lowest possible filling costs of hydrogen to be around 5 $€_{2020}$/kg in 2030 (Sens *et al.*, 2022).

Electricity supply from in-vehicle batteries provides another option, being frequently referred to as Battery Electric Vehicles (BEV). Whereas electric trucks for short-haul feeder services already reached cost parity in most European cities (Basma *et al.*, 2022), long-haul heavy-duty electric trucks impede significant costs for the vehicle, the battery, and the infrastructure – which can solely be cost-effective in specific settings (Karlsson and Grauers, 2023; Teichert *et al.*, 2023). Frequently discussed challenges include the supply of energy from renewables, the sourcing and production of batteries, the scarcity of recharging infrastructure for trucks, long recharging times, and short ranges (Mojtaba Lajevardi *et al.*, 2019; Jahangir Samet *et al.*, 2021; Middela *et al.*, 2022; Shoman *et al.*, 2023). The use of overhead catenary or in-road inductive charging facilities, summarized under the umbrella term electric road systems (ERS), can remedy this by supplying energy to the vehicles while they are in motion. Nevertheless, they necessitate high investments in infrastructure, which only pay off on routes with heavy traffic, e.g., freeway axes between conurbations.

Another option is using negative-emission fuels in combustion engines – enabling near-net-zero transportation. As stated in the 2nd EU Renewable Energy Directive, a vast number of such fuels exists, using different resources and production pathways. Depending on those characteristics, the fuels entail different levels of emission reductions and different challenges in resource sourcing, production, storage, and combustion (Breuer *et al.*, 2022; European Parliament, 2018). Eligible fuel alternatives for heavy-duty trucks discussed by the latest IPCC report are advanced biofuels from different sources, direct air capture Fischer-Tropsch (DAC FT) Diesel, and Ammonia from low-carbon renewables or natural gas steam methane reformation. Of those, DAC FT Diesel and low-carbon Ammonia show the lowest emission intensities, while the reduction potential of advanced biofuels depends heavily on the assessment model used for calculating emissions (Jaramillo *et al.*, 2022, p. 1083).

This discussion addresses the various actions available to mitigate climate change in transportation, along with associated challenges. Manufacturing companies, however, face difficulties addressing these challenges as they lie outside their core competencies. Nonetheless, they must comprehend the environmental impacts of logistics decisions and their potential contributions to decarbonization. To address the urgent need for emissions reduction in the years ahead, we aim to investigate the following research question:

RQ4: How can Austrian manufacturing firms identify the "most promising" measures to reduce greenhouse gas emissions from industrial logistics?

There are several sub-questions raised by this research question, the most important of which is the definition of "most promising". This definition is particularly compelling since all aforementioned measures affect multiple logistical dimensions. These dimensions include the technical and operational feasibility within the logistics network, economic competitiveness, emission reduction potential, and scalability of the solution. This non-exhaustive list of criteria will serve as a starting point for providing evidence-based decision-support to manufacturing companies.

Thus, in parallel with the strategic part, the thesis's operational part should enable companies to make a measurable and competitive contribution to decarbonization, demonstrate possibilities in Austria that exceed the current state, and provide a basis for immediate action.

To summarize the focus of this thesis, the object under investigation is visualized in Figure 7.

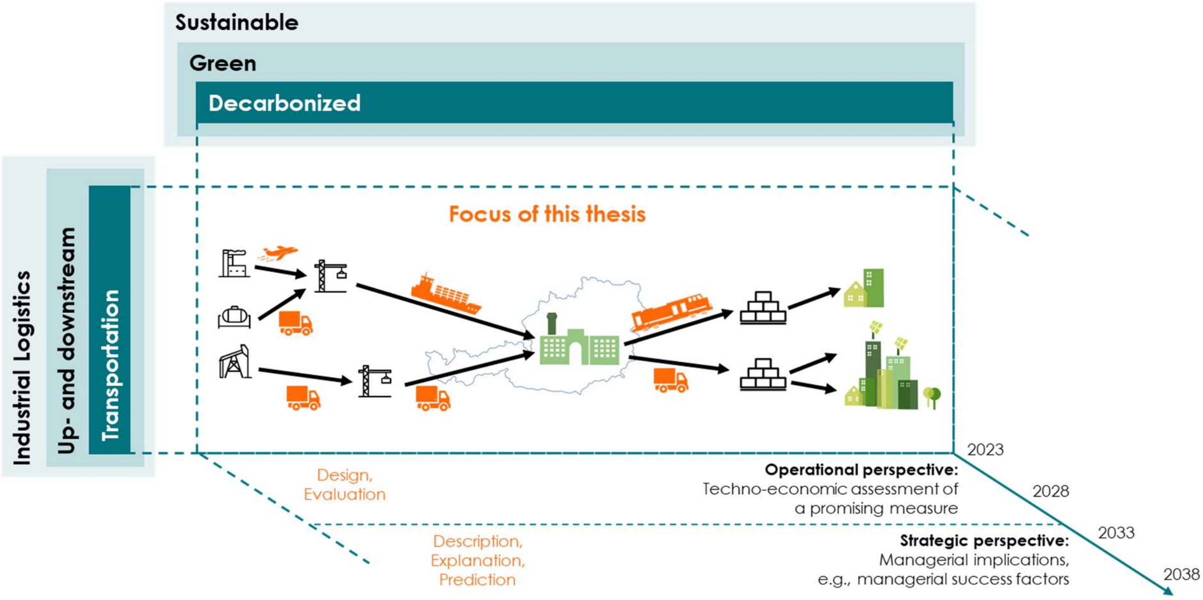

Figure 7. Visual summary of the object of investigation and the research questions (own illustration)

3. Applied Research Methodology

According to Kornmeier, 2007, the purpose of a scientific thesis can be the *description*, *explanation*, *prediction*, *design*, and/or *evaluation* of the object under investigation. In the theoretical part of this doctoral thesis, we, therefore, aim to describe the current situation regarding the decarbonization of industrial logistics in Austria, *explaining* mechanisms underlying the adoption of green practices as well as managerial success factors and thereby *predicting* how long-term logistics competitiveness, concerning the dependency on emissions, can be ensured in Austrian industrial firms. Furthermore, in the applied part, we aim to develop indications on how to *design* and *evaluate* the most promising measure regarding short-term decarbonization.

To do so, we use a triangulative approach, which investigates the object under consideration from three sides. First, the current state of the literature is used to provide a view of the research that has already been conducted. Subsequently, empirical studies serve on the one hand, to elaborate the practical state of the art, and, on the other hand, to provide insights into pioneering companies. The grounding of the research in the aforementioned organizational and behavioral theories thereby ensures its quality (Defee *et al.*, 2010). In line with Popper's view of theories as "fishing nets" that capture only parts of reality (Popper, 1935), we consider the perspectives of the most prominent theories in the field, e.g., the (natural) resource-based view, resource dependency theory, institutional theory, or stakeholder theory.

This multi-pronged approach ensures that the dissertation considers the research already conducted in the field as well as relevant theories. Further, the techno-economic-oriented, interdisciplinary research approach guarantees that all necessary dimensions of the object under investigation are included in the considerations and that the research does not lose sight of the real world.

Therefore, we split the research into four work packages, aligned to the four research questions defined in Section 2, each utilizing a methodology that is well suited for the aim of the package. Thereby, we consider the approaches used in relevant research on the field, as well as methodological and epistemological considerations.

In addition to the work packages presented in Table 1, the results of the paper have been continuously disseminated to practitioners. Moreover, there have been accompanying research projects in which the knowledge was directly applied. These did not directly contribute to the doctoral thesis or scientific literature but consolidated the knowledge of the researchers in the field and transferred relevant findings to the industry. Ongoing discussions of the researchers with practitioners and participation in theoretical and practical conferences ensured the relevance and rigor of the research.

The work packages' results were either published in peer-reviewed scientific journals or presented at scientific conferences. This ensures that each part of this doctoral thesis complies with modern scientific standards and contributes to the current knowledge in the field. References to these publications are made in Table 1 and, in depth, in the next section.

Table 1. Work packages with their corresponding purpose and method

RQ	Purpose		Methods	Paper	Key Outcomes
RQ1	Understanding	Describe	Systematic Literature Review	Miklautsch and Woschank, 2022a	Elaborate the state-of-the-art regarding decarbonization measures in literature.
RQ2		Describe	Analysis of secondary data and firm reports	Miklautsch *et al.*, 2022	Develop an understanding of the most pressing industrial sectors.
		Explain	Quantitative survey	Miklautsch and Woschank, 2023b	Elaborate the state-of-the-art decarbonization measures among Austrian practitioners.

RQ3			Explain	Qualitative interviews with 10 experts from exemplary organizations	Miklautsch and Woschank, 2022b	Understand the differences in exemplar organizations that do already implement measures.
			Predict	Qualitative interviews with 15 experts from exemplary organizations	*Under Review*	Derive propositions on how firms can ensure competitiveness in the long run.
RQ4	Supporting		Evaluate	Mixed Methods, Design Science Research	Miklautsch and Woschank, 2023c	Multi-criteria decision-making tool for shippers to evaluate decarbonization measures.
			Design	Mathematical modelling	Miklautsch and Woschank, 2023a	Methodology to calculate the most promising routes in a logistics network for utilizing combined road-rail transportation.
			Evaluate	GHG emission quantification	Miklautsch *et al.*, 2024	Scenario-based GHG quantification of an exemplar combined transport chain.
			Evaluate	Simulation	Miklautsch *et al.*, 2023a	Simulation model for a techno-economic assessment of combined transportation.

4. Summary of the Scientific Contributions

In the following subsections, the research that was conducted to answer the overarching goals of this doctoral thesis is summarized. Thereby, the motivation, method, and key findings of all publications are presented and their role in answering the research questions is outlined. The detailed contribution of the author to those papers is clarified according to the Contributor Roles Taxonomy (CRediT) (Allen *et al.*, 2019) in a separate table in Appendix 9.10.

A visual representation on how the specific publications contribute to the thesis research questions can be found in Figure 7. To ensure clarity for the reader, we define each contribution using a numbered sequence, demonstrating how they form the building blocks of the thesis. This figure further connects the scientific contributions to the bachelor theses that were supervised and the master theses that were co-supervised, which are summarized in Section 5. Therefore, we emphasize the significance of these theses to the central thesis's outcome. The (co)supervision enhanced understanding of various aspects of the object under investigation and provided evidence and inputs for various research works.

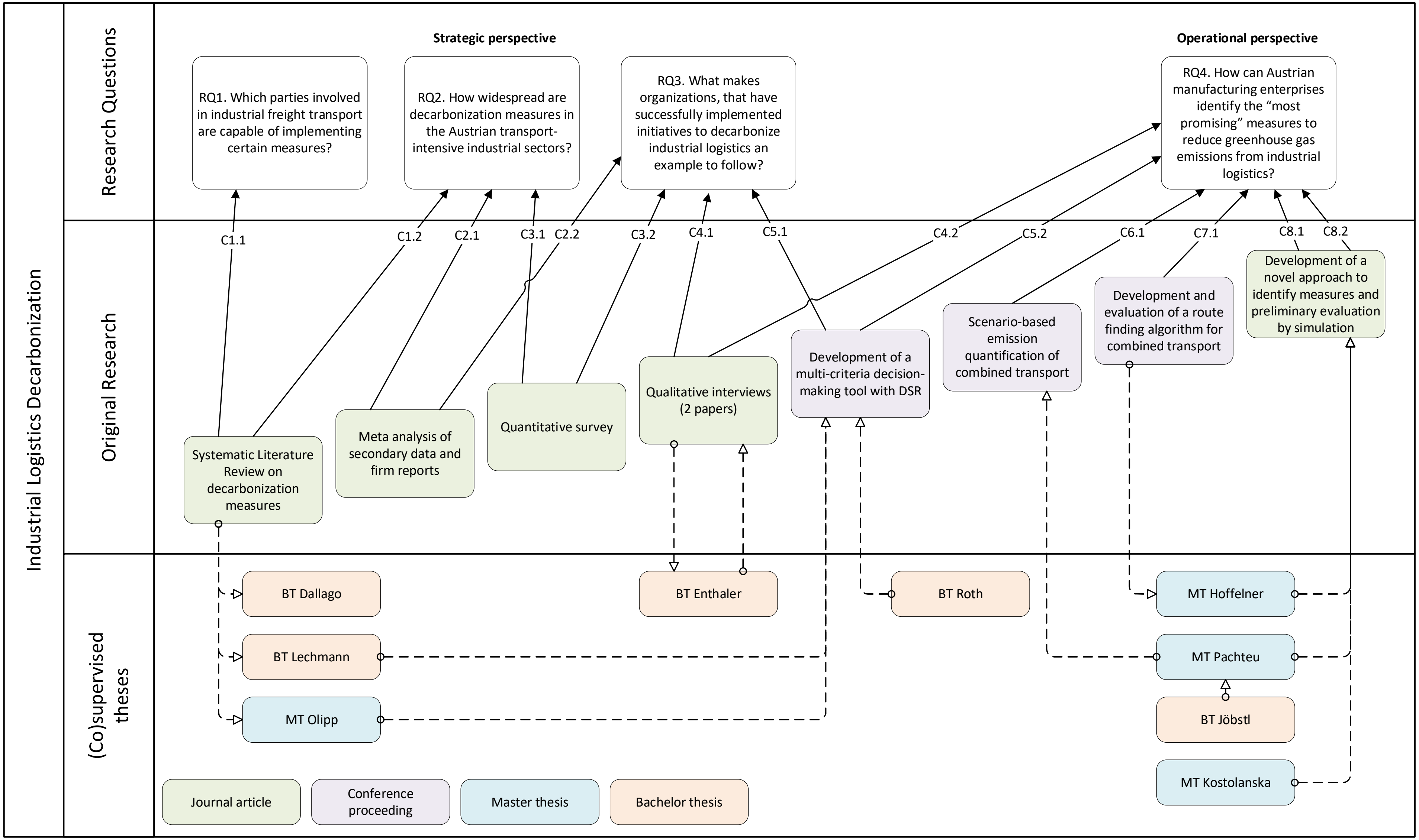

Figure 8. Visual representation of scientific contributions and their connection to the (co-)supervised theses, as well as how they contribute to the research questions (own illustration)

4.1. Systematic Literature Review (Paper 1)

4.1.1. Summary of Motivation, Method, and Key Findings

The purpose of this paper is the synthesize of scientific findings on emission reduction measures in transportation. A focus is thereby set on the perspective of shippers, e.g., manufacturing companies, as those companies do have a significant impact on industrial logistics emissions. A Systematic Literature Review was conducted by searching the SCOPUS database with a predefined search string. A total of 410 papers were found and their abstracts were screened. Due to preceding defined inclusion and exclusion criteria, 281 papers could be excluded, as they did not fit the overarching goal of the paper. 18 articles could not be retrieved, so 111 were eligible for the full-text analysis. During this phase, a further 55 were excluded due to their content, but 25 other articles from a backward search were included. In the end, 81 articles were subject to the text full-text analysis, which resulted in 215 measures, that were clustered into 27 measure categories and nine high-level clusters. Those are presented and discussed subsequently in a descriptive analysis of the papers. Besides the presentation of the measures and clusters, the emission reduction potentials of the measures were collected from the articles and brought together in the analysis phase. Thus, in the discussion, a comparison of different measures is possible, concluded by an outlook to further research directions on the field. The hierarchical framework by McKinnon and Woodburn, 1996 was extended by two more hierarchical layers to include all perspectives of industrial logistics decisions (Miklautsch and Woschank, 2022a).

4.1.2. Contribution C1.1 to the Research Question 1

First, the SLR has revealed the activities in industrial freight transport that emit emissions and the actors involved. The entities commissioning transports and parties involved in their execution are crucial to decarbonization efforts. Depending on the contract type, many actors can participate in freight transport.

Second, a comprehensive catalogue of measures to decarbonize industrial freight transport has been created. Examining the potential benefits, drawbacks, and connections between these approaches served as a foundation for subsequent research. Interestingly, some of the measures identified fall outside of the widely established ASI framework and pertain to long-term strategic decisions. This suggests that focusing solely on ASI could potentially constrain the ability to reduce emissions in the long run.

Third, by expanding on the hierarchical framework introduced by McKinnon and Woodburn, 1996, a more comprehensive understanding of the role of industrial enterprises in decarbonizing freight transport is presented. The distinction between long-term and short-term initiatives, enabled by the implementation of two further layers in the framework, thereby ensures that all aspects of logistics decision-making are addressed. The first dimension, the management system, defines the decision criteria and targets of transportation buying in manufacturing enterprises and, thus, lays the boundaries for all further decisions on transportation. Shippers' management and employees thereby play a major role in shaping the long-term success of decarbonization in the shippers' logistics network. On the second new level, the technical level, shippers are, for example, able to modify load carriers and thereby reduce weight. Such modifications enable short-term reductions but are limited in their potential. Furthermore, the power to decide on specific measures can vary among different hierarchical levels on the shippers' side – depending on the decision to out- or insource transportation. In the first case, the decisions are made on a higher hierarchical level in the procurement of transportation services – which implies longer decision horizons. Detailed technical or operational decisions are thereby deferred to another party. In case transportation is done by the shippers themselves, operational departments on lower hierarchical levels inside the company decide on those aspects.

Fourth, the meta-analysis of emission mitigation potentials from the studies identified throughout the SLR highlighted the uncertain reduction potential of several measures. To name the most drastic measure, drivetrain technology and fuel selection show a share from nearly zero to nearly 100% emission reduction. This high variability reflects the low readiness level of those technologies in practice, as the actual emission reduction depends on many operational parameters.

4.1.3. Contribution C1.2 to the Research Question 2

First, the importance of focusing on interdisciplinary research and including approaches from social sciences was confirmed by the research – underlining the use of qualitative and quantitative research methodologies for the subsequent studies.

Second, by identifying the key players in industrial logistics and their different types (e.g., shippers with/without own vehicles) as well as the comprehensive list of decarbonization measures, this article laid the foundation for the definition of the target group as well as the formulated questions for the quantitative survey.

4.1.4. Further Contributions

The measure with the most robust Interquartile Range is mode selection, i.e., the shift to less carbon-intensive modes of transport. Half of the values found report a reduction between 23% and 41%. That is why, already in the first step of the research, this measure category is identified as one of the most promising for the decarbonization of freight transport in the short and medium term.

4.2. State of the Art-Analysis via Desk Research (Paper 2)

4.2.1. Summary of Motivation, Method, and Key Findings

The overarching aim of this publication is the presentation of a methodology that enables the identification of a country's transport-intensive industries and the relative importance of the companies to decarbonize logistics. In the first step, the analysis of transportation statistics is suggested to select the sectors of the economy that demand most transport. Thereby, a shortlist of sectors is created that guides policymakers on which sectors to concentrate on first and challenges the idea of creating policies for the whole transport sector. Second, an analysis of sustainability reports of the largest companies in the transport-intensive sectors leads to the collection of figures on logistics emissions concerning the total emissions of the companies. This indicator thereby presents the relative importance of logistics decarbonization in companies as well as the individual reduction potentials. In the second part of the paper, the authors apply the developed methodology exemplarily to Austria and thereby find four transport-intensive value chains, which are the metal, mineral, food, and wood value chains. Transportation of goods from those value chains, together with firms that collect waste and vehicle manufacturers, accounts for more than 80% of transportation demand in Austria. The second part of the methodology finds companies in the mineral value chain to have the most relative emissions, although confidence in this finding is low due to a low number of data points (Miklautsch *et al.*, 2022).

4.2.2. Contribution C2.1 to the Research Question 2

Defining the transport-intensive economic sectors in Austria allowed for a more targeted selection of companies to participate in the subsequent research questionnaire and a more nuanced evaluation of the answers.

4.2.1.Contribution C2.2 to the Research Question 3

First, the possibility of clustering the transport-intensive sectors into four value chains highlighted that supplier-demander relationships dominate the transportation intensity. This is not a surprising finding, but strengthens the proposition of many researchers, that a focus on the supply chain perspective is crucial. Studies in the field of SCM, thereby, mostly adopt a social science approach due to the human interactions and decisions that influence those relationships. This supports the findings of the first paper, and further underlines the importance of the following ones.

Second, this line of argumentation provides a first indication of how successful "carbon-reducers" might decrease emissions in their transport operations. Since transportation emissions are interconnected with transportation demand, which, in turn, is connected to supply chain design, a sustainable way to reduce emissions is through incorporating transportation into supply chain management. By doing so, the impacts of decisions on logistics key performance indicators, including carbon emissions, can be evaluated comprehensively. These implications offer a preliminary indication of how to ensure sustainable industrial logistics decarbonization in the long term.

4.2.2. Further Contributions

First, to facilitate decarbonization in the near-term, this paper provides recommendations on the initial sectors to prioritize in Austria. Emphasis is placed on industries with high levels of logistics emissions, as they provide the greatest potential for emission reductions. Notable examples include companies involved in glass, clay building products, and cement manufacturing.

Second, the analysis of the firms' reports suggests that calculating and reporting emissions is not a concern for small businesses. This could be due to the lack of requirements for these companies. However, it is to be expected that in the future more regulations and requirements regarding emissions reporting will also apply to smaller companies. This highlights the relevance of, first, strategically addressing this issue, and second, efficient and effective reporting of logistics emissions supported by information technology.

4.3. State of the Art-Analysis via Quantitative Survey (Paper 3)

4.3.1. Summary of Motivation, Method, and Key Findings

This paper reports findings from a survey administered to industrial logistics practitioners in Austria. The survey had two main objectives: first, to gather data on the extent to which various green logistics measures are currently implemented, and second, to examine the relationships between certain organizational factors and the adoption of sustainable logistics practices. This resulted in answering two research questions: "RQ1: What are the prevalent practices implemented in Austria to decarbonize freight transport?" and "RQ2: How do organizational anchoring, practitioners' perception, and the industry sector affect the level of implementation of decarbonization measures in Austria?". Results are based on 94 responses to the organizational questions and 69 responses to the full questionnaire, providing compelling insights into the Austrian industrial logistics sector. Briefly summarized, no difference in the level of implementation between industrial sectors could be found, but the organizational anchoring was proven to be a significant factor in green logistics adoption. Further, in most cases, the perceived potential or barrier correlates positively or negatively to the measures' adoption, respectively (Miklautsch and Woschank, 2023b).

4.3.2. Contribution C3.1 to the Research Question 2

First, a low level of industrial logistics decarbonization measures adoption was found across the whole industry in Austria. This shows that there is a lot of potential to be tapped, but while the willingness to decarbonize is low.

Second, there were no significant differences found between companies in transport-intensive sectors and those in non-transport-intensive sectors. This finding is concerning from an environmental perspective since transport-intensive companies make up 80% of transportation demand in Austria. However, from a business standpoint, this could impact the future competitiveness of these companies. As regulations become stricter, they may be compelled to decarbonize their logistics operations.

Third, there are indications that practitioners' perceptions of the barriers and potentials of specific measures differ from scientifically validated ones. This finding is concerning since perceived potentials and barriers are correlated with the level of adoption. Over-estimated measures might thereby lead to greenwashing accusations and the potential reduction of under-estimated, but in fact effective measures, might be wasted.

Fourth, it is evident that there are varying levels of implementation among shippers with and without their vehicles, as well as logistics service providers. For instance, shippers without their own vehicles had uniformly low utilization rates of alternative fuels and drives, which supports the differentiation in decision-making levels discussed in paper 1. Conversely, it was discovered that some LSPs utilize these measures while others do not – which is, again, a reason to investigate those companies that do. Despite a shared interest in the shift to rail, LSPs face numerous barriers, hindering progress. Overall, in Austria, companies have widely implemented collaborating with other carriers to reduce unnecessary transportation and backhauling.

4.3.3. Contribution C3.2 to the Research Question 3

First, this research highlights the absence of effective reduction measures on a broad scale, but, at the same time, the existence of firms that do tackle decarbonization and implement innovative technologies and practices. This provides the authors with a reasoning for aiming at understanding how and why these exemplary organizations made these decisions and derive propositions on how other companies can tackle this challenge. It further enabled the authors to identify companies successful in decarbonizing logistics and ensured that the companies contacted for the qualitative interviews formed a solid sample.

Second, the study proves that the low level of implementation is related to a low organizational anchoring of green logistics. This in turn feeds the hypothesis that the successfully decarbonizing companies calculate and report emissions, have anchored decarbonization responsibilities in organizational role descriptions, train their employees regarding awareness for and knowledge of decarbonization measures, and allocate budget pots for decarbonization.

Third, logistics service providers (LSPs) have been identified as the most consent group in terms of potential emission reductions. This might be attributed to their primary focus on transportation and results in better-informed decision-making. Therefore, manufacturing companies may require an expert group specialized in transportation and/or decarbonization to make effective decarbonization decisions in industrial logistics.

4.3.4. Further Contributions

This contribution can be considered as the second part of establishing the "state-of-the-art" in decarbonizing industrial logistics. The first, literature-based part was presented in Section 4.1.

4.4. Qualitative Studies (Papers 4 and 5)

4.4.1. Summary of Motivation, Method, and Key Findings

Throughout the qualitative research, we interviewed industrial logistics practitioners from companies that seriously trying to decarbonize their logistics activities and succeed in this. Therefore, we defined an interview guideline through brainstorming and discussions with researchers and practitioners. The developed guideline incorporated questions regarding the managerial aspects of decarbonization, collecting information on which decarbonization measures have been set, why and how the organization found a consensus or dissensus on them, and which problems they faced in decision-making and implementation. Besides practitioners from manufacturing companies, we included logistics service providers, digital and management consultants, and other scientists to generate a holistic view. The results of the qualitative surveys are presented in two papers. The first insight into factors influencing the decisions to decarbonize and their interrelationships is derived from ten expert interviews in the first paper (Miklautsch and Woschank, 2022b). This article presents factors influencing the willingness to adopt low-carbon practices, internal enablers that helped exemplar organizations foster innovation, and interrelationships among those factors and enablers. Subsequently, five more interviews have been conducted to expand the sample and improve data quality. The grounded theory approach resulted in propositions on how to eschew the managerial zero-sum game and guarantee the competitiveness of future industrial logistics (Miklautsch *et al.*, 2023b). In the following paragraphs, the contributions of both papers are presented together.

4.4.1.Contribution C4.1 to the Research Question 3

First, during our interviews, logistics costs were the most frequently mentioned factor. This indicates that, even for companies that have successfully reduced their carbon emissions in logistics, the cost is the most critical criterion. It is necessary to ensure that low-carbon transportation activities do not become more expensive for customers, as most of them are not yet willing to pay more for environmentally friendly services. However, we found that successful companies in decarbonization invest more resources in the discovery, exploration, and development of new practices and technologies for their logistics processes.

Second, most initiatives were driven by single key individuals inside the company. If there is intrinsic motivation among logistics managers or other key individuals to reduce emissions and improve the outlook for future generations, top management of exemplar organizations has generally responded positively and earmarked resources to further explore the topic. Thus, we delineate that top management commitment and the prevalence of informed and motivated logistics managers and employees is crucial for successful decarbonization.

Third, we identified several aspects that could impact the decision to allocate resources to this topic. From our empirical interviews, one factor seems to be the firm's industrial sector and its proximity to the end customer, which several experts indirectly highlighted. For instance, a company in the construction materials industry demonstrated little interest in proactively decarbonizing its logistics because these activities are not visible enough to attract customers' attention. Emissions of material transportation do not appear to be the determining factor in this market, as material suppliers are typically sub- or sub-sub-contractors for construction projects under intense cost pressure. On the contrary, a logistics service provider responded that label owners in the white goods industry, specifically household electronics, often inquire about decarbonization. We infer that proximity to the customer is a crucial factor, given that sustainability is progressively gaining significance in marketing. Similar responses from practitioners in the automotive industry indicate that their environmental impact is receiving more media attention. Therefore, promoting green logistics, a highly visible aspect of the supply chain seems to be imperative for industries close to the end customer. Other research has demonstrated the upstream diffusion of sustainable practices in the supply chain (Mir *et al.*, 2021), further highlighting the importance of this proposition. Another driving factor behind investment in environmentally friendly delivery is mimetic pressure resulting from competitors adopting similar practices.

Lower-carbon solutions have only been implemented on a large scale when abatement costs were equal to or less than zero, as previously stated. However, **fourth**, pioneering companies calculated these costs from a supply chain perspective instead of solely considering transportation costs. The management of transportation is mainly concerned with the operational aspects of moving goods from point A to point B. However, taking a higher-level perspective that considers goods movements as part of the bigger picture is necessary to incorporate new technologies or practices. Most of the successful decarbonization initiatives in the sample companies were initiated from a supply chain perspective, considering storage, transportation, production planning, and all other aspects of good's movement. This perspective allows for specific measures to be taken. For instance, if a change in goods location is the only consideration, avoiding the shipment is not a viable option. Expanding the view to the supply chain level, consolidation could avoid a single shipment, thereby saving costs and reducing emissions. Moreover, extending the boundaries of the cost consideration, such as beyond departments, could result in cost savings rather than additional costs for some measures. Implementing a supply chain department that supervises all product movements from suppliers to customers enabled an exemplary company to shift transportation to rail and inland waterways while increasing service levels. Consequently, integrated planning and control of material flows are regarded as crucial factors in achieving competitive and decarbonized industrial logistics.

Fifth, objective understanding of decarbonization measures and knowledge of functioning pilot projects of the technology or practice under consideration was observed as a critical factor. From our interviews, the transportation industry appears to be somewhat cautious about the use of new technologies. However, exemplar organizations were willing to invest resources in a broader roll-out of a measure when a positive business case was reported from a pilot project – regardless of whether it was implemented inside or outside the company.

To summarize, the main factors that we discovered that make exemplar organizations exemplar are:

- The existence of motivated and well-informed key individuals who want to drive a change regarding the emission of greenhouse gases.

- The organization's increased willingness to allocate resources to the topic, assumingly driven by the proximity to the end customer or mimetic pressure.
- The holistic supply chain perspective on logistics cost and emissions when evaluating novel technologies or practices, integrating production planning, storage, and up- and downstream transportation.
- The knowledge of existing pilot projects or other implementations of the measure under consideration.

4.4.2. Contribution C4.2 to the Research Question 4

First, the results of the interviews suggest that one can base the discussion of alternatively powered trucks on the availability of local energy resources. An example from the interviews shows that the use of surplus energy from production waste in transportation can lead to a reduction in fuel costs and emissions. Other such examples from the waste sector (Gasverbund Mittelland AG, 2022) and public transport (Infineon Technologies Austria AG, 2022) underline the benefits of such approaches. The use of excess energy from an industrial facility in district heating is established in Austria (Moser and Lassacher, 2020) but use in transportation has not been to date. However, our data from the interviews show that this is an economically and environmentally promising approach for decarbonizing industrial logistics. In this respect, we suggest that manufacturing companies consider whether and how excess or waste energy streams can be used for transportation.

Second, due to the importance of successful implementation projects of specific measures, we suggest participating in relevant stakeholder association working groups where knowledge is shared among practitioners. Exchanging costs, success factors, and experienced challenges; or even inviting experts for a real-world demo of pilot projects may relieve practitioners of their skepticism regarding specific measures. As for the industries' strict data-sharing policies, such working groups might need a moderator that controls data exchange and privacy. Besides this, the participation of academics is recommendable to validly estimate GHG savings for the discussed measures and real-world pilot projects.

Third, during the research process, various significant factors emerged, which provoked a debate regarding logistics decisions. The conflict mainly revolves around whether to prioritize short-term operational success or long-term strategic considerations. Decarbonization measures in logistics mostly have a direct impact on operations, but their positive influence on the strategic effect is uncertain and distant. It is precisely because of these tradeoffs that it seems extremely relevant to us to thoroughly comprehend these factors and offer decision support in the field of industrial logistics, especially when considering the new contingency of "logistics emissions". This finding led us to develop the decision-support tool presented in the next publication.

4.5. Multi-Criteria Decision-Making Tool (Paper 6)

4.5.1. Summary of Motivation, Method, and Key Findings

Intuitive decision-making has been shown to contribute to an organization's success in many empirical studies. Nevertheless, this solely accounts for experienced individuals, who have extensive expertise in the decision-making field (Matzler *et al.*, 2014). Non-experts utilizing heuristics may jeopardize their decision's quality. This is particularly concerning during the early stages of development, as ill-informed decisions may result in lasting disadvantages. For the field of decarbonization, this is problematic, as the broad-scale application of low-carbon technologies and practices is a relatively new field in practice – and wrong intuitions might hinder novel technologies from scaling up. Because of these reasons, we consolidated the knowledge gained from the preceding literature, qualitative, and quantitative studies and developed a multi-criteria decision-making tool that can be used to evaluate potential decarbonization measures objectively. During development, we adhered to the Design Science Research (DSR) approach and used a well-known decision-support method, PROMETHEE II, to ensure the decision-support quality. For the sake of usability, the tool was developed in Microsoft Excel and evaluated in a case study with a Styrian industrial company (Miklautsch and Woschank, 2023c).

4.5.2. Contribution C5.1 to the Research Question 3

First, during the development of the tool, we elaborated upon the decision criteria of industrial logistics managers when deciding upon decarbonization measures – or more generally, changes made in logistics. This was done by collectively analyzing the findings of the qualitative interviews and challenging them with findings from other literature. Thereby, we were able to present the decision criteria in a more structured way than in the previous studies and conclude with 10 distinct criteria that describe the factors influencing the decision to implement a specific measure. The results of the methodological comparisons here suggest that the flagship organizations weight the criteria differently when making decisions.

Second, the very oriented findings from the previous studies are operationalized and made measurable in this article.

4.5.3. Contribution C5.2 to the Research Question 4

First, managers who apply this tool to support their decisions need to deal with every measure in detail and reflect on aspects that may not have been considered so far. During the practical evaluation of the tool, this phenomenon was even observed with one very experienced industrial logistics manager who did not consider one perspective of a certain measure before evaluating the respective criterion. Thus, we delineate that the in-depth consideration of all impactful criteria will lead to enhanced decision-making quality.

Second, due to the decision-making methodology, managers to evaluate measures without subjective bias. In the end, a ranking of all evaluated measures is presented that reflects the decision-makers' relevance. The calculated rank is not absolute, i.e., it does not reflect how well a certain measure will decarbonize logistics, but how well it performs related to the other measures. This, in turn, allows the decision-maker to efficiently select the most promising measures for the near-term decarbonization of logistics top-down.

Third, it is imperative to underscore the significance of clearly defined measures in the application of the tool. Accurate assessment of measures is contingent upon their precise delineation. For instance, in the case of employing alternatively powered trucks, specific details regarding their operational parameters such as distance covered, frequency of use, and available infrastructure must be established. This necessitates thorough scrutiny of the measures and precludes hasty conclusions. Moreover, a meaningful comparison of measures is contingent upon their costs and potentials being realizable within a reasonably proximate timeframe. It is illogical to compare technologies with a realistic implementation timeline two decades apart from each other, for example.

In summary, it can be affirmed that the correct utilization of this tool, in conjunction with comparable and detailed measures, empowers logistics managers in manufacturing companies to enumerate, evaluate, and compare various measures for decarbonizing industrial logistics. If measures that can be implemented soon are assessed, the findings presented in this research assist companies in selecting the most-promising near-term decarbonization measures for their logistics system.

4.6. Greenhouse Gas Quantification of Combined Transport (Paper 7)

To assist companies in choosing the "most promising" near-term decarbonization measures, we have chosen to conduct a comprehensive examination of a specific measure: the utilization of combined road-rail transportation (CRRT). Given that the selection of this measure significantly influences the structure and outcomes of this thesis, it warrants a thorough discussion regarding its selection.

The rationale for opting for CRRT as the focus of investigation is manifold. Within the spectrum of decarbonization measures, mode selection emerged as one of the few categories showing solid results regarding the emission reduction potential in the SLR. The measure was frequently mentioned during the interviews and was associated with both positive and negative connotations. The potential for emissions and cost savings in certain cases was seen as positive, while the complexity and operational hurdles in suboptimal use cases were viewed as negative. The positive reception of a competitive CRRT use case during the demonstration of the Multi-Criteria Decision-Making (MCDM) tool further underscores its operational feasibility. Nevertheless, questionnaire results revealed considerable perceived barriers hindering the transition to rail, suggesting a prevalent reluctance among practitioners. This empirical evidence underscores the intricate nature of identifying competitive use cases for CRRT, despite its robust potential in emissions mitigation.

Furthermore, the European "Sustainable and Smart Mobility Strategy" has set forth ambitious targets to double the volume of freight transported by rail by 2050 (European Commission, 2020b), while the Green Deal calls for a transition of 75% of all freight to alternative modes (European Commission, 2019). These policy directives create expectations for infrastructural advancements and incentives to promote the shift to rail. Noteworthy developments in the logistics sector towards CRRT, with numerous service providers and freight proprietors transitioning to intermodal transportation, have been widely reported in pertinent magazines (e.g., Nallinger, 2023a, 2023b; Jüngst, 2023). Additionally, initiatives such as the "Intermodal Coaching" program offered by the Vienna Chamber of Commerce seek to alleviate entry barriers for Small and Medium-sized Enterprises (SMEs) venturing into this domain (WKO Wien, 2023).

In conclusion, the complexity coupled with the decarbonization potential led to the determination that CRRT merits a more comprehensive investigation. From our perspective, it represents one of the most promising near-term strategies for decarbonizing the European transportation system. The challenge of establishing competitive use cases, particularly for manufacturing firms, underscores the significance of our detailed investigation as a pivotal lever for mitigating climate change and safeguarding the future competitiveness of industrial logistics.

4.6.1. Summary of Motivation, Method, and Key Findings

The first article subjected specifically to the use of CRRT quantifies the GHG emissions of cement transportation from a cement manufacturer to its customers via combined road-rail transportation. The use case under study is especially interesting because it utilizes a novel load carrier that was specifically designed for intermodal cement transportation. The conventional use of 30-foot silo containers poses constraints on train utilization due to weight limits exceeding those of trucks. The novel 22.5-foot container enables both trucks and trains to achieve high-capacity utilization – and, thus, competitive CRRT on short distances. Nevertheless, the paper does not investigate economic competitiveness, but the environmental impact of the intermodal system. According to current norms and standards, the energy consumption of the transport chain is modelled in nine different scenarios, assessing different drivetrain technologies and fuels for the post-carriage by truck and the transshipment equipment. Results indicate on the one side, that any configuration of intermodal transportation is mitigating GHG compared to the reference scenario by truck, but that the decarbonization potential varies from 75% to 93%. Interestingly, as the emissions of the road leg shrink, the transshipment terminals become the bottleneck regarding the emission reduction if Diesel-powered equipment is used (Miklautsch *et al.*, 2024).

4.6.2. Contribution C6.1 to the Research Question 4

First, the use case behind the quantification highlights that CRRT can be competitive on short distances under certain circumstances, which are mainly high volumes and well-utilized load carriers, trucks, and rail wagons.

Second, the necessity to utilize a specifically designed load carrier to achieve these factors highlights the need to invest significantly more resources into planning intermodal transportation in comparison to road transportation. This is due to the different regulations and restrictions that apply to each mode, and the transshipment operations. For manufacturing companies, this, again, implies that dedicated human resources are imperative to develop a positive CRRT business case in the logistics system. If the shifting option is only superficially investigated, chances are high that no viable use case is found.

Third, the scenario-based quantification of GHG emissions highlights the different factors affecting GHG emissions from transportation and their impact on the decarbonization potential. Albeit investigating solely the use of combined transport, the authors also integrated a scenario where trucks are fueled by Hydrotreated Vegetable Oil (HVO), a second-generation biofuel. The decarbonization potential of this scenario amounts to nearly 63% compared to conventional diesel. This represents a major lever for rapidly reducing emissions – but is more difficult to implement for manufacturing companies. On the one hand, the use of HVO cannot usually be contractually required, and on the other hand, the availability and price of HVO prevents its widespread use. Nevertheless, the GHG quantification highlights the potential of alternative fuels for road transport.

4.7. Development of an Algorithm to Suggest Combined Transport Use Cases (Paper 8)

4.7.1. Summary of Motivation, Method, and Key Findings

The article presents a method to identify potential CRRT use cases in the logistics network of a manufacturing company. The approach involves dividing the network's routes into distinct segments that do not overlap. Then, all possible combinations of contiguous segments are evaluated based on their distance and freight volume per calendar week, enabling the algorithm to identify all potential consolidation opportunities in terms of space and time. The identification of the section combinations on the Pareto-frontier then highlights all section combinations for which one dimension cannot be improved without worsening the other. The proposed algorithm thus provides a list of routes in the company network that have potential for a switch to rail based on distance and freight volume. The approach was described both informally and formally and demonstrated using logistics data from an Austrian manufacturing company (Miklautsch and Woschank, 2023a). The implementation in Python is available as an open-source repository (Miklautsch, 2023).

4.7.1. Contribution C7.1 to the Research Question 4

First, the developed approach can be used by industrial logistics practitioners to efficiently analyze their logistics network and identify consolidation options for freight transport. Since the application of the algorithm is quite simple and the data is usually available, industrial companies can get an initial overview of which route sections in their network are busiest. With this knowledge, they can further investigate opportunities to shift to CRRT. In this respect, this tool provides an initial assessment of possible concrete decarbonization opportunities for the logistics system in the coming years with little effort.

Second, this article presents a comprehensive discussion of factors that must be considered when planning to implement CRRT. Besides the distance and the freight amount, the paper briefly discusses other factors in the discussion. For practitioners, this brief presentation of factors can be a source of information if they plan to implement CRRT.

4.7.2. Further Contributions

The development of the algorithm proved to be a captivating process for the authors, requiring detailed attention to the operational challenges associated with implementing combined transport. The two dimensions assessed have been identified as the primary criteria from the perspective of manufacturing companies. In situations where there is insufficient volume within a designated time frame, combined transport no longer holds a competitive advantage. In the sample network, we observed that shorter distances offer more opportunities for consolidation. However, CRRT is also not attractive for short distances. Therefore, we decided to take a Pareto-optimal view of the dimensions of time and freight volume. Nevertheless, there are many other factors to be considered for a competitive implementation of CRRT, including the availability of terminals and rail connections. To comprehensively evaluate the factors, we have developed a detailed assessment of combined road-rail transportation, which is outlined in the following section.

4.8. Techno-economic Assessment of Combined Transport (Paper 9)

4.8.1. Summary of Motivation, Method, and Key Findings

As discussed in the preceding paragraphs, we developed a discrete-event simulation (DES) to evaluate the impact of shifting transports to CRRT on the environmental (GHG emissions) and economic (total logistics costs) performance of the company. During the development of the simulation, we observed that the demand characteristics and the value of the goods impact the total logistics costs, mainly due to differences in the time available for scheduling transports and the inventory holding costs of the goods. From this observation, we developed the proposition that freight owners' abatement costs for one decarbonization measure differ when goods of different ABC/XYZ categories are transported. The first part of this paper, thus, presents a literature review of the mechanisms behind the selection of decarbonization measures and delineates the developed proposition. In the second part of the paper, we then scrutinize the developed DES for CRRT to exemplarily test the proposition within two case studies from Austrian industrial companies. In the analysis of the simulations' results, we were able to provide statistical evidence that abatement costs of goods' transportation differ between some good categories (Miklautsch *et al.*, 2023a).

As is the approach of this paper, the contributions of it to the thesis' research questions are twofold. While the first aspects relate to the developed proposition and its tests, the second aspects relate to the findings generated through simulating CRRT.

4.8.2. Contribution C8.1 to the Research Question 4

The theory that is developed in the first part of the paper proposes that one decarbonization measure, e.g., CRRT, creates costs of different heights when goods of different ABC/XYZ categories are transported. While we were unable to statistically prove a difference across all ABC/XYZ categories, we could provide evidence that abatement costs for goods in the X, Y, and Z categories differ.

First, this implies that when evaluating a decarbonization measure, careful consideration should be given to the commodities being transported via these measures. In the case of CRRT, it can be demonstrated that the costs of emission reduction are the lowest for X items. This is not contingent on the variability of demand itself, but rather on a reliable forecast and, consequently, an extended planning horizon for transportation.

Second, lifting this consideration of differences in abatement costs from one measure to a variety of measures suggests that abatement costs of goods in the same category also differ between measures. This means that for decarbonization to be cost-effective, the combination of different measures for different goods must be considered. Simultaneously, it suggests that within each category of goods, there may exist a distinct lowest cost decarbonization measure. This underscores that devising an optimal decarbonization strategy in terms of cost entails a nuanced assessment of measures at the level of the transported goods. Figure 9 visualizes this theory.

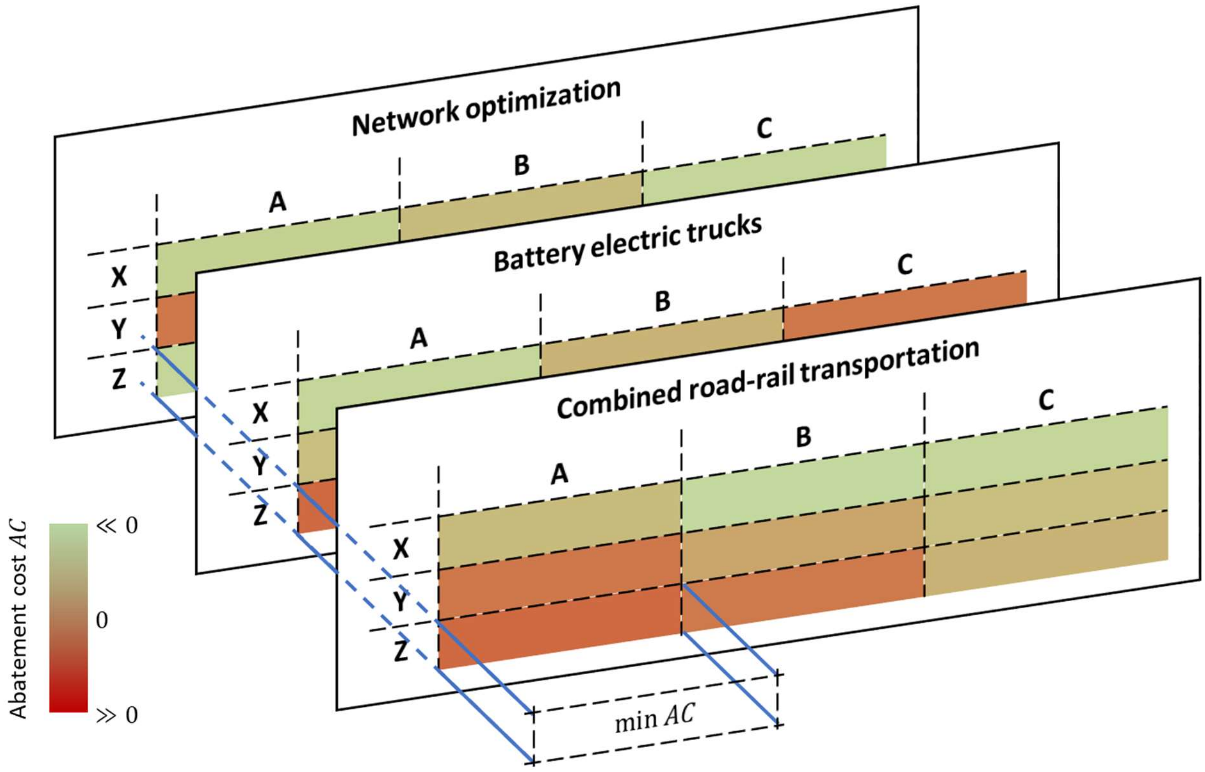

Figure 9. The consideration of differing abatement costs for combinations of measures and good categories might lead to the most cost-effective decarbonization portfolio (own illustration)

4.8.3. Contribution C8.2 to the Research Question 4

Although the impact of inventory holding costs cannot be neglected, in our case studies, it was not the decisive factor. The factor that had the biggest lever on abatement costs is the planning horizon, which is impacted by the XYZ category. This implies that for the use of CRRT, a stable demand forecast is necessary to book time slots for transshipment activities and slots on the rail wagons.

5. Summary of Additional Work in the Field

In parallel to conducting their own research on the decarbonization of Industrial Logistics, the author contributed to industrial projects and co-supervised and supervised other master´s and bachelor's theses in the field. In the following subsections, a summary of those activities is highlighted, because working on them significantly deepened understanding of the object under investigation and has thus substantially enhanced the quality of this work. Again, the author's contribution is defined by using CRediT in Appendix 9.10.

5.1. Evaluation of Greenhouse Gas Emissions in Logistics Operations

5.1.1. State of the Art in GHG Emission Calculation of Logistics Sites

In her bachelor thesis, Lara Jöbstl investigated which standards, scientific methods and guidelines regarding GHG calculation and accounting in logistics sites exist. Beginning with commonly accepted literature like the Greenhouse Gas Protocol and the GLEC Framework, a search string was formulated that was used for a systematic literature research in the SCOPUS database. Thereby, most scientific contributions were found to deal with GHG calculation in ports. A research gap was identified for other storage or transshipment hubs like intermodal terminals for combined road-rail transport. Existing literature further mainly introduced guidelines and suggestions on how emissions should be calculated, but does not introduce specific calculation models or software tools (Jöbstl, 2022).

5.1.2. Development of a GHG Calculator for Intermodal Terminals

In cooperation with KombiConsult GmbH, a GHG calculation tool for intermodal terminals for combined transport was developed by Sandra Pachteu during her master's thesis. At the beginning of the work, scientific studies in the field, current standards and guidelines, and similar projects were screened. Therefore, a calculation and data model for the calculation tool was designed from a theoretical perspective. During a total of four visits to terminals, practical processes were recorded, clustered, and subsequently incorporated into the tool. Thus, the tool represents a combination of scientific calculation methods and terminals' general activities. The user of the tool must finally specify the energy consumption of the processes, as well as the cargo units handled, and can do so in any detail. The result of the calculation is energy consumption as well as emissions per cargo unit handled (e.g., swap bodies, ISO containers or semi-trailers), per process (e.g., horizontal handling, vertical handling, administration) and for the entire terminal in the period under consideration (Pachteu, 2023).

The author thereby contributed as the project lead and the co-supervisor of the master thesis. Thus, he was involved in defining the calculation model, on-site visits, process definitions, and all organizational aspects of the project.

5.2. Evaluation of Alternative Fuels and Drivetrains for Transport Decarbonization

5.2.1. An Outlook to Future Electric Truck Battery Technologies

A frequently discussed problem in the application of battery electric trucks is the storage capacity of the on-board batteries. Longer ranges and shorter recharging times are necessary for electric trucks to be fully commercialized among freight practitioners. One solution to this problem is the technological aspect of the battery, i.e., how the electricity is stored in a truck. In his bachelor thesis, Mario Lechman focused on alternatives to the conventional Lithium-Ion batteries which are currently deployed. Using a systematic literature research, he identified six battery technologies, which he subsequently assessed for their technological parameters, their potential to fulfil freight transportation's operational requirements as well as their technology readiness level. He concluded that two of them, namely solid and liquid Lithium-Sulfur batteries, might be ready for commercialization and adoption in battery electric trucks until 2030 (Lechmann, 2023).

5.2.2. Waste-to-Energy for Transportation

In his bachelor thesis, Konstantin Karl Dallago conducted a narrative and a systematic literature research aimed at finding practical applications, as well as research papers regarding the use of Waste-to-Energy (WtE) technologies in transportation. First, an overview of WtE technologies that are eligible for use in transportation was given. Following this, a systematic search in SCOPUS was conducted to analyze scientific contributions on this topic. To the authors' surprise, no studies were found that describe or assess application scenarios of WtE technologies in logistics, albeit indications for economic and environmental potentials of cross-sectoral applications exist in literature. In addition, no practical use cases were identified during the analysis. Thus, this thesis highlighted the research gap in the application of WtE technologies in logistics and transportation (Dallago, 2022).

5.2.3. An Investigation of the Potential Future Austrian Heavy-Duty Truck Fleet

During her employment at the Chair of Industrial Logistics, Nadine Olipp investigated the multiplicity of studies that predict future truck fleet compositions. The overarching goal of this research, which she summarized in her master's thesis, was the identification of potential scenarios for the Austrian freight transport sector. Besides conducting a systematic literature review on the topic, she included several reports and other studies done by different organizations, like the International Energy Agency. After thoroughly screening and clustering the studies, she evaluated how applicable the scenarios developed in the studies are for Austrian freight transport. This was done based on several official strategic documents – including the "Mobilitätsmasterplan" (strategic mobility plan), the "Wasserstoffstrategie" (hydrogen strategy) and the general legislative program. The results show that in 2030 in Austria the share of battery electric trucks in new registrations will be between 3 and 17%, and that of hydrogen-powered trucks between 5 and 15%. For 2050, no valid conclusion can yet be drawn (Olipp, 2023).

5.3. Understanding the Importance of Combined Transportation for Decarbonization

5.3.1. Investigation of the Potentials and Barriers for the Use of Combined Transports in the Transport of Dusty Goods

On behalf of SiloRiedel GmbH, Hana Kostolanska dedicated her master's thesis to the shift of dust transports to rail. In a narrative literature research, basic terms were defined at the beginning, which were subsequently used for a systematic literature review. This led to an overview of the potentials, barriers and case studies that already exist in the scientific literature for intermodal transportation. Subsequently, expert interviews were conducted with various stakeholders in the transportation of stowage goods. The results of the research are insights into how intermodal transportation is currently used and can be used in future. For example, break-even distances found in literature were doubted by the experts – who mention that the distance is not the decisive factor. In contrast, the additional organizational effort required to handle intermodal transport was perceived as a more serious barrier. In addition, the fact that means of transport do not account for their external costs leads to a distortion of competition between them and is detrimental to intermodal transport. In general, large potentials for intermodal transportation were discovered in energy-intensive firms that need to transport a large amount of freight, e.g., the cement and steel industry (Kostolanska, 2023).

5.3.2. Simulation for Combined Road-Rail Transportation

During the development of the optimization algorithm for CRRT routes (Miklautsch and Woschank, 2023a), the authors defined the key building blocks of a discrete-event simulation that models the operations involved in the replenishment process of an industrial company via CRRT. Mario Hoffelner's master thesis expanded on these components to craft a comprehensive simulation capable of assessing various CRRT scenarios against direct road transportation. His primary responsibility entailed integrating the provided blocks, creating additional mechanisms such as dispatching to rail or road services and verifying and validating the simulation and its outcomes. Additionally, an exemplary case study was conducted as a demonstration of the simulation's applicability (Hoffelner, 2023). In the course of this thesis, the simulation was further specified and used to evaluate the proposition made in the last paper (Miklautsch *et al.*, 2023a).

5.4. Supporting Strategic Decisions Regarding Decarbonization

5.4.1. Framework Conditions for the Decarbonization of Logistics in Austria

Gregor Enthaler dedicated his bachelor thesis to the framework conditions that logistics-intensive firms face in Austria regarding the decarbonization of transportation. Thereby, framework conditions are defined as factors that cannot be influenced by the companies but affect decision-making. Depending on the current situation of the factor they can either support decarbonization and act as drivers – or hinder decarbonization and act as barriers. Factors and their perceived sentiment were created based on a literature review and following interviews with logistics experts from Austrian firms. Important drivers in Austria were thereby found to be the environmental awareness of the public – motivating firms to invest in decarbonization initiatives – and a high technological readiness level – leveraging possibilities for decarbonization. Nevertheless, high investment costs and high regulative uncertainty limit enthusiasm for the broad-scale implementation of novel technologies and practices (Enthaler, 2023).

5.4.2. Decision-Support Systems in Production and Logistics

In her bachelor thesis, Ulrike Elisabeth Roth investigated and defined the state of the art in Decision-Support Systems (DSS) in production and logistics systems, with a special focus on transportation decisions. A preceding narrative literature research led to the definition of search strings for a systematic search in SCOPUS. Different types of DSS are presented in the evaluation phase and their application in transportation problems is highlighted. Six application areas were identified, of which the commonly known vehicle routing problem is the most promising one in transportation research. An investigation into how well the studies entitled as "DSS" fit the definition of DSS indicated the appropriate use of the term throughout the literature and did not highlight further research needs in this area (Roth, 2022).

6. Discussion and Implications

The present thesis enhances the understanding of the mechanisms underlying the decarbonization of industrial logistics. Thereby, its publications add to the body of knowledge and present practical tools that support industrial logistics decision-makers on the strategic and operational level in mitigating their transportation's carbon footprint competitively. To do so, a multitude of literature-based, empirical, and engineering approaches was combined – each of which has been independently published in scientific journals or conference proceedings.

In detail, the four overarching research questions were answered in Section 4 by elaborating the contributions of the individual papers. Briefly spoken, answers to the first question highlight the impact of freight owners on the higher-level strategic measures. Their impact on the operational level shrinks, the more levels are in between the freight owner and the companies' owning fleets and carrying out transportation. Nevertheless, tendering has a big lever on the operational characteristics of transportation – and thus, its emissions. The second question that research was conducted for was the question to which extend transport-intensive companies already focus on reducing emissions. Analysis of nonfinancial reports of Austrian companies thereby highlighted little standardized logistics emission reporting, and the quantitative survey also underlined little awareness for reduction. At the same time a positive correlation between green logistics anchoring and the implementation of green practices highlighted the first aspects influencing green logistics implementation. This leads to answering the third question, investigating what makes companies, that successfully implemented green measures, an example to follow. Although costs are still the most important decision criteria in those companies, organizational and human factors, as well as tendering strategies, impact the discovery and implementation of green measures that eschew the managerial zero-sum game. Finally, the operational perspective of this thesis revolves around the question of how companies can identify the most promising measures for decarbonizing their logistics system. To support companies in doing so, a multi-criteria decision-making tool, an emission quantification spreadsheet, and a techno-economic simulation for evaluating combined road-rail transportation economically and ecologically was developed.

Besides only answering the four questions in detail, implications for practice and science were derived from a high-level perspective and are presented in the following sections.

6.1. Strategic and Operational Implications for Industrial Logistics Practitioners

For practitioners, the main question for this thesis is how to reduce transportation GHG emissions competitively. As all researchers, we are not able to provide the answer to the universe, but we have enriched the body of knowledge in this field enough to conclude with a comprehensive suggestion on which building blocks a decarbonization strategy for industrial logistics should have to be effective and cost-efficient. Figure 10 presents the findings in what we call the "industrial logistics decarbonization portico". In ancient Greek architecture, a portico is a room that leads to the entrance of a building and is often decorated with pillars and accessed by a staircase. In the context of this work, the portico is one of the entrances through which companies can achieve a GHG reduction in industrial logistics. The steps of the staircase form the necessary aspects over which the management must step. The pillars form the efficient and effective selection of measures, for which we propose differentiation according to the ABC/XYZ analysis. Finally, the roof that protects against environmental influences is formed by top management, whose support is urgently needed to keep the door open to reducing emissions even in economically or technically difficult times.

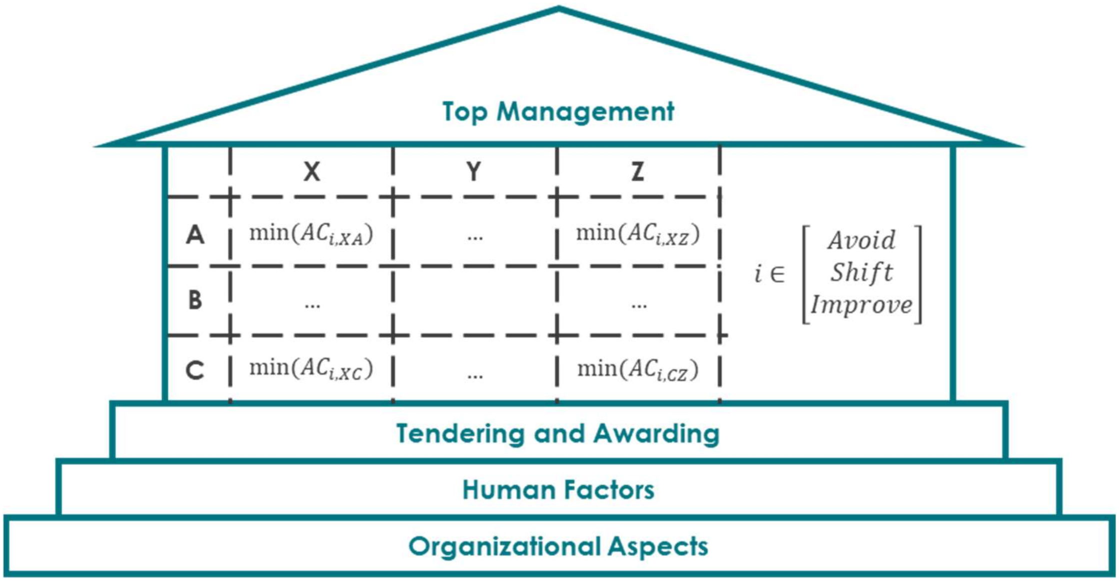

Figure 10. The industrial logistics decarbonization portico (own illustration)

Thereby, the organizational aspects and the human factors are managerial aspects that must be considered in the long-term. For the first one, two elements should be enabled:

- The establishment of end-to-end process accountability within the organization: A recurrent issue identified in our engagements with the industry pertains to the lack of synchronicity among procurement, production, sales, and the cross-functional logistics division. In cases where logistics is not integrated into these domains, it results in the formulation of isolated logistical strategies that hinder global GHG mitigation. A notable remedy for this issue involves instituting a dedicated supply chain department that encompasses all aspects from supplier engagement to customer delivery. This department mirrors the fundamental operational functions of a manufacturing enterprise and facilitates a comprehensive assessment of transportation GHG emissions over the whole supply chain.
- The establishment of control over transportation activities: This facet primarily pertains to the Incoterms negotiated with both suppliers and customers. The greater the extent to which a manufacturing company assumes responsibility for transportation, the greater its capacity to exert influence over it. The most substantial influence can be wielded in instances involving the Incoterm Ex Works (EXW) for inbound logistics and Delivered at Place (DAP) for outbound logistics, while the converse holds true in less influential scenarios. It is imperative to bear in mind that reporting Scope 3 emissions becomes progressively challenging in cases where there is limited internal knowledge about transportation processes within the company.

Regarding the human factors, two further aspects are to be considered:

- Granting leeway for innovation to key individuals: While this observation may not appear as a revolutionary revelation, we have discerned the presence of pivotal figures within various organizational hierarchies who have demonstrated exceptional prowess in mitigating GHG emissions. Serving as catalysts for novel ideas, champions of internal endeavors, and catalysts for visibility, these individuals play a pivotal role in the successful implementation of GHG reduction strategies. Furthermore, it has become evident that the supervisors of such individuals must afford them the latitude to innovate, particularly in terms of allocating ample time and resources. Without this provision, inherent motivation can swiftly transmute into disenchantment.
- Integrating specialized expertise in logistics: Beyond possessing adeptness in logistics processes, the incorporation of specialized knowledge about environmentally sustainable alternatives is imperative for identifying efficacious and competitive decarbonization strategies.

This may be facilitated through consistent knowledge-sharing mechanisms between a central "decarbonization unit" and the geographically dispersed logistics units. Typically, innovative ideas originate from process experts, who can garner support from the central office in the stages of conception, assessment, and execution. Realizing this necessitates the allocation of temporal resources to such an office or procuring such services from pertinent consulting firms.

Tendering and awarding, in comparison to the other aspects, we see more as a medium-term tactical aspect that needs careful consideration and connects the pathways given by the strategic level to the operational and functional tasks. By attaching conditions to the awarding of transport services, the manufacturing company can have great leverage over the GHG emissions of transportation. We propose four aspects that can be implemented immediately:

- Requiring GHG reporting at shipment level: The integration of emission values into the communication between logistics service providers and manufacturing companies sounds easier than it is in practice – mainly due to the lack of data and communication standards in logistics. Nevertheless, this data can be analyzed and thereby uncover tactical and operational mitigation potentials. In addition, Scope 3 reporting will be made available by utilizing emission reporting on a shipment level.
- Requiring compulsory and regular eco-driving training: While instruction in fuel-efficient driving techniques may be commonplace in numerous nations, research consistently underscores the efficacy and cost-effectiveness of this intervention. Particularly for operators hailing from less industrialized nations, this practice can yield enduring reductions in emissions and costs. Imposing obligatory driver training as a prerequisite in procurement processes represents a straightforward means to forestall superfluous energy consumption and the consequent emissions.
- Requiring the adoption of elevated biodiesel blends: Implementing this measure presents a somewhat more nuanced challenge compared to the preceding ones. Numerous truck operators-initiated experimentation with biofuels several years ago, albeit often encountering unfavorable side effects, such as heightened maintenance demands or the emission of a distinct odor during cold starts. Presently, biofuels have undergone significant advancements in terms of both maintenance requirements and olfactory properties and can be utilized in a diverse range of blend ratios. Consequently, an effective strategy for emissions reduction entails stipulating the use of slightly elevated biodiesel blends, for instance, B25. The adoption of pure biodiesel, such as HVO, remains impractical for most hauliers due to limited availability. Nonetheless, attaining higher biodiesel blending ratios is comparatively more feasible.
- Requiring a modal share from large LSPs: Large logistics service providers in Europe mostly utilize combined transport to a certain extent and can integrate a smaller number of LTL or FTL shipments into their existing rail network. Requiring larger LSPs for a certain modal share could thereby motivate them to increase their intermodal activities and enhance rail transportation. Putting this requirement on smaller LSPs might put them at a disadvantage, as they might not be able to deal with the complexity of the intermodal system.

For the selection of other operational measures, referring to the ABC/XYZ classification and investigating the transportation activities from the inventory management perspective is proposed. This perspective is well-known in most manufacturing enterprises and – as showed in Paper 9 – can facilitate the discovery of cost-effective decarbonization measures.

6.2. Implications for Research on Industrial Logistics Decarbonization

Being at the end of one research is the starting point for a new one. During the empirical research and literature studies, many potential novel research endeavors were discovered. A detailed description of many of those ideas can be found in the respective papers –but spanning the arc across all contributions and research questions yields some interesting insights, which are presented in the following sections.

6.2.1. The Strategic Perspective

Scientifically, this thesis deepens the understanding of the mechanisms underlying the slow progress in decarbonizing the transport sector, especially the Austrian freight transport. Many of these aspects can be explained by Green Supply Chain Management theories, as logistics is a key part of it. GSCM in general is well researched and many ideas from it can be imported into the more detailed field of transport decarbonization – although logistics decarbonization seems to face more operational barriers than other areas of GSCM. One important concept that was found can be applied to transport decarbonization is the downstream diffusion of green practices – starting with end-customer demand for green operations. However, at present, ambivalent results regarding the diffusion of green transportation practices in the supply chain were found. As of now, only a minority of companies have allocated a budget to greening measures, indicating the industry's unwillingness to accept additional costs for the decarbonization of logistics. The qualitative data from the interviews underline this – especially if costs cannot be passed on to customers. This mechanism seems to be less pronounced in industries closer to the end customer, which are more in the media spotlight (e.g., automotive, or white goods, where sustainable aspects can be partially priced in) than in industries further down the supply chains (e.g., suppliers for the construction industry, which are strongly cost-driven). Generally, the threat of increased regulatory pressure seems to be the most important reason for adopting green practices. Research conducted during this thesis research did not allow to delve deeper into these motivations and, especially, their changes over time – which would be interesting insights for predicting decarbonization progress. Thus, the importance of all stakeholder roles in the diffusion of lower-carbon practices and technologies, as well as how, why, and to what extent these roles may change, could be explored in more detail to get a more nuanced view of how to accelerate decarbonization.

One interesting research method that could help investigating these aspects is the Qualitative Comparative Analysis (QCA). Its configurational approach allows for very nuanced insights into the object under study. In the case of decarbonizing industrial logistics, different combinations of factors could determine how important decarbonization is for a company. Some indications from this thesis are, for example the proximity to the end customer paired with brand value. Or the industrial sector paired with corporate strategy. By bringing evidence to these indications, QCA could lead to interesting results and insights, which is why we propose its application in this research area.

In addition, Structural Equation Modelling (SEM) would allow researchers to examine similar relationships between different scales. However, SEM requires detailed planning and a large sample, which is why its application in this area might be critical. There are SEM studies investigating GSCM that include logistics or transportation. Although the logistics-specific application would be interesting, data collection might be difficult.

Regarding the country aspects of this thesis, a comparison of the organizational environment between Austria and a country known for its green applications, e.g., a Scandinavian country, would be of high interest. Shedding light on the question of why other countries are adopting EVs at a higher pace could provide the key to EV adoption in Austria, both for passenger and freight transportation.

6.2.2. The Operational Perspective

An interesting psychological concept that is applied in some areas is nudging, which should be more researched in logistics. A good example of effective nudging is Alibaba's food delivery service, which changed the default packaging option to plastic-free and rewards its customers with "green points" (He *et al.*, 2023). More logistics-related companies with direct end-customer interactions could implement this, for example, large online retailers. One idea of how this could work is the implementation of a traffic-light system, where customers can choose from different modes of delivery. The lights may thereby not reflect the delivery time, but the GHG emissions from transportation. In addition to the green color, the lowest carbon mode could be selected by default. While this is contrary to current efforts to provide large-scale "same day delivery", it could encourage the use of more environmentally friendly modes of transportation like combined transport or deep-sea shipping instead of road or air freight, respectively. Besides the B2C area, nudging inside one company should be researched, as well. At first glance, it may seem unlikely that nudging can be effective in companies, as employees are expected to make decisions in the best interest of the company. It is indeed unlikely to have a significant impact on larger strategic decisions. However, in the case of small, decisions made daily by dispatchers or logistics planners, nudging could indeed prove effective. Investigating how and under what conditions this could work would be an intriguing interdisciplinary task for researchers.

Regarding the measure that was opted for investigating in more detail, Combined Road-Rail Transportation (CRRT), an avenue for promising research progress lies in providing a more detailed examination of the application potential within a manufacturers' network. While the approach and simulation presented in this thesis hold promise in simplifying the CRRT system's intricacies, a more comprehensive and nuanced methodology could potentially diminish obstacles to CRRT adoption to an even greater extent. Collaborative efforts with forward-thinking entities in the rail industry, including rail service providers, integrated transportation service providers, and other pertinent stakeholders, may engender novel insights on strategies to substantially augment the modal share.

Furthermore, within the specific domain of CRRT, there exists a paucity of data pertaining to European emission intensity factors. Diverse transportation routes and equipment contribute to variations in energy consumption and emission intensity, consequently influencing specific emission factors. Notably, the Global Logistics Emissions Council (GLEC) framework does not furnish comprehensive information in this regard. While certain practical tools, such as EcoTransIT World, offer broad factors for multimodal transport in the European context, they do not supply the requisite level of granularity.

In conclusion, establishing a moderated working group that brings together industry professionals and researchers to exchange experiences and knowledge in the transportation sector could be a pivotal step. Such a collaborative platform would not only facilitate the sharing of insights from pilot projects and scientifically validated emission reductions but also foster joint initiatives, thereby raising awareness and promoting widespread implementation. Emphasizing the strides made by logistics and manufacturing enterprises in decarbonizing logistics further has the potential to drive competitive peers toward accelerated adoption of sustainable practices. Thus the creation of such a group and the careful selection of participants could speed up decarbonization.

7. Conclusion

The energy and transport sectors are growing ever closer together, which is why decarbonization of freight transport is an important part of achieving climate targets and will not be possible without decarbonizing the energy sector. Vice versa, the energy transition may be threatened by negative developments in logistics. Therefore, to hinder more severe impacts on the environment, the next decade of development must be dedicated to zero-carbon production, transportation, and energy systems.

Although manufacturing companies often do not see it as their responsibility to reduce emissions from transportation, they are the transportation principals – and therefore set the pace in terms of costs and emissions. In addition to influencing logistics service providers through green tendering and awarding practices to improve the technical and operational emission intensity, numerous tactical and strategic measures can be taken within the logistics network to avoid or shift transportation.

This thesis aimed to investigate the industrial logistics system towards the existing decarbonization practices in detail. Thereby, recent advances in academic literature and nonfinancial reports from transport-intensive manufacturing companies were studied, expert interviews with decarbonization frontiers and surveys of the Austrian industrial logistics landscape were conducted, and decision-support tools and a novel perspective to investigate decarbonization practices developed. All in all, the contributions are presented in six journal papers of which one is under review at the time of writing these lines, and three conference proceedings of which one was an industry conference and the other two scientific conferences.

While the articles published throughout this thesis contribute to the scholarly knowledge of the respective fields and provide nuanced suggestions for practitioners, the focal thesis as a summary work combines this collective knowledge and provides a bigger picture on the overall research questions. Researchers might benefit from this picture as a spur for novel research ideas, while practitioners can comprehensively derive suggestions on how to integrate the knowledge in their firms.

To sum up the work of the last years, the most stringent challenge for companies seems to be choosing the right speed in the adoption of new technologies. Oversleeping developments in this high-paced area is likely to be as dangerous as investing in the wrong technology too early – which was evident in the application of LNG trucks in middle Europe. Regarding future truck technologies, the use of zero-emission vehicles will be unavoidable, but impossible on a large scale at the moment. Thus, the most promising measures in the coming years are, from the authors' perspective, the use of combined transport, intelligent planning systems and higher biofuel blends.

Conclusively, it is to be optimistic that decarbonization of transportation will proceed in Europe in the coming decade at a high pace. Novel technologies and advanced planning techniques will impact the movement of goods – and customers will probably not even recognize how severely the transportation system changed, albeit being spammed with advertisements of the companies achieving "zero-carbon logistics".

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9. Appendix

9.1. Paper 1

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A framework of measures to mitigate greenhouse gas emissions in freight transport: Systematic literature review from a Manufacturer's perspective

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ABSTRACT

The publication of the sixth assessment report of the IPCC finally cleared out voices mentioning that the increase in surface temperature of the last 100 years was not man-made and that substantial changes are necessary to still reach the goals set in the Paris climate agreement. Two economic sectors contributing strongly to climate change due to their high greenhouse gas emissions are industry and transport. Whereas cross-sectoral dependencies between the energy and the transport sector are widely investigated, measures that can facilitate an emission mitigation in the crossings of the industrial and the transportation sector are merely researched systematically, diminishing the perspective of a manufacturing firms' supply chain. To contribute to this gap, the focal paper presents the results of a Systematic Literature Review conducted in 2021, presenting first, a comprehensive categorization of measures that are presented in scientific literature and can be implemented to decarbonize transport operations of manufacturing companies, and second, the expected maximum reduction potential of those measures. Analyzing 81 peer-reviewed articles from several journals, the authors identify a total of 215 measures and assign them to 27 categories in nine clusters, that can be adopted by manufacturing companies themselves or by their logistics service providers. In general, categories related to drivetrain and fuel selection stand out in the number of identified measures, but a consensus on the reduction potential of those measures is missing, which is, among others, due to different technologies, baseline scenarios, assumptions, and carbon intensities. The most confidential estimation of the reduction potential can be made in the mode selection, where the median of all found figures is located at 28.5%. The lowest number of measures was found in the cluster Shippers' Employees, highlighting the need to further investigate the role of the human in decarbonizing the economy. Changes in operations, for example a higher utilization of vehicles due to a shift away from the Just-in-Time concept are mentioned in literature, but its impacts cannot be underpinned by figures.

1. Introduction

Since the publication of the sixth assessment report of the Intergovernmental Panel on Climate Change (IPCC) in August 2021, it is "unequivocal" that human activities caused the atmosphere, ocean, and land to warm. In detail, the past 50 years are very likely to be the period with the steepest increase in global surface temperature in the last 2,000 years. This is because the concentration of anthropogenic greenhouse gases (GHG) was continuously increased in the last years. The report, which references more than 14,000 pertinent scientific studies on the topic of climate change, points to a bleak future for achieving the Paris climate goals and the avoidance of irreversible effects if "deep reductions" in GHG emissions across the ecosystem do not occur soon (IPCC, 2021b; 2021a). To enable those reductions, all sectors of the economy must contribute to reductions in the near future. Looking at the sectors with the biggest contribution to worldwide GHGs, transport and industry stand out, accounting for 16.2% and 29.4%, respectively (Ritchie and Roser, 2020). Due to the need for industrial firms to

Abbreviations: GHG, Greenhouse Gas; IPCC, Intergovernmental Panel on Climate Change; BEV, Battery Electric Vehicle; FCEV, Fuel-Cell Electric Vehicle; ICEV, Internal Combustion Engine Vehicle; JIT, Just-in-Time; ASI, Avoid-Shift-Improve; SLR, Systematic Literature Review; EV, Electric Vehicle; HV, Hybrid Vehicle; ERS, Electric Road Systems; EREV, Extended-Range Electric Vehicles; PHEV, Plug-In Hybrid Electric Vehicle; LNG, Liquid Natural Gas; CNG, Compressed Natural Gas; CCU, Carbon Capture and Utilization; WtW, Well-to-Wheel; PtL, Power-to-Liquid; SNG, Synthetic Natural Gas; LCA, Life Cycle Assessment; LSP, Logistics Service Providers; IQR, Interquartile Range.

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transport and handle commodities, intermediate- and end-products, as well as returns (Bowersox et al., 2002), the industry (e.g., manufacturing companies) determines the amount of transport required and acts as the demanding party, requesting transportation services, and the transport sector (e.g., logistic service providers) acts as the supplier, carrying out those transportation services. In this respect, the manufacturing companies also determine indirectly the number of emissions generated, which is why those two sectors are highly interconnected and must be considered jointly for deep emission reductions in transportation.

When investigating decarbonization of transport from a manufacturers' perspective, proposed solutions so far mostly deal with structural factors in the supply chains and concern the avoidance of transport, for example by selecting suppliers (Govindan and Sivakumar, 2016; Yamada et al., 2015; Yu et al., 2018) or relocating production sites (Bojic et al., 2018; Nieuwenhuis et al., 2012; Roy et al., 2015), which often encounter barriers in practice and, in the end, the decisive factor is often not the GHG savings (Neri et al., 2018). On the other side, practices undertaken by logistics service providers to green transport primarily focus on the shift to other modes of transport (Leal Junior and D'Agosto, 2011), the application of lower-carbon fuels, often in combination with alternative drivetrains (DHL, 2019), or measures to increase fuel efficiency like eco-driving (Centobelli et al., 2017a). Those initiatives often encounter obstacles in practice due to their economic disadvantage and operational barriers, which lead to higher transportation costs and longer delivery times not accepted by the customers (Abbasi and Nilsson, 2016; Anderhofstadt and Spinler, 2019). In the supply chains, these customers are the manufacturing companies, which, due to their role as contracting authorities, not only determine the amount of transport required, but can also define the specifications of these purchased services through tenders and awards of transport services (Pålsson and Kovács, 2014). Thus, to fully exploit potentials in transportation and achieve deep reductions, manufacturing companies need to be aware of possible measures at all levels, whether they implement them on their own or require their service providers to do so. While there is extensive literature on each of those levels independently, to the best of the authors' knowledge, there is little research presenting the "big-picture" of measures to be potentially implemented.

To fill this gap, the current paper aims on gaining a comprehensive view of measures to reduce GHG emissions in transport operations of manufacturing companies that are presented in the current scientific literature. In addition to the provision of a broad categorization of those measures, the expected maximum GHG emission reduction potential of those is elaborated and estimated throughout the study, based on the findings of 81 peer-reviewed articles. Due to the need to gain a holistic picture of the topic, it was found that an appropriate methodology for this research project will be the systematic literature review, because of its ability to ensure the inclusion of all relevant literature in a specific research stream (Snyder, 2019), Furthermore, this method is transparent, replicable, and reliable (Tranfield et al., 2003), and was used in researching different sustainability issues in manufacturing (Schanes et al., 2018) and decarbonization measures in transportation (Bjerkan and Seter, 2019; Bouman et al., 2017). By using this methodology, the paper gives an overview of measures potentially being able to reduce GHG emissions in transport operations of manufacturers to practitioners and serves as a holistic guide for further research targeting decarbonization in the overlaps of manufacturing and transportation.

The remainder of this paper is structured as follows: Section 2 provides the theoretical background of this research study by focusing on the reduction of GHG emissions in the specific area of manufacturing and companies and their interrelated transport operation processes. Section 3 presents the research design and, therefore, the standardized methodology of the systematic literature review as well as the descriptive results from the PRISMA-based secondary data analysis. Following this, Section 4 introduces a classification of emission reduction measures on transport operations and discusses elaborates on the resulting nine clusters with 27 categories of potential measures more in detail. Based on the research findings, Section 5 discusses the resulting possibilities for manufacturers, addresses the expected reduction potential, and outlines unexpected findings and limitations of the research study. Finally, Section 6 provides the conclusions and implications drawn for researchers and practitioners.

2. Background

As mentioned at the beginning, it is inevitable to reduce GHG emissions to limit global warming and, thus, climate change (IPCC, 2021a). This has also been the topic of discussion in numerous international conferences, finally leading to the Paris Agreement (UNFCC, 2015) and the European Green Deal. One of the main aspects of the latter is the path to climate neutrality, which should be reached in 2050 (European Commission, 2021). To achieve this goal, ambitious intermediate targets are proposed by the Commission, inter alia, a 100% cut in tailpipe emissions from cars in 2035 (Carey and Steitz, 2021) to mitigate emissions from the transport sector, which is responsible for approximately 23% of all GHG emissions in the EU27 (European Environment Agency, 2020). Although this measure is mainly aimed at passenger transport, freight transport is also increasingly coming under the spotlight due to its 7% share of global GHG emissions, its prevalent nature, and the expectations that the trend toward rising demand for transportation will continue in the future (ITF, 2021; Ma et al., 2012; OECD/ITF, 2015).

Much of this demand is generated by the manufacturing industry, for which the transportation of freight from a source to a destination is a crucial task, due to the need for goods to be moved through the value chain to be manufactured, assembled, or processed (Rodrigue, 2020). Short product life cycles, the use of Just-in-Time (JIT) operations, and multinational production further push the number of required freight movements (FHWA, 2020). Looking at the primary activities in Porters' value chain, transport activities can be found primarily in the inbound and the outbound logistics, ensuring the smooth supply of goods closely linked to the procurement, and enabling the distribution closely linked to demand management, respectively (Christopher, 2006; Porter, 1985; Zsifkovits, 2017). Looking at those transport activities in manufacturing companies through the lenses of the resource-based view, several dimensions of the logistics resources configuration exist (Pålsson and Kovács, 2014). One of the most critical dimensions for companies is the decision on whether to control and execute logistics activities in-house or to outsource them to logistics service providers (LSP) to any extent (Kovács and Tatham, 2009). In all cases, however, the reason for the occurrence of emissions is the need for transportation to supply production with the necessary resources and to maintain the company's ability to fulfill customer demands. Thus, also those emissions have to be accounted to the manufacturing company, resulting in Scope 1 or 3 emissions, depending on the executing party of transport (Smith, 2004).

Figures on the share of those emissions on the total carbon footprint of manufacturing companies are vague, but some indication is available, proposing that about 3–35% of the overall emissions of a manufacturer, depending on the industry sector, attribute to in- and outbound transportation (Apple Inc, 2021ITF, 2021, p. 67; Crippa et al., 2021; NIKE ITF, 2021, p. 47; Poore and Nemecek, 2018; Punte and Bollee, 2017, p. 12). Whereas low-carbon practices in manufacturing processes already have an impact on the enterprises' carbon performance, decarbonization initiatives in logistics have still not developed their expected effects (Lopes de Sousa Jabbour et al., 2020). Additionally, manufacturing companies generally pay more attention to the decarbonization of their core business activities because they provide a bigger lever to reduce emissions (McKinnon, 2018, p. 32). This gives rise to the presumption that the share of logistics-related emissions will increase in the future, exerting more pressure on decision-makers in business logistics.

In addition to this potential future risk, other motivators have been identified by researchers that drive manufacturing companies towards, first, generally implementing sustainability strategies (Neri et al., 2018;

Trianni et al., 2017; Zailani et al., 2012) and carbon management (Liu, 2012), and second, specifically reducing emissions in their logistics activities. For the latter, external pressure, for instance by taxes on emissions (Sarkis et al., 2011), environmentally conscious buying behavior of customers (Carter and Jennings, 2004; Liu, 2012; Sesini et al., 2020) or a strong medial attraction of transportation (White et al., 2014), complements internal motives, like business and logistics strategies (Eng-Larsson and Kohn, 2012), future business models (Quintás et al., 2018), risk management, or organizational culture (Carter and Liane Easton, 2011; Eng-Larsson and Kohn, 2012).

When companies ultimately decide to reduce emissions in transportation, a structured approach is needed to turn the mere motivation into actual impacts. To do so, several attempts have been made to guide managers to develop and operationalize green logistics strategies. Hoffman (2006), as one of the first, proposes an eight-step methodology to develop climate-related strategies. McKinnon, 2018 further elaborates this strategy specifically to the needs of the transport sector and adapts it to the decarbonization of logistics, leading to the 10C-approach (McKinnon, 2018, p. 29). One of the central steps in both approaches deals with the consideration of possible measures to decarbonize transport activities, which immediately leads to the question of which possibilities to mitigate emissions in logistics exist generally, and more specifically, for manufacturing companies.

A systematic way to adopt different decarbonization measures was presented by Dalkmann and Brannigan (2007), introducing the ASI approach and thereby proposing to first, avoid transport, second, shift it to lower-carbon modes of transport, and third, improve the fuel efficiency of the remaining transports. The study conducted by Piecyk and McKinnon (2010) further elaborates the connection between key logistics variables and their influence on GHG emissions and thereby presents six factors affecting emissions. More specific actions for changing each of those factors to reduce emissions have been frequently discussed in the literature (Wiedenhofer et al., 2020), leading to decisions to change logistics activities on the strategic, commercial, operational, and functional level (McKinnon and Woodburn, 1996). Structural decisions thereby influence the number and type of nodes in the company-controlled parts of the supply chain, e.g., the number and location of production facilities or warehouses. Commercial factors relate to decisions influencing the company's supply and customer base, defining from whom tangible or intangible goods are purchased and to whom they are sold. Operational decisions relate to the scheduling of orders and thereby determine the time and quantity of each singular delivery. Finally, on the lowest hierarchical level, functional decisions affect how the transports that are requested are carried out, e.g., which vehicles are used. All these decisions together determine the GHG emissions generated by transportation activities of manufacturing companies and must therefore be considered when deeply decarbonizing logistics.

According to contingency theory, each firm must tailor those decisions on contingent factors, such as the size of the company, its industrial sector, the country of operation, its customer base, or its role in the supply chain, which is why no universal recommendations for decarbonizing logistics can be provided for all organizations (Choi et al., 2001; Donaldson, 2001; Ginsberg and Venkatraman, 1985). Considering the last factor, typically, manufacturing companies decide on the hierarchically upper levels on their own, whereby, lower levels tend to be outsourced to LSPs (Chopra and Meindl, 2016), creating two ways to influence GHG emissions, a direct and an indirect one. First, emissions from activities conducted in-house can obviously be influenced directly. Secondly, considering outsourced activities, manufacturing companies are in the role of the contracting entity, laying down the basic principles on how those operations are to be carried out in the purchasing process, and, hence, having a strong indirect influence on the execution of the transport (van Weele, 2014). Therefore, manufacturing companies can very well "require changes in transportation-related decisions (e.g. modal choice, routing, use of less polluting vehicles), as well as exercise their stakeholder pressure in the sheer choice of LSP" (Pålsson and Kovács, 2014). Once LSPs are contracted and are in their role of carriers, they carry out what is contractually stipulated on the part of the shippers, thus having little to no options to influence GHG emissions. The shippers, therefore, must be aware of the measures the carriers can potentially adopt and include them in their contracting process. Thus, independent of the hierarchical level from which the activities are outsourced, shippers must be aware of measures on all hierarchical levels because the decision-making area of manufacturing companies not only encompasses activities conducted in-house but also the outsourced hierarchical levels. Hence, to deeply reduce emissions in freight transport, the consideration of measures on all logistics decision levels is necessary for manufacturing companies.

To sum up the relevance of investigating decarbonization measures in transport from a manufacturer's perspective, we conclude that.

- from a global perspective, transportation activities from the industry account for about 7% of total GHG emissions
- from a manufacturing firm's perspective, emissions from logistics account for about 3–35% of total GHG emissions, whereby this share is expected to rise
- manufacturing firms determine the basic demand for transportation by defining the supply chain nodes and links and thus must be aware of measures on the upper hierarchical levels (i.e., structural and commercial decisions) to enable deep GHG mitigation
- manufacturing firms, in their role as principals in transportation contracts, can determine the details of the execution of transports and thus must be aware of measures on the lower hierarchical levels (i.e., operational, and functional decisions) to enable deep GHG mitigation

This indicates the need for a comprehensive review that allows managers to fully understand what levers they have at their disposal, as well as which potential reductions can be expected by implementing those measures. The relevance of providing sound potential estimations of measures is further highlighted by Pålsson and Johansson, 2016), who show a high correlation between the perceived potential of a measure and the company's intention to implement it, by LSPs as well as freight owners. This implies, that the provision of quantified reduction potentials by researchers might lead to an effective reduction of emissions. Looking at existing literature on this topic reveals, that previous studies presenting sets of measures analyze literature mostly in a non-systematic, 'narrative' way, leading to a potential lack of thoroughness and rigor (Tranfield et al., 2003). Furthermore, reduction potentials are either not mentioned at all, or only qualitatively (McKinnon, 2018, p. 50; Pålsson and Johansson, 2016). Centobelli et al. (2017b) underlines this statement by analyzing current literature on green logistical initiatives and highlighting the need to develop a comprehensive taxonomy of green initiatives supporting environmental sustainability, as well as the clarification of its impacts.

From the aforementioned considerations, two gaps in the literature were identified. First, the need to create a comprehensive framework of measures that can be considered by manufacturing companies on all hierarchical decision levels to reduce their transport emissions is identified. Second, the impacts of measures in such a taxonomy, quantified by their reduction potentials, have to be elaborated. By analyzing the pertinent literature on the topic by the means of a systematic literature review (SLR), the current paper contributes to both of those research gaps by, first, proposing a framework of measures to decarbonize transport, as well as collecting their reduction potentials systematically. The SLR was chosen due to its wide scholarly acceptance in management, social, as well as engineering sciences as a means to identify relevant trends and advances (Centobelli et al., 2017b; Manders et al., 2017), provide holistic perspectives on the literature of specific research streams (Antony et al., 2021; Bouman et al., 2017; Manders et al., 2017; Woschank et al., 2020), provide an overview of practical implications

(Antony et al., 2021; Bjerkan and Seter, 2019) and reveal future research suggestions (Antony et al., 2021; Centobelli et al., 2017b; Manders et al., 2017; Woschank et al., 2020). By using the SLR methodology, an approach to synthesize evidence-based knowledge in a specific research field is adapted from medical sciences, providing results from a review done in a "systematic, transparent, and reproducible manner with the twin aims of enhancing the knowledge base and informing policymaking and practice" (Tranfield et al., 2003). Thus, the results of this article provide a basis for practitioners, as well as a reflection of existing advances and gaps in research for the scientific community.

Summarizing these paragraphs and reflecting on the existing literature in this field, the goals of this research for practitioners are twofold: First, measures for manufacturers to reduce the GHG emissions in the transportation operations related to the production are to be identified and a classification of those is to be developed. Second, the potential emissions savings as a result of implementing those measures, and, thus, the savings a producer can expect, are to be elaborated. Contributions to the scientific knowledge base are done by highlighting the current state-of-the-art in research, as well as pointing out future research directions to facilitate emission mitigation in transportation activities of manufacturers.

3. Methodology

In this section, the design and quantitative results of the literature review are presented.

3.1. Review design and methodology

The research methodology of this paper is based on the conduction of a systematic literature review (SLR) which is used to substantially develop knowledge in a specific domain of research. Therefore, from an epistemological perspective, the authors transfer the SLR approach, which has been established for years as a sound scientific method in disciplines such as medicine or pharmacy, to the specific area of operations management. The SLR will be used to systematically retrieve, select, synchronize, and analyze current research studies based on the usage of quantitative and qualitative content analyses. This novel approach will be used to push operations management research to the frontier of current methodological standards and to significantly contribute to the further development of research and practical applications, as well (Durach et al., 2017; Hökkä et al., 2014). Current literature furthermore stresses the application of SLRs for the generation and assessment of new knowledge because this instrument minimizes various judgment biases by systematically evaluating relevant insights from recent research studies (Ali and Usman, 2018; Palmarini et al., 2018; Tranfield et al., 2003; Woschank et al., 2020). This paper aims to investigate the potential for the reduction of GHG emissions in freight transport operations. Therefore, according to the guidelines of SLR, first, a scientific database was selected (Denyer and Tranfield, 2009; Durach et al., 2017; Petticrew and Roberts, 2006). Therefore, the authors used Scopus, and as an additional search in other databases did not lead to any significant differences in the articles identified, it has remained the only one. This decision is supported by similar studies in the field of operations management, where little added value was found when additionally consulting other scientific databases, such as Web of Science, Emerald, or EBSCO (Woschank et al., 2020; Zunk, 2018). Afterward, the search string was defined, covering all aspects of the subject under study, and excluding all non-relevant keywords for freight transport in manufacturing companies. The keyword combination is presented in Table 1 To reflect the aim of the paper, all measures should be found that can potentially be adopted by manufacturers in their transport operations. Thus, the term "manufacturing" was intentionally not included in the search string to avoid limiting the results to articles dealing only with measures in manufacturing companies. By searching with the provided string, measures for all stakeholders of the transport sector were covered.

Table 1
Search string keywords.

	AND	AND	AND NOT
OR	green	freight transport	urban*
OR	decarbon*	transport sector	city log*
OR	defossil*		reverse log*
OR	carbon emission*		warehouse*
OR	co2*		car*
OR	greenhouse gas emission*		

The Scopus search string was then further limited to conference papers, articles, and book chapters to focus on highly relevant and qualitative literature; the subject areas of economics, engineering, and business management were chosen due to the object of investigation, manufacturing companies, and the character of the study, and the language was limited to English to ensure only the inclusion of internationally peer-reviewed literature. The limitation of the year was broadly discussed by the authors because a considerable amount of literature was found to be published earlier than 2016, but, due to the rapid developments in technology, the focus was set on more current research. The final search string is provided in the supplementary material.

The selection of articles for the final review was carried out in line with the PRISMA guidelines (Page et al., 2021) as visualized in Fig. 1, but slightly adapted to the inclusion of articles found through a backward search, as suggested for example by vom Brocke et al., 2009.

In total, 410 papers were identified by the search string, which was subjected to the title and abstract screening. In this phase, articles indicating a promising contribution to the framework were further selected for a full-text review. The indication of whether one article was promising or not was done by the in- and exclusion criteria and was conducted by each of the authors separately to ensure internal validity (Thomé et al., 2016). Articles presenting measures to decarbonize transport operations for manufacturers in their role as shippers, as well as logistic service providers in their role as carriers, were included in further analyses. In contrast, articles indicating the investigation of only public or individual passenger transport, the planning and operations of infrastructure, or the investigation of carbon taxes or policies were excluded from the article set, because these do not present measures for microeconomic entities.

After the titles and abstracts were screened, 129 papers presenting potential measures were identified and, thus, sought to be included in the full-text analysis; 18 of those could not be retrieved, so a final number of 111 articles was assessed for eligibility. During this second step of screening, the focus was set on the results and conclusions of those papers due to the high number of results. From the set of relevant papers, 56 (50.45%) were identified that indeed met the inclusion criteria and, thus, contributed to the overall aim of this paper.

In this last phase, a backward search was also conducted, leading to 25 additional research papers that presented relevant measures. Here, no timely restriction was set to ensure a holistic view of the research topic. Thus, a total number of 81 peer-reviewed articles were analyzed, which is a reasonable number of sources for an SLR compared with similar studies ($n = 70$ in Bjerkan and Seter, 2019, $n = 41$ in Centobelli et al., 2017b, $n = 92$ in Manders et al., 2017, $n = 103$ in Woschank et al., 2020). From analyzing the found papers, a PostgreSQL database was built up, in which all presented measures were collected. All measures, the conducted categorization, as well as the sources including their description, can be found in the respective Mendeley Data repository (Miklautsch, 2022). For each paper, several measures could be included in the collection. For each measure, the respective mode(s) of transport and, if possible, the GHG emission reduction potential was added to the database. Based on Rodrigue et al. (2013), the possible modes of transport mentioned are Road, Rail, Water (including inland waterway, deep sea, and short sea), Air, and, if the measure affects or can be applied

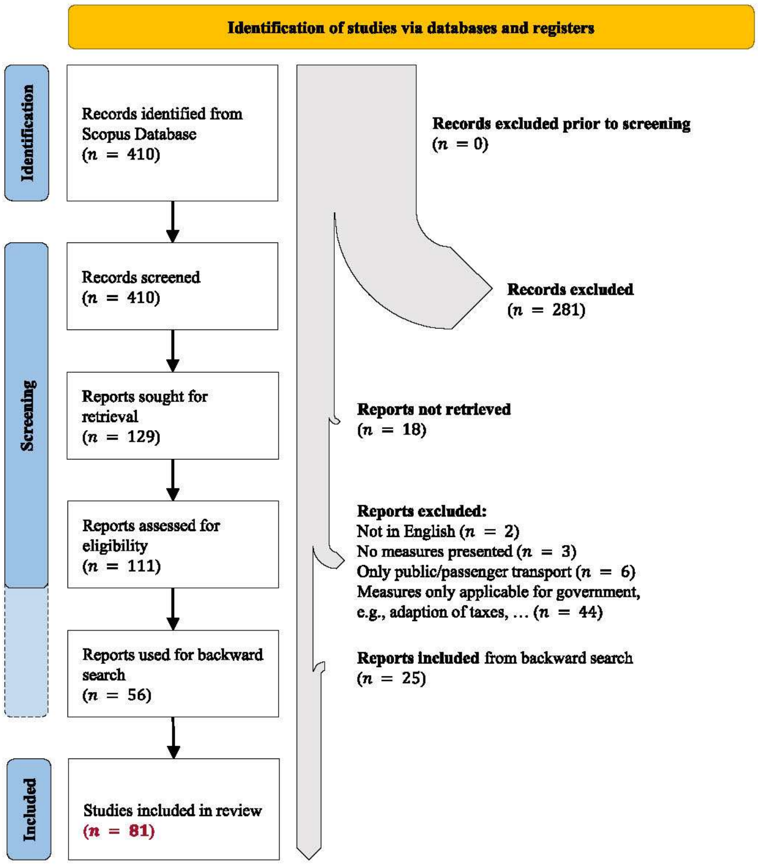

Fig. 1. Slightly modified selection process of relevant studies according to PRISMA (Page et al., 2021; vom Brocke et al., 2009).

to multiple modes, Intermodal. The relative reduction potential of the discussed measure was stated concerning the emissions from the mean of transport currently considered as "conventional" for one mode of transport, e.g., emissions of diesel trucks.

3.2. Descriptive analysis

Analysis of the document type distribution in Fig. 2 (a) leads to the finding that most of the identified literature are journal articles, indicating a high quality of literature. Only a small number of research was published as book chapters, which were dominated by literature found through backward search.

Investigating the research papers according to their methodological approach was conducted in line with other literature reviews (Seuring and Müller, 2008; Srivastava, 2007; Woschank et al., 2020). Derived from those, the categories used are empirical studies, reviews, papers presenting frameworks and approaches without a specific methodology, modeling and simulation, and mixed-method approaches. The result is visualized in Fig. 2 (b). The plot reflects the current trend to use mathematical modeling and simulation approaches to estimate emission reduction potentials of specific measures or a set of combined ones. Another frequently used methodology is a Case Study, whereby most of them also apply models or simulations to data from case studies or use case studies to validate specific models. Nine empirical studies were found, four of them in the direct search. Frameworks/Approaches, as well as reviews, tended to appear mainly in the papers identified in the backward search. Three mixed-method papers were found, including an empirical study as well as a simulation or modeling, further processing the empirical data.

In this regard, Fig. 2 (c) demonstrates that most of the research is conducted in groups of two and three ($n = 20$ each), or four ($n = 18$). A closer look at the composition of the groups reveals mostly international collaborations, which emphasizes the necessity of cooperative research. Anticipating the findings of the next paragraph shows the movement to larger research groups and more collaboration in the last years because newer papers found in the direct search tend to compose a higher number of authors.

Fig. 2 (d) plots the papers grouped by their publication year, showing, that literature found in the direct search is distributed from 2017 to 2021, having a peak in 2020 with $n = 15$ papers. Due to the time of the research (June 2021), it can be expected, that the number of literature on this topic in 2021 will outpace the last years, which indicates a strong movement of research in direction of climate change mitigation.

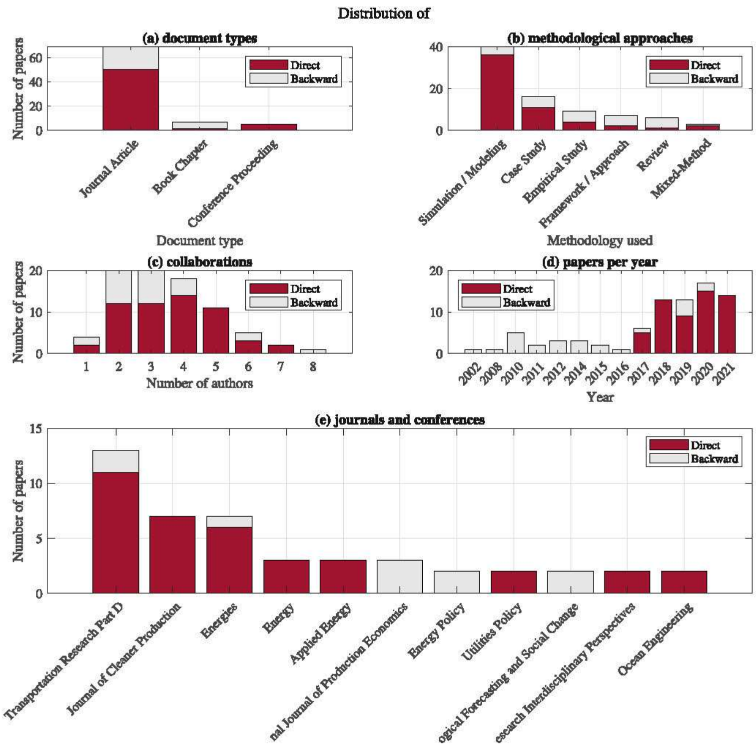

Fig. 2. Descriptive analysis of the included papers.

In Fig. 2 (e), all journals or conferences are visualized in which more than one of the papers found was published. The leading journal is *Transportation Research Part D: Transport and Environment* with $n = 11$ papers found directly in the database search and two papers found additionally in the backward search. *Journal of Cleaner Production* and *Energies* followed at some distance with seven papers, solely found in the direct search and one found in the backward search, respectively. In another three journals (*Energy*, *Applied Energy*, and *International Journal of Production Economics*), three papers were found, and in other journals, two papers were presented. A significant number of papers found in energy-related journals point out the strong link between the transport and energy sector and the close coupling of decarbonization in transport to the decarbonization of the energy system.

4. Content analysis and results

During the full-text analysis, all measures that can be decided on one of the four decision levels discussed earlier were collected, which guarantees that the classification is specifically tailored to manufacturing companies and encompasses all GHG reduction options, regardless of the resource configuration of individual companies. In this section, the identified measures are categorized, clustered, and described. The terminology adheres to the following established logic: on the lowest level, there are "measures" that can be implemented by companies. Measures that have the same effect are aggregated into "categories", and these categories are aggregated into "clusters." Clusters and categories are visualized in Fig. 3. A total number of 215 identified measures was clustered into nine clusters with 27 categories of measures.

Measures, for which a reduction potential was reported, were plotted in Fig. 4 using the MATLAB boxplot function. Thus, the symbology is standardized, showing the median as a red line, the bottom and top edges of the box as the 25th and 75th percentiles, and the whiskers extend to the extremes, separately displaying outliers with the "+" symbol (MathWorks, 2021). Additionally, all data points are plotted separately as small black dots to gain an understanding of the number of measures identified.

The categories *VS2 Drivetrain technology* and *FS1 Fuel selection* have been combined in this figure but included in the framework separately. This is because the drivetrain selection only affects the type and amount of energy (e.g., kWh/km), and the decision on the fuel selection then determines the carbon intensity (e.g., CO_2e/kWh). Thus, in the end, both factors together determine the emissions, but can be decided separately and, therefore, also have been included in the framework separately. Many cited papers mention reduction potentials as a function of propulsion technology and fuel type together and do not separate these two factors, which is why those categories are plotted as one in this study.

In the following sections, all measures included in each category and mode of transport are listed in the table at the beginning (see Tables 2–10), including references to the articles in which they were found. To maintain readability, transport modes without measures in this cluster have been deleted from the respective table. Following the table, all categories are described. If a reduction potential was found, the corresponding data are explained by the use of Fig. 4. To conclude a category, the measures presented are discussed regarding their barriers and benefits found in the literature.

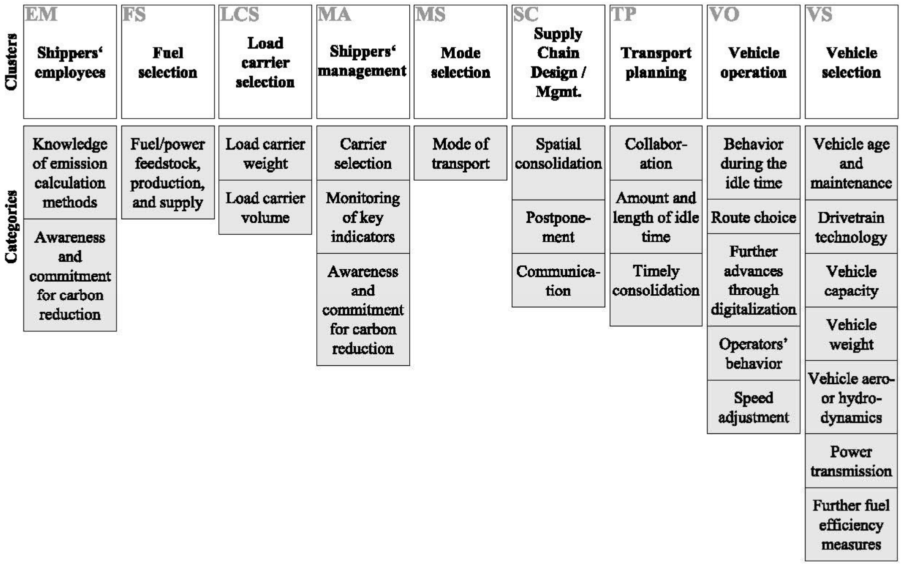

Fig. 3. Classification of emission reduction measures in transport operations of manufacturers.

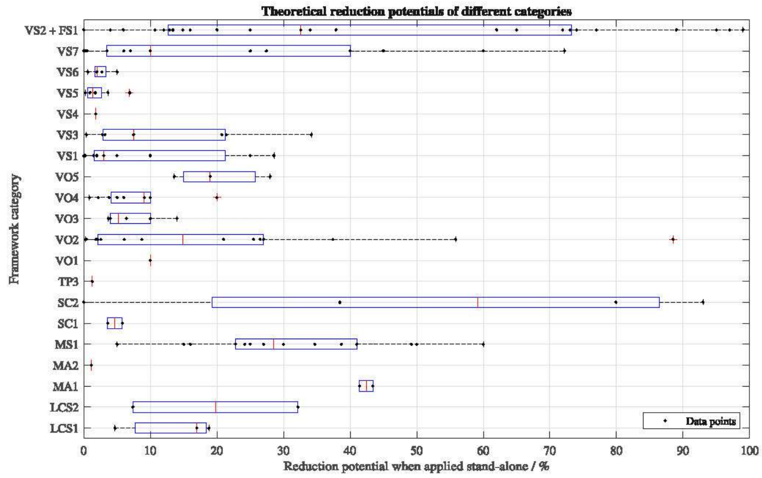

Fig. 4. Reduction potentials of the identified measures.

4.1. Vehicle selection (VS)

4.1.1. Description

VS1: Failure to meet the latest Euro standards for trucks or the Energy Efficiency Design Index and the Ship Energy Efficiency Management Plan for vessels inevitably leads to an increase in emissions. Depending on the country, new vehicles must meet the current standards and, thus, contribute to a decrease in emissions (Christodoulou and Cullinane, 2020; Dioha and Kumar, 2020). Nevertheless, some of those standards can also be fulfilled by old vehicles, in the event their main or auxiliary engine is retrofitted, overhauled, and brought up to the state of the art (Ali et al., 2021). Effective maintenance and inspection prevent leakage of gases, fuels, or lubricants and, thus, lead to lower wastage (Deenapanray and Khadun, 2021). When ships are maintained, their hull and propeller can be cleaned and adjusted, thereby reducing future water resistance and fuel efficiency (Prasad and Raturi, 2019; Sames and Köpke, 2012). Modern, low-friction lubricants lead to reduced resistance and thrashing and can enhance the energy efficiency and fuel consumption of engines. This is more important the larger the engine gets (Ang-Olson and Schroeer, 2002).

VS2: Due to the broad mass of measures in this category, they are further divided and described separately.

Table 2
Categories and measures in the Vehicle Selection cluster.

		Road	Water	Air
VS1	Vehicle age and maintenance	**Replacement of old trucks** (Ali et al., 2021, 2021, 2021; Dioha and Kumar, 2020; Grant-Muller and Usher, 2014; Liimatainen et al., 2014; Maduekwe et al., 2020; Marcilio et al., 2018; McKinnon, 2010a), **Frequent inspection and maintenance** (Deenapanray and Khadun, 2021; McKinnon, 2010a), **Engine retrofit** (Ali et al., 2021), **Low-friction lubricants** (Ang-Olson and Schroeer, 2002)	**Hull coating and maintenance** (Prasad and Raturi, 2019; Sames and Köpke, 2012), **Propeller cleaning** (Prasad and Raturi, 2019; Sames and Köpke, 2012), **Engine retrofit** (Sames and Köpke, 2012)	
VS2	Drivetrain technology	**Engine power adjustment** (McKinnon, 2010a), **EV** (González Palencia et al., 2020; Jahangir Samet et al., 2021; Mojtaba Lajevardi et al., 2019; Zhang and Hanaoka, 2021), **HV** (Zhang and Hanaoka, 2021), **FCEV** (Kotze et al., 2021; Mojtaba Lajevardi et al., 2019; Perez et al., 2021), **Gas-ICEV** (Dioha and Kumar, 2020; Mojtaba Lajevardi et al., 2019; Sharafian et al., 2019)	**Engine power adjustment** (Sames and Köpke, 2012), **EV** (ben Brahim et al., 2019; Christodoulou and Cullinane, 2020), **HV** (ben Brahim et al., 2019; Christodoulou and Cullinane, 2020; Ghenai et al., 2019; Prasad and Raturi, 2019), **FCEV** (ben Brahim et al., 2019; Sames and Köpke, 2012), **Gas-ICEV** (ben Brahim et al., 2019; Sames and Köpke, 2012)	**EV** (Trancossi and Pascoa, 2018), **HV** (Trancossi and Pascoa, 2018)
VS3	Vehicle capacity	**Longer and heavier trucks** (Burg et al., 2019; Kumar, 2021; Martinsen and Huge-Brodin, 2014; Palmer et al., 2018), **High cube/double-deck trailers** (Marcilio et al., 2018; Palmer et al., 2018)	**Larger ships** (ben Brahim et al., 2019; Christodoulou and Cullinane, 2020)	
VS4	Vehicle weight	**Use of lightweight materials** (Ang-Olson and Schroeer, 2002; McKinnon, 2010a)		
VS5	Vehicle aero- or hydrodynamics	**Attachment of parts for the reduction of air resistance (e.g., spoilers)** (Ang-Olson and Schroeer, 2002; Islas-Samperio et al., 2020; McKinnon, 2010a)	**Changes to reduce air resistance** (Sames and Köpke, 2012), **Changes to reduce water resistance** (Sames and Köpke, 2012)	
VS6	Power transmission	**Low emission tires** (Ang-Olson and Schroeer, 2002; Martinsen and Huge-Brodin, 2014) **Tire inflation systems** (Ang-Olson and Schroeer, 2002; Islas-Samperio et al., 2020)	**Propeller dimension** (Christodoulou and Cullinane, 2020), **Propulsion improvement devices** (Prasad and Raturi, 2019; Sames and Köpke, 2012)	
VS7	Further fuel efficiency measures		**Wind propulsion devices** (Ballini et al., 2017; ben Brahim et al., 2019; Sames and Köpke, 2012), **Waste heat recovery system** (ben Brahim et al., 2019; Lampe et al., 2018; Sames and Köpke, 2012), **Improvement of auxiliaries** (Sames and Köpke, 2012)	

Engine power adjustments: By optimally matching the engine power supply to the necessary power demand, excess engine power is omitted. This leads to lower usage of resources in production, lower weight of the engines, and lower fuel consumption due to running the engine at the optimum operating point (McKinnon, 2010a; Sames and Köpke, 2012).

Electric Vehicles (EV) are solely powered by electric engines and, thus, do not need any kind of fuel, but only electricity. The most common technology is Battery Electric Vehicles (BEVs), that store the necessary energy to power the drivetrain and the auxiliaries on board. Current challenges for BEVs are a limited freight weight due to the high weight of the battery, a limited range, and long recharging times. A solution for these challenges might be the implementation of EVs by Electric Road Systems (ERS), which supply power to EVs through overhead lines, rails, or inductive charging technologies and, thus, make large-capacity batteries obsolete (Börjesson et al., 2021; González Palencia et al., 2020; Jahangir Samet et al., 2021). Besides the application of EVs in road transport, research is also made on implementing it on vessels (ben Brahim et al., 2019) and light-utility commuter aircraft (Trancossi and Pascoa, 2018).

Fuel Cell Electric Vehicles (FCEV) are powered by electricity that is generated from hydrogen in a fuel cell, emitting only water vapor and no carbon emissions in the Tank-to-Wheel phase. The hydrogen is thereby stored in a tank on the vehicle and refueling takes about as long as refueling a conventional diesel vehicle. Due to a much higher energy

Table 3
Categories and measures in the Fuel Selection cluster.

		Road	Water	Air
FS1	Fuel/power feedstock, production, and supply	**Blend conventional Diesel with supplement** (Mandal et al., 2021; Valera and Agarwal, 2019), **Electricity production** (Haugen et al., 2021), **Electricity supply via electric road systems** (Börjesson et al., 2021; Jahangir Samet et al., 2021), **Alternative liquid fuel production and usage** (Albrecht and Nguyen, 2020; Ali et al., 2021; Blanco et al., 2018; Dwivedi et al., 2019; Kirsch et al., 2020; Kumar, 2021; Liu et al., 2020; Martinsen and Huge-Brodin, 2014; Meisel et al., 2020; Mojtaba Lajevardi et al., 2019; Schreiber et al., 2020), **Alternative gaseous fuel production and usage** (Götz et al., 2016; Schiebahn et al., 2015), **Hydrogen supply** (Blanco et al., 2018; Haugen et al., 2021; Navas-Anguita et al., 2020; Perez et al., 2021)	**Alternative liquid fuels** (ben Brahim et al., 2019; Christodoulou and Cullinane, 2020; Styhre et al., 2017), **Hydrogen supply** (Ortiz-Imedio et al., 2021), **Electricity supply** (Ortiz-Imedio et al., 2021)	**Alternative liquid fuels** (Wise et al., 2017)

Table 4
Categories and measures in the Load Carrier Selection cluster.

		Water	Intermodal
LCS1	Load carrier weight	**Use of lightweight containers** (Doukas et al., 2021)	**Choice of unitization** (Harris et al., 2018; Martinsen and Huge-Brodin, 2014), **Use of lightweight containers** (Buchanan et al., 2018), **Use of lightweight packaging** (Harris et al., 2018)
LCS2	Load carrier volume		**Choice of dimensions and shape** (Martinsen and Huge-Brodin, 2014; McKinnon, 2010a; Tiwari et al., 2021)

density than a BEV and a higher efficiency of the power drive than a Diesel-powered internal combustion engine (ICE), the current FCEV trucks have a range of about 400–500 km but are still in the early market phase (Kotze et al., 2021; Perez et al., 2021). Only Hyundai Hydrogen

Table 5
Categories and measures in the Mode Selection cluster.

		Road	Intermodal
MS1	Mode of transport	**Shift to rail** (Colicchia et al., 2017; Harris et al., 2010; Palmer et al., 2018; Regmi and Hanaoka, 2015; Watson et al., 2018), **Shift to short sea** (Svindland and Hjelle, 2019)	**Combination of different modes of transport** (Dioha and Kumar, 2020; Harris et al., 2010; Heinold and Meisel, 2018; Kumar, 2021; Nasir and Rahmat, 2020; Palmer et al., 2018; Pittman et al., 2020; Regmi and Hanaoka, 2015)

Table 6
Categories and measures in the Supply Chain Design/Management cluster.

		Road	Intermodal
SC1	Spatial consolidation	**Location of hubs** (Heidari et al., 2020)	**Vendor Managed Inventory** (Harris et al., 2010), **Extensive use of consolidation centers** (Bergenwall et al., 2012; Harris et al., 2010, 2010, 2018, 2018, 2018, 2010; Martinsen and Huge-Brodin, 2014; Palmer et al., 2018),
SC2	Postponement		**Postponement of packaging process** (Harris et al., 2018) **Local production** (Nieuwenhuis et al., 2012)
SC3	Communication		**Information sharing between supply chain members** (McKinnon et al., 2010)

Table 7
Categories and measures in the Transport Planning cluster.

		Road	Water	Intermodal
TP1	Collaboration			**Use of cloud-based open collaborative logistics platforms** (Palmer et al., 2018)
TP2	Amount and length of idle time		**Reduction of turnaround time at berth** (Christodoulou and Cullinane, 2020; Styhre et al., 2017)	
TP3	Timely consolidation	**Elimination of JIT/emergency deliveries** (Bergenwall et al., 2012; Harris et al., 2010; McKinnon et al., 2010), **Flexibility in arrival and departure times** (McKinnon et al., 2010; Rogerson, 2017)		**Elimination of JIT/emergency deliveries** (Bergenwall et al., 2012; Harris et al., 2010; McKinnon et al., 2010), **Buyer consolidation** (Lin, 2019)

Mobility, a joint venture between Hyundai Motor and the Swiss company H2 Energy, is currently producing an FCEV truck in series (Hyundai Motor Company, 2021), but other competitors are close to

Table 8
Categories and measures in the Vehicle Operation clust

		Road	Water	Intermodal
VO1	Behavior during idle time	**Automatic engine idle** (Ang-Olson and Schroeer, 2002), **Auxiliary power unit** (Islas-Samperio et al., 2020)	**Cold ironing** (Binti Ahamad et al., 2018; Christodoulou and Cullinane, 2020; Styhre et al., 2017)	
VO2	Route choice	**Use of route optimization concerning emissions (green routing)** (Aloui et al., 2021; Baumgartner et al., 2008; Demir et al., 2019; Harris et al., 2018; Llopis-Castelló et al., 2019; Maduekwe et al., 2020; Poonthalir et al., 2020; Stellingwerf et al., 2018; Ubeda et al., 2011)	**Weather routing** (Christodoulou and Cullinane, 2020; Sames and Köpke, 2012), **Alternative port selection** (Harris et al., 2018; Liao et al., 2010)	**Use of route optimization concerning external costs** (Vukić et al., 2020)
VO3	Further advances through digitalization	**On-board monitoring via telemetrics** (Baumgartner et al., 2008), **Platooning** (Muratori et al., 2017)		
VO4	Operators' behavior	**Raising the drivers' awareness of environmental issues** (Fu et al., 2020; Kumar, 2021), **Eco-driving training of the drivers** (Ang-Olson and Schroeer, 2002; Grant-Muller and Usher, 2014; Kumar, 2021; Liimatainen et al., 2014; Marcilio et al., 2018; Martinsen and Huge-Brodin, 2014; Prasad and Raturi, 2018, 2019)	**Captains' training concerning environmental issues and fuel consumption** (Christodoulou and Cullinane, 2020; Sames and Köpke, 2012)	
VO5	Speed adjustment	**Speed reduction** (Ang-Olson and Schroeer, 2002; Eglese and Black, 2010)	**Slow steaming** (ben Brahim et al., 2019; Lindstad et al., 2011; Styhre et al., 2017)	

following up on this technology path (Daimler, 2021; Nikola Corporation, 2021). The application of fuel cell technology is not only restricted to road transportation but its implementation is also researched in the maritime sector (Sames and Köpke, 2012).

Hybrid Vehicles (HV) combine several different drive technologies, although it is not specified whether a specific technology must be included. The most frequent combination in road transport is the support of an ICE with an electric motor, powered by a battery or an ERS (Zhang and Hanaoka, 2021). When not specified in detail, these vehicles are called hybrid electric vehicles (HEV). A more detailed categorization can be made into extended-range electric vehicles (EREV) that implement an electric range extender and plug-in hybrid electric vehicles (PHEV) that are charged during idle time by wire (Jahangir Samet et al., 2021). However, the hybrid power supply also plays a large role in maritime transport, because the possibilities to combine power drives are manifold due to a greater amount of space in the ship's hulls (Ghenai et al., 2019). Ships can be equipped with batteries to ensure the power supply of the auxiliaries while at berth or, in combination with electric motors, replace parts of the propulsion system (ben Brahim et al., 2019; Christodoulou and Cullinane, 2020).

Gas-powered Internal Combustion Engine Vehicles (Gas-ICEV) are vehicles with combustion engines that combust gaseous fuels, instead of liquid ones. The gas can be stored in two different states of aggregation, namely liquid and gaseous. When the feedstock is fossil gas, these fuels are called Liquid Natural Gas (LNG) and Compressed Natural Gas (CNG),

Table 9
Categories and measures in the Shippers' Employees cluster.

		Road	Intermodal
EM1	Knowledge of emission calculation methods		**Availability of sound and easy-to-use tools to calculate emissions** (Cichosz and Pluta-Zaremba, 2019)
EM2	Awareness and commitment to carbon reduction	**Provision of awareness programs to the employees** (Kumar, 2021)	**Raise the willingness of transport planners to reflect on emissions** (Cichosz and Pluta-Zaremba, 2019)

Table 10
Categories and measures in the Shippers' Management cluster.

		Road	Water	Intermodal
MA1	Carrier selection	**Require sharing of vehicles and horizontal cooperation between LSPs** (Aloui et al., 2021; Kumar, 2021), **Require increased usage of alternative fuels** (Martinsen and Huge-Brodin, 2014)		**Require environmental management standard** (Kumar, 2021; Martinsen and Huge-Brodin, 2014), **Require emission reporting** (Ali et al., 2021; Cichosz and Pluta-Zaremba, 2019; Martinsen and Huge-Brodin, 2014), **Take costs of externalities into account** (Cichosz and Pluta-Zaremba, 2019)
MA2	Monitoring of key indicators	**Monitoring of load factor** (Baumgartner et al., 2008)	**Environmental performance monitoring** (Sames and Köpke, 2012)	
MA3	Awareness and commitment for carbon reduction		**Top management commitment** (Jasmi and Fernando, 2018)	**Top management commitment** (Ali et al., 2021)

respectively. In road transport, CNG is an often discussed topic (Dioha and Kumar, 2020; Mojtaba Lajevardi et al., 2019). The use of LNG is a recurring measure to reduce emissions in maritime transport. The fuel is injected either in a dual-fuel engine in combination with conventional liquid fuels or in a dedicated gas engine. The latter results in higher efficiency, but at the same time in a reduction in flexibility in fuel choice (ben Brahim et al., 2019; Sames and Köpke, 2012).

VS3: In general, the higher the possible load of the vehicle is, the more the economies of scale can be exploited, as long as the vehicle utilization is high enough. Longer trucks like the German Mega-trailer that can have a length of up to 25.25 m have thus been discussed considerably in literature, as well as higher capacitated trailers that, for example, have an increased maximum height (Burg et al., 2019; Kumar, 2021; Marcilio et al., 2018; Palmer et al., 2018). The same trend can be observed in the maritime sector, where vessels with a higher carrying capacity are suggested as a measure to mitigate emissions (ben Brahim et al., 2019; Christodoulou and Cullinane, 2020).

VS4: Although not frequently mentioned, the application of lightweight materials in trucks and trailers reduces fuel consumption and, thus, also emissions (Ang-Olson and Schroeer, 2002; McKinnon, 2010a).

VS5: Design optimization is a commonly cited measure to reduce air drag and, thereby, increase fuel efficiency. When applied to vessels, technical adaptions like the introduction of air cavity systems, hull form optimizations, hull openings, or the adoption of the draft can be done (Sames and Köpke, 2012). Aerodynamics improvements for tractors and trailers include the installation of spoilers, side skirts, or spats over the wheels to reduce friction (Ang-Olson and Schroeer, 2002; Islas-Samperio et al., 2020; McKinnon, 2010c).

VS6: Power transmission describes the transmission of energy from the engine to the medium the vehicle operates on or in. On the road, this is the tiring that can be designed specially to reduce fuel consumption and emissions. To ensure that this consumption is not offset by suboptimal pressured tires, automatic tire inflation systems can be installed in trucks (Ang-Olson and Schroeer, 2002; Islas-Samperio et al., 2020; Martinsen and Huge-Brodin, 2014). In the maritime sector, propellers transferring the power from the engine to the water can be adjusted in size or design to reduce friction and improve power transfer. Further propulsion improvement devices can also be installed (Sames and Köpke, 2012).

VS7: These measures include the installation of additional technology on the vehicle to reduce fuel demand. As already discussed in the case of hybrids, the increased space available and the high absolute energy demand on ships necessitate the increased development of these technologies for shipping. Thus, several ways to reduce the efficiency of ships were developed, including wind propulsion devices like Flettner rotors, fixed- or soft-sails, or kites (Ballini et al., 2017; ben Brahim et al., 2019; Sames and Köpke, 2012). Furthermore, waste heat recovery systems to exploit the energy potential of heat produced during the combustion of fuels for the main or auxiliary engines were developed (ben Brahim et al., 2019; Lampe et al., 2018; Sames and Köpke, 2012).

4.1.2. Reduction potential

The potential of emission reduction due to reducing vehicle age and increasing maintenance (*VS1*) is reported to be up to 28%. However, a quite low median value of 3% lower the expectations for large emission reductions and question mentioned values above the 75th percentile at about 21%. Similar reduction potentials are reported when adopting the vehicle capacity (*VS3*). Simulation studies show that even if longer trucks will be allowed in Germany, the emissions reduction from this measure is limited by 0.4–3.2% due to logistical constraints (Burg et al., 2019). The potential reduction of *VS4* is only outlined in one paper, which is why it is not possible to make a valid statement about it. Category *VS5*, aero- or hydrodynamics, offers a small reduction potential below 5%, but research is relatively uniform on this. Only one outlier exists, reporting a potential of 6.9% in improving the aerodynamics of trucks. Papers reporting about measures regarding *VS6* Power transmission lie in the same order of magnitude. An extraordinary wide distribution can be observed in *VS7*, increasing the uncertainty of the reduction this measure entails. The median is located at around 10%, whilst the 75th percentile can be found at around 40%. One could argue that this is due to the broad topic of VS7, and further fuel efficiency measures, but even when looking at the same measure in this category, a wide distribution can be observed: some papers report savings of as little as 0.53% when implementing waste heat recovery systems, and other papers attribute it a potential of up to 72%.

As mentioned earlier, the reduction potential of the technologies described in *VS2* depends only on the fuel selection, which is described in the fuel selection section. For this reason, we will refrain from a discussion of the reduction potentials at this point.

4.1.3. Discussion

VS1: An emission mitigation due to the replacement of old vehicles with new ones and improved maintenance is the more promising, the higher the average age of the fleet, and the lower the technical standards are, respectively. Tendentially, this is more prominent in developing countries, as can be observed in the geographical representativeness of the measures found in the recent literature for this category, e.g., India (Ali et al., 2021), Mauritius (Deenapanray and Khadun, 2021), Nigeria (Dioha and Kumar, 2020; Maduekwe et al., 2020), the Fiji islands (Prasad and Raturi, 2019) or Brazil (Marcilio et al., 2018). Only one older paper mentioned this measure for a European country, Finland (Liimatainen et al., 2014). The absence of newer literature in Europe indicates that a reduction potential might no longer be exploitable in developed countries. That is, especially for Finland, supported by the finding that research on emission mitigation is quite extensive in the northern European countries.

VS2: All in all, there is a vast amount of research regarding drivetrain technology, frequently discussing the benefits and barriers of diverse technologies. The following paragraphs summarize the scientific discussion, focusing focus on the comparison of energy efficiencies, as this determines the final energy demand and, thus, depending on the energy carrier, the emissions. When comparing different drivetrain technologies regarding their efficiency, EVs with power supply via ERS perform best because of the high efficiency of the electric drive. BEVs have the same power drive but carry additional weight due to the battery packs and, thus, have a lower efficiency. FCEVs are closely following, because they also feature high propulsion efficiency, but lose the advantage of reduced weight compared to BEVs due to low efficiency in converting hydrogen into electricity in the fuel cell (Haugen et al., 2021; Jahangir Samet et al., 2021; Liimatainen et al., 2014; Svindland and Hjelle, 2019). Some figures highlighting this ordering and comparing it to conventional Diesel-ICEVs are visualized with the help of a box plot in Fig. 5. Hybrids of all kinds are located between the just-described technologies. At the lower end of the efficiency scale of drivetrains, ICEVs powered with CNG are found, especially when carrying out short-distance drayage and driving on hill climb highways (Mojtaba Lajevardi et al.,

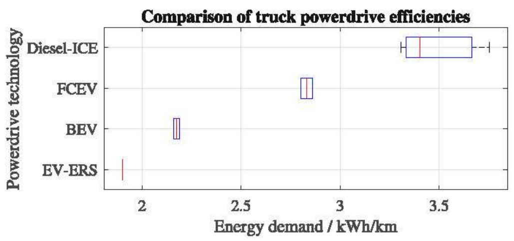

Fig. 5. Comparison of different drivetrain technologies regarding their energy efficiency in kWh/km (Haugen et al., 2021; Jahangir Samet et al., 2021; Liimatainen et al., 2014; Svindland and Hjelle, 2019).

2019).

Literature states that electrifying road freight transport vehicles with a total permissible weight of over 30 t might only be possible with ERS, but having BEVs with a weight beneath 30 t is already feasible in Finland and Switzerland due to well-established on-road plug-in stations. The broad application of BEVs is, besides the aforementioned restrictions of weight and range, currently further limited due to high infrastructure costs to build charging stations and power transmission systems, high vehicle costs, and, applicable to all-electric vehicles, a highly volatile future energy demand (Jahangir Samet et al., 2021). Similar challenges are faced when discussing the use of hydrogen in transport. The missing infrastructure in refueling stations to supply trucks and ships with replenishment and the production of green hydrogen implies high investments in infrastructure and the energy system (Schiebahn et al., 2015).

VS3: Higher capacitated vehicles can only be used for an emission reduction when the utilization of those is high enough. The average load factor of European commercial air freight transport fluctuated between 66.7% in 2015 and 74.3% in 2019 (IATA, 2020). Regarding rail transport, data from the UK show similar load factors for container trains (Woodburn, 2017). Although precise data are absent, it is assumed that the load factor in road transport is significantly lower than that of air or rail freight transport (McKinnon, 2010b). As long as this load factor cannot be raised, an enlargement of carrying capacity does not seem to be economically or ecologically beneficial. Instead, matching the capacity to the demand and choosing the vehicle according to this can lead to an emission reduction (Wittenbrink, 2016). This argumentation supports the simulation results from Germany (Burg et al., 2019).

VS4-6: Improvements in hydro- and aerodynamics (*VS5*) were not found during the full-text screening but appeared as a frequently mentioned measure in literature found in backward-search. Since this literature is tendentially older, this implies that hydro- and aerodynamics are no longer investigated in current literature. This could have two reasons: first, the improvements that can be reached are too low, or the potentials are already fully exploited. A similar trend can be seen in vehicle weight (*VS4*). Power transmission (*VS6*) is also a measure that is mainly discussed in older literature, but it is mentioned once in maritime transport, suggesting a smaller propeller size (Christodoulou and Cullinane, 2020).

VS7: The possibility to implement the mentioned fuel efficiency measures on ships highly depends on the ship type and route. Additional wind propulsion devices are only beneficial on routes with consistently high wind speeds and the possibility to tack against the wind, if necessary. Waste heat recovery systems are mostly already installed up to a profitable operation or technical feasibility (Bouman et al., 2017).

4.2. Fuel selection (FS)

4.2.1. Description

The cluster *FS* only contains one category, *FS1* Fuel/power feedstock, production, and supply, which includes all relevant factors of the fuel. A vast number of alternatives to conventional fossil fuels can be found in literature, and classified in various ways, e.g., by the feedstock, by the production process, or by the physical state. Many alternatives exist because of the diversity of vehicle drivetrain technologies, as explained in vehicle selection. For FCEVs to produce electricity, hydrogen is necessary for liquid or gaseous state. Other kinds of EVs have to be supplied with electricity – whether at the time of consumption via ERS, or during the idle time, temporarily stored in batteries. Both mentioned technologies have the potential to be "zero-carbon", i.e., producing energy without emitting CO_2. In contrast, ICEVs have the potential to become "carbon-neutral" when their fuels are produced on the appropriate pathway. Gas in the liquid or gaseous form must be provided to gas-powered ICEVs to generate power, and liquid fuels are necessary for conventional ICEVs.

The carbon intensity of those technologies depends on the used feedstock and the production process. Hydrogen, for example, is in general classified as green, blue, turquoise, purple, or bio – being produced via electrolysis with renewable energy, from fossil fuels with carbon capture and utilization (CCU), via pyrolysis, via heat and power from nuclear power plants, or biological feedstocks, respectively (Kotze et al., 2021).

Liquid fuels are mainly used as a replacement for fossil fuels in conventional ICEVs, which is why they can reduce the GHG emissions of the existing fleet immediately and in the short term. To be combusted in ICEs they need to have similar physical and chemical properties to fossil fuels and, thus, basically consist of hydrocarbons. Therefore, the combustion of the fuels still results in a similar amount of carbon emissions, which is referred to as the "Tank-to-Wheel" emissions. The GHG savings only become apparent when the entire "Well-to-Wheel" (WtW) life cycle of the fuel is considered, because the fuels' feedstock is either considered carbon-neutral (e.g., biofuels), or carbon is bound to the fuels in its production stage (e.g., electro-fuels and synthetic fuels).

For biofuels, there is a wide range of possible feedstocks that are presented and classified in the European Renewable Energy Directive II (REDII) (European Parliament, 2018). One commonly used classification is the division between first-, second-, and third-generation biofuels. When the feedstock is edible, like crops, fuels are considered first-generation biofuels. The feedstocks of second-generation biofuels are lignocellulosic and non-edible, and third-generation biofuels are made from microalgae. From an environmental and social perspective, the use of non-edible feedstocks is preferred because these are cultivated on land that is not appropriate for the cultivation of crops, so there is no rivalry for food production. The production of diesel-like fuels from algae is still in its infancy, but extensive research is currently being done to make this path technically and economically feasible (Dwivedi et al., 2019).

Regarding electrofuels and synthetic fuels, the terminology is rather inconsistent in the literature. Results of a comprehensive review on this topic suggest that, when looking at fuels that are based on the conversion of electricity to liquid fuels ("Power-to-Liquid", PtL), the term electrofuels should be used. For these kinds of fuels, it is not possible to know which resources or production paths are included, and, thus, the carbon emission reduction potential is unknown at the first glance. The same applies to the term synthetic fuels, which are fuels from coal, natural gas, and biomass, that are, among other process steps, produced with the Fischer-Tropsch-Synthesis. Both terms are, according to the review, parent terms for different fuels and at the same level of terminology as oil (Ridjan et al., 2016). If the production of such fuels was economically feasible, they are a possibility to reduce the WtW emissions to nearly zero, because the carbon emitted at the end of the fuel life cycle is bound to the fuel at the production stage and, thus, the "Well-to-Tank" emissions are negative. Because of this, these fuels can be considered "carbon-neutral" fuels (Kirsch et al., 2020).

For the useage in conventional ICE road trucks, diesel blends with methanol (Valera and Agarwal, 2019) or biodiesel (Mandal et al., 2021) are proposed as a temporary solution to reduce emissions. For air transport, the only measure found is the production and use of bio-jet-fuel, produced from corn, fatty acids, or lignocellulosic biomass (Wise et al., 2017).

Carbon-neutral gaseous fuels can be produced when excess energy from the power grid is converted into gas via hydrogen electrolysis and methanation. The produced Synthetic Natural Gas (SNG) can be classified as a synthetic fuel and is not used solely for transport, but also as a supplement in the gas network (Götz et al., 2016; Schiebahn et al., 2015). SNG is a replacement for CNG or LNG, depending on whether it is supplied in a gaseous or liquid state, respectively (Meisel et al., 2020). Due to the frequently discussed use of LNG in vessels, liquefied SNG could be an interesting way to further decarbonize shipping (Christodoulou and Cullinane, 2020; Sames and Köpke, 2012).

4.2.2. Reduction potential

Liquid fuels: Conducting a Life Cycle Assessment (LCA) study of two synthetic diesel pathways with direct air capture and Fischer-Tropsch-Synthesis, research finds that the synthetic fuel pathway can be beneficial to the conventional diesel pathway up to a grid electricity emission factor of 139 g CO_2/kWh. The lower the grid emission factor is, the higher are the savings in fuel production (Liu et al., 2020). The difficulty this implies can be seen when looking at the current emission factory of different countries. The 2019 emission factor of all EU-27 countries is about 255 g CO_2/kWh but is subject to strong fluctuations depending on the member state. Looking at the two neighbors, Germany and Austria, the electricity grid results in emissions of 350 g CO_2/kWh and 94 g CO_2/kWh, respectively (European Environment Agency, 2021). Similar results have been found in a modeling and simulation study, investigating a plant producing liquid synthetic fuel by Fischer-Tropsch-Synthesis and exploiting the carbon potential of a nearby cement plant. A reduction of GHG emissions in the gate-to-gate production process of 95% was found when the energy used is produced in an offshore wind park. In contrast, emissions increase by 16% or 200% when the fuel is produced with electricity from the Danish or German electricity mix, respectively (Albrecht and Nguyen, 2020). These economic and environmental figures highlight the close coupling of the energy-to the transport sector in the future. When powering a marine engine with methanol instead of Heavy Fuel Oil (HFO), CO_2 savings of up to 77% can be reached when methanol is produced from biomass (Christodoulou and Cullinane, 2020).

Gaseous fuels: LNG-fueled ships are mentioned to reduce GHG emissions by about 6% (Sames and Köpke, 2012), whereas LNG-fueled trucks are estimated to lower emissions by up to 25% (Sharafian et al., 2019). A frequently discussed challenge in using gas is the so-called "methane slip," meaning the gas volatilizes when injected into the combustion chamber and escapes into the atmosphere. The ability to reduce methane leakage is stated to be crucial for LNG to reduce GHG emissions (Sharafian et al., 2019). Due to Methane having a higher global warming potential than CO (Myhre et al., 2013), the methane slip is possibly offsetting the reduction of CO_2 emissions and resulting in even higher GHG emissions, compared to conventional fuel (ben Brahim et al., 2019; Sharafian et al., 2019).

Hydrogen: A high range of reduction potentials of FCEVs is reported in the literature, reaching from 4% by using hydrogen from steam methane reformation up to 97% by using green hydrogen (Mojtaba Lajevardi et al., 2019). Furthermore, the large-volume production and provision of hydrogen are repeatedly questioned in the literature. Modeling the Spanish hydrogen production and demand for road transport yields the assumption that enough hydrogen could be produced with conventional pathways to power the Spanish truck fleet under techno-economical aspects. As soon as the environmental aspect begins to play a role, the demand for clean hydrogen from electrolysis or biological feedstocks rises. The large-scale production of these is still not economically competitive. If incentives are developed that speed up the distribution of green hydrogen production, large WtW savings are possible. In general, the model shows that an FCEV is suitable for GHG emission reduction when the replaced vehicle is powered by a fuel mix that is above 1 kg CO_2/kg fuel (Navas-Anguita et al., 2020), which is the case in conventional Diesel, having 3,165 kg CO2/kg diesel (Juhrich, 2016).

When comparing FCEVs to BEVs and considering different production paths for each, it is found that the potential of FCEVs to reduce emissions is large, but strictly connected to the usage of carbon capture and storage (CCS) technology during the production of the hydrogen. Furthermore, the potential of BEVs rises in comparison to FCEVs as the grid carbon intensity shrinks because of higher energy efficiency (Haugen et al., 2021).

Combinations: In contrast to single-fuel engines, HVs can combine the usage of two or more energy carriers. Hybrid trucks with ICEs and a supplementary engine are shown to contribute to the short-term reduction of emissions but cannot fulfill long-term goals. The broad application of zero-emission alternatives like BEVs of FCEVs are therefore needed (Jahangir Samet et al., 2021; Zhang and Hanaoka, 2021). In a simulated case study, a hybrid ferry powered by a fuel cell, a solar photovoltaic panel, and a diesel generator results in emission reductions of about 15% (Ghenai et al., 2019). Unfortunately, the lack of emission factors for hydrogen and electricity reduces the significance of these data.

To sum up the chapter on emission mitigation potentials of different fuels, it can be concluded that the reduction of emissions highly depends on the fuel feedstock and production. The same applies to electricity, as can be seen in the different carbon emission intensities of countries. The reduction potentials found in the literature thus vary extensively, as visualized in Fig. 4. When using methanol from non-biomass sources, the emissions remain the same as when using HFO in maritime transport (Christodoulou and Cullinane, 2020). The potential reduction starts at the lower end at a 4% reduction by using FCEVs with hydrogen from steam methane reformation and reaches up to 99% by using EVs supplied via ERS with electricity from renewable energy sources (Mojtaba Lajevardi et al., 2019). The 75th percentile is located at about 72%, indicating a massive reduction potential for alternative fuels and drivetrains. At the same time, the spread shows that the switch to other technologies must be carefully scrutinized and analyzed on a case-by-case basis, as otherwise dangerous pseudo-savings can result, which in the end increases emissions. This leads to the conclusion that a technology mix will be the future solution to mitigate GHG emissions, exploiting reduction potentials and cross-sectoral synergies wherever they appear.

4.2.3. Discussion

Methanol: The use of methanol in ICEVs is a long-discussed measure to reduce the carbon intensity of conventional diesel vehicles. It might seem like a promising way at first sight due to the producibility of methanol from renewable resources and biomass, lower carbon and noise emissions, and higher combustion efficiency compared to diesel. To date, however, methanol has not achieved the initially expected breakthrough due to several limitations of the fuel that did not make its use economically feasible. Around half the energy density compared to diesel requires modifications to the engine; the lower viscosity and lubricity entail the danger of leakage of methanol from a diesel engine, and different influences on emissions at different engine loads can offset possible GHG savings (Valera and Agarwal, 2019).

Biofuel: Talking of biofuel quickly provokes discussions about the origin of the feedstock, assuming that fuel production is in rivalry to food production, or using oils from questionable sources, like palm oil. Indeed, attention must be paid to those aspects when selecting biofuels, for which REDII provides sound guidelines. Nevertheless, problems arise when thinking of biofuels as the main part of the solution to GHG emission reduction. First, it was found in a simulation study investigating the future fuel mix of Germany, focusing on the type of feedstock, that REDII alone will not be enough to reach the demanding German climate protection target (Meisel et al., 2020). Second, other mathematical models conclude that not enough biomass will be available to deal with the demands in 2030 when the GHG goals are met (Haugen et al., 2021).

Synthetic/Electrofuels: For the PtL process, high operational expenditures are reported in the literature, leading to net production costs (NPC) of 2.01 €/l fuel (Albrecht and Nguyen, 2020). The same trend can be observed for the production of gaseous fuels because its economics highly depend on Capex and Opex for the electrolysis. Prices for CNG prepared for fueling Gas-ICEVs begin at 19.6 Eurocent/kWh (Götz et al., 2016; Schiebahn et al., 2015). The price of diesel in June 2021 in Germany at the fueling station excl. tax is about 114.48 Eurocent/liter, resulting in 10.8 Eurocent/kWh (Mineralölwirtschaftsverband, 2021). With the additional consideration of the higher energy demand of CNG compared to diesel (Mojtaba Lajevardi et al., 2019), the use of SNG results in significantly higher costs for truck operators. Furthermore, the availability of carbon for fossil substitutes on a large scale could be problematic. In a simulation study, it was assumed that a cement plant was the supplier of carbon. When those fuels are used to power a high number of vehicles, smaller carbon sources also have to be considered, leading to a high number of smaller PtL plants, and, due to the economy of scale, to even higher NPC (Albrecht and Nguyen, 2020).

4.3. Load carrier selection (LCS)

4.3.1. Description

LCS1: The gross weight of the transported goods is a major factor influencing carbon emissions (Piecyk and McKinnon, 2010) and can thus be used as a lever to reduce those. Reducing the gross weight can either be achieved by reducing the net weight of the goods, or by reducing the weight of the load carrier and the packaging. In the shipping industry, a recent study investigated the replacement of conventional containers with ones made from lightweight and, from a life-cycle perspective, more environmentally friendly materials. In detail, the Corten steel used is minimized by innovative design, and the wooden floor is replaced by metallic materials. These changes lead to a reduction of 21% and 4.8% of the net container weight and gross weight when fully loaded, respectively (Doukas et al., 2021). A similar modeling study was conducted for intermodal transport, assessing six different lightweight container scenarios (Buchanan et al., 2018). Another way to reduce the relative weight of the load carrier to the number of goods transported is the exploitation of the economies of scale, i.e., the enlargement of the volume. In an international wine supply chain, this was done by not transporting the wine in bottles, but in larger tanks (Harris et al., 2018).

LCS2: To exploit the cubic and weight capacity of containers, the shape and dimensions of the load carrier can be adjusted to the transported goods. Thereby, containerization and consolidation of transport can be achieved, which is a promising way to reduce emissions by reducing the number of necessary transports (Martinsen and Huge-Brodin, 2014; McKinnon, 2010a; Tiwari et al., 2021).

4.3.2. Reduction potential

For both categories, a low number of figures regarding the emission mitigation potential was found. *LCS1* is reported to be able to reduce emissions between 4.7% and 18.8%. The wide variation is again due to the different nature of the transport chains, as well as different underlying assumptions. Only one mathematical modeling study calculates the potential emission reduction of an enhanced containerization strategy, which was assigned to *LCS2*, concluding that resulting emission reductions in the transport chain under study vary from 7.4% to 32.17%..(Tiwari et al., 2021).

4.3.3. Discussion

Besides the weight, volume, and design of load carriers, the product properties themselves are a highly influencing factor in the emissions of the transport. Lightweight materials in the product design or 3D-printing can reduce emissions in transport significantly due to a reduction of transport demand, but the influence of logistics on these factors is limited and decision regarding those is mostly not in the responsibility of logistics managers, thus, the product design and manufacturing was not considered as a measure that can be implemented by logistics (Christopher, 2011; Deckert, 2016). On the other hand, increasing consideration of logistic requirements in product design is reported in the literature (Piecyk and McKinnon, 2010). It is to be investigated whether an increasing pressure on reducing emissions influences this relationship.

4.4. Mode selection (MS)

4.4.1. Description

MS1: Since rail transport is commonly a less carbon-intense transport mode than road transport, literature mainly elaborates and assesses concepts where road transport is completely shifted to rail, or a combination of both modes is applied (Dioha and Kumar, 2020; Heinold and Meisel, 2018; Nasir and Rahmat, 2020; Palmer et al., 2018; Pittman et al., 2020). A complete shift from road to rail can mostly only be carried out on single legs for terminal-to-terminal transport, for example when a dry-port is used and the transport operations between those two hubs are shifted from road to rail (Regmi and Hanaoka, 2015). Especially interesting for express delivery services is the shift from road to high-speed railways, where the existing infrastructure and train schedules of a high-speed rail network are used for freight transport (Watson et al., 2018). Short sea transport can be another alternative to road transport, but only if the geographical conditions permit this (Svindland and Hjelle, 2019). Maritime transport is frequently a key issue when the combination of different modes of transport is discussed, especially when intercontinental trade is the object around which the research revolves (Harris et al., 2010, 2018).

4.4.2. Reduction potential

As with every systemic issue, the reduction potentials of *MS1* highly depend on the baseline configuration of the system. Therefore, the box plot in Fig. 4 shows broadly distributed values, reaching from as little as 5% to as much as 60%. Nevertheless, the emission reduction potential for this measure can be estimated quite well due to a low Interquartile Range of the reported reduction potentials. But again, reduction potentials have to be estimated case-by-case, because sparse rail networks in some countries lead to higher overall emissions when using intermodal chains due to large pre- or post-carriages on the road (Heinold and Meisel, 2018). Research further states that the missing consideration of emissions produced while handling goods between different modes of transport is a further topic to investigate (Cichosz and Pluta-Zaremba, 2019). Only when these emissions are also taken into account can conclusions be drawn about the actual emission reduction potential.

4.4.3. Discussion

For a shift from road to rail to be successful, more flexibility regarding the shipment sizes and departure and arrival times from the side of the railway operator were found as key success factors during a case study in Italy (Colicchia et al., 2017). This statement is supported by an empirical study among Polish LSPs, in which it was found that multimodality is perceived as a great thing, but LSPs partially stopped conducting multimodal transport because of operational challenges and customers unacceptance of longer delivery times (Cichosz and Pluta-Zaremba, 2019). An already built, but at the time of conducting the research not in use, railway connection hindered the implementation of rail freight transport between Laos and Thailand within a research project (Regmi and Hanaoka, 2015). Regarding the use of high-speed railways for freight transport, high investment costs in new terminals, as well as high maintenance costs, may hinder the widespread application.

A shift away from water mostly requires a change in the supply chain structure due to fewer alternative transport solutions for high-volume or heavy goods over large distances between continents (Harris et al., 2018; Nieuwenhuis et al., 2012). At least for transport between China and Europe, this could change soon due to the use of the rail-based Silk Road.

4.5. Supply chain design/management (SC)

4.5.1. Description

SC1: On the strategic level, decisions can also be made regarding the spatial location of supply chain actors and members. Measures starting from an optimized hub location selection to the use of consolidation centers and up to local production initiatives all relate to the spatial consolidation, thus reducing transport demands and thereby directly contributing to emission reduction. The optimization of hub locations is not necessarily restricted to minimizing emissions, although this bears the highest potential regarding them, but can be used to optimize a multi-objective model whilst still reducing environmental impacts (Heidari et al., 2020).

SC2-3: From the supply chain management perspective, postponement (Harris et al., 2018) and information sharing (McKinnon et al., 2010) are denoted as major factors influencing transportation demands and utilization, respectively. Furthermore, the concept of Vendor Managed Inventory (VMI) is mentioned to offer the possibility to raise the loading factor due to better options for the supplier. On the other hand, VMI leads to high inventory levels, possibly resulting in excess stocks that have to be thrown away (Harris et al., 2010, 2018; McKinnon et al., 2010).

4.5.2. Reduction potential

The reduction potential from the categories forming this cluster depends on the reduction of transport demand resulting from a specific measure. This is highly case-dependent and the reason why the distribution of reduction potentials of SC2 in Fig. 4 is extremely large. To derive a general statement on how large the emission reduction potential due to changes in international supply chains is, detailed case studies in a larger number were necessary.

Exemplary case studies found in the literature review study a wine supply chain from Italy to the UK, in which the postponement of the bottling process closer to the destination was reported to ensure emission mitigation of up to 38.46% due to a reduction of transport weight. Such potential could not be found in the transport from Australia to the UK, because the wine is already transported in a tank and not in bottles (Harris et al., 2018). This, again, shows the highly different potentials of measures in different supply chain structures and baseline conditions. Depending on the location of regional consolidation centers an emission reduction potential from 3.6% to 5.8% was found in the UK when companies in the consumer goods sector collaborate and thereby consolidate their transport (Palmer et al., 2018).

By shifting the production of cars from the Hyundai-Kia group sold in the EU and the US from production in Korea near to the final customer, the research identifies emission saving potentials of nearly 80% up to 93%, respectively. This is due to the elimination of emissions from the maritime sector, which is the main leg in the baseline scenario (Nieuwenhuis et al., 2012). It is noteworthy that this reduction potential is strongly biased because the supply of the plants is neglected and only the distribution of cars is investigated in the paper. This further highlights the different baseline conditions when reporting an emission reduction in literature.

4.5.3. Discussion

The attempt to mitigate emissions on the strategic level might be overrun by other factors that are more important for logistics managers, i.e., the higher stock levels and costs when implementing VMI. Regarding the shift of production to the final customer, the overall supply chain has to be considered. If the suppliers stay at the same location as before, goods must be transported to the new plant, which probably results in higher transport demand in inbound. It must be questioned whether the oppositely developing emissions in inbound and outbound compensate each other and whether a saving remains, or not. That is why the holistic consideration of all emissions is of utmost importance to not create a burden shift to other process phases.

4.6. Transport planning (TP)

4.6.1. Description

TP2: A reduction of the time at berth can decrease pollution and emissions in coastal areas and be achieved by a close collaboration of ships and land (Christodoulou and Cullinane, 2020).

TP1: When companies of the same sector collaborate, several benefits regarding emissions are reported, including backhauling, load sharing, usage of rural and urban consolidation centers, and the possibility to shift transport from road to rail due to higher volumes (Palmer et al., 2018).

TP3: Flexibility in arrival and departure times can lead to the abandonment of scheduled delivery time windows for suppliers and, thus, to an increased vehicle utilization (Rogerson, 2017) and can be realized, among other things, by an increased storage capacity at the delivery point (McKinnon et al., 2010). Upstream buyer consolidation is a concept of international transport where an LSP in the source country consolidates goods belonging to one customer and containerizes those. This leads to an increase in utilization and the possibility to shift to other modes of transport in the country of destination (Lin, 2019). In general, timely consolidation leads to higher utilization and, thus, to a lower number of necessary transports. Abandoning the JIT concept may lead to such a higher utilization because suppliers can make better use of the vehicle's capacity (Bergenwall et al., 2012; Harris et al., 2010).

4.6.2. Reduction potential

As visualized in Fig. 4, the only potential expressed in numbers in the literature is buyer consolidation in *TP3*. It was found in a case study that emissions can be lowered significantly in the country of destination due to a shift to rail, but the overall transport emissions to the customers only shrink by 1.5%. This is because of the maritime transport in the main leg, which accounts for more than 80% of the overall emissions and, thus, prevents a larger emission reduction (Lin, 2019).

4.6.3. Discussion

A frequently mentioned way to reduce emissions, that could be assigned to the cluster *TP* (Transport Planning), is the reduction of empty running (Kumar, 2021; Liimatainen et al., 2014; McKinnon, 2010a). The authors do not see this as a measure that can be decided, but rather as a factor that directly influences emissions. Because of this, the reduction of empty running will not be included in the framework. Different measures in the framework, e.g., those from *TP1*, can reduce empty running and thereby the emissions. In general, measures in *TP1* are often mentioned in recent literature, which indicates that there is still an exploitable potential. To achieve a successful implementation of this category, high flexibility is required and the broadly implemented Lean Manufacturing concept might be an additional barrier.

4.7. Vehicle operation (VO)

4.7.1. Description

VO1: The term "cold ironing" refers to the shore power supply of a vessel while it is at berth to replace auxiliary engines that are necessary to generate electricity for oil warming, ensuring communication, lighting, or other operations. This is not common practice, but several ports around the world have begun to implement it, preferably in cooperation with shipping companies whose ships call at the port regularly. The implementation of cold ironing necessitates slight technical changes at the vessel, enhanced port infrastructure, and power supply (Binti Ahamad et al., 2018; Styhre et al., 2017). In trucks, the automatic engine idling can also save emissions but is only applicable when no further electricity demand is present, which is, for example, not the case when reefer containers are transported (Ang-Olson and Schroeer, 2002). For these purposes, a second power source for the auxiliaries can be installed (Islas-Samperio et al., 2020).

VO2: Several route optimization algorithms exist for road and maritime traffic, that aim either solely to minimize GHG emissions, or as multi-objective optimization, including GHG emissions. These optimizations and other simulation studies show that an alternative route choice can lead to GHG savings. When considering road transport across Europe, simulation studies have shown that shipping through the Alps has the worst emission factors due to the hilly, or even mountainous nature of the road. Besides this, emission factors differ greatly between different pairs of nodes because the altitudes of different countries vary. Furthermore, traffic congestion and road type have a high impact on road transport emissions due to many acceleration processes and higher energy demand, respectively. Thus, it is not possible to apply a unified emission factor for Europe to a particular relation or shipment (Heinold and Meisel, 2018; Llopis-Castelló et al., 2019). Besides the use in road transport, maritime weather routing is stated to be state-of-the-art in literature due to its fuel-saving possibilities (Christodoulou and Cullinane, 2020; Sames and Köpke, 2012). Additionally, the port selection was assigned to this category, although it is certainly also assignable to *MS1*. Studies show reduction potentials when ports closer to the destination are chosen, instead of ports with lower fees or better accessibility (Liao et al., 2010).

VO3: In a survey conducted in German freight forwarding companies, the application of onboard monitoring systems to collect data regarding fuel consumption or load factors were seen as highly relevant for the reduction of emissions (Baumgartner et al., 2008).

VO4: Eco-driving training and drivers' behavior are a well- and long-discussed measure in literature, aiming at anticipatory driving behaviors to reduce aggressive acceleration and deceleration, speed, idling time, additional factors like air conditioning, and, thus, fuel consumption (Ang-Olson and Schroeer, 2002; Prasad and Raturi, 2018).

VO5: In the shipping industry, reducing the speed to save fuel is called "slow steaming," which comes from the early times of steam navigation. Reducing the speed of vessels reduces fuel consumption per mile and, thus, also reduces emissions (ben Brahim et al., 2019; Lindstad et al., 2011). While not calling the speed reduction slow steaming, it is also suggested for road transport to reduce GHG emissions (Ang-Olson and Schroeer, 2002; Eglese and Black, 2010).

4.7.2. Reduction potential

Literature on the reduction potential of *VO1* behavior during idle time is quite scarce, only one estimation of the reduction potential was found, stating a 10% reduction of vessels' emissions by using a shore power supply. The majority of papers mentioning *VO2* route choice as an emission reduction measure present figures well below the 75th percentile at 27%. One outlier reported savings of up to 88% when selecting another port in an intermodal transport chain (Liao et al., 2010). Regarding *VO3*, the reduction of air resistance due to platooning is reported to be up to 14%, whilst the median is lying around 5%. A few more numbers were found for *VO4* operators' behavior, where research seems to have found a consensus that realistic values are up to 10%, indicated by the 75th percentile and the median both near the 10% reduction. In a simulation study, a saving of 20% was calculated, which represents the only outlier. Emission reductions between 19 and 28% were reported when slow steaming is applied to an extent, so no abatement costs arise (Lindstad et al., 2011). Due to a limited number of figures found in the literature, these two values represent the median and upper bound of the reduction potential, respectively. In contrast, it is stated that newer vessels are designed to reach the optimal engine efficiency at cruise speed and, thus, the reduction potential of slow steaming is minimized (ben Brahim et al., 2019), which is supported by the minimum value of 13.6% in *VO5*.

4.7.3. Discussion

VO2: When considering the selection of another port, the transport chain following the port must be taken into account. If transport is shifted away from ports that are connected to a major railway network with a low carbon intensity, it might have opposite effects. Furthermore, infrastructural barriers may hinder the change to alternative ports(Liao et al., 2010).

VO3: Recent literature on emission mitigation measures no longer reports the onboard monitoring of key indicators as an enabler to reduce emission, which leads to the assumption that this is already a state-of-the-art technology. Platooning seems to be more promising nowadays, but its use is strictly bound to legal framework conditions (Muratori et al., 2017).

VO4: The effectiveness of eco-driving training certainly depends on the country in which it is applied. In Sweden, for example, eco-driving training for individuals is mandatory since 2008 and for truck drivers since 2009, so the reduction potential there has probably been exhausted (Filks, 2008).

4.8. Shippers' employees (EM)

4.8.1. Description

EM1: In combination with planning guidelines for intermodal transport and a visualization platform of intermodal links, the creation of an online, easy-to-use CO2 calculator was the main goal of a research project to facilitate intermodal transport in the chemical industry in Eastern European countries. The ability to calculate emissions was found as a key factor to reduce emissions proactively in the planning phase of transport (Cichosz and Pluta-Zaremba, 2019).

EM2: Another finding reported in the aforementioned research project is the relevance of employee awareness and commitment to carbon reduction. To enable a priori decisions during transport planning, the employees carrying out this planning need to be aware of, first, the necessity to reduce emissions, and, second, the possibilities to reduce emissions (Cichosz and Pluta-Zaremba, 2019; Kumar, 2021).

4.8.2. Reduction potential

No figures regarding the emission reduction potential of measures found in *EM1* or *EM2* were observed in the respective literature.

4.8.3. Discussion

The low number of measures and the absence of figures in the literature indicate a low amount of employee-related research. Therefore, it is proposed for further researchers to investigate the relationship between employee commitment, awareness, and knowledge about measures in freight transport and the success of manufacturing companies in mitigating emissions.

4.9. Shippers' management (MA)

4.9.1. Description

MA1: Several authors report the necessity to specify environmental criteria in the bidding and awarding process of LSPs (Cichosz and Pluta-Zaremba, 2019; Martinsen and Huge-Brodin, 2014). An empirical study in the chemical industry in Poland reveals that the specification of environmental criteria (e.g., the share of alternative fuels used) gives indications to the market, that environmentally friendly transport operations are preferred in the short, and required in the long term (Cichosz and Pluta-Zaremba, 2019). Manufacturers can also make other demands on their carriers, such as collaborations with other LSPs to exploit sharing potentials and share know-how in measures and assessment methods (Aloui et al., 2021; Kumar, 2021), certification according to current environmental management systems (Kumar, 2021; Martinsen and Huge-Brodin, 2014), or the reporting of emission according to international standards and the inclusion of these figures into the relevant KPIs and, thus, into the working process (Ali et al., 2021).

MA2: Performance monitoring tasks required by LSPs also have to be done by the focal company itself to ensure the detection of vulnerabilities and the initiation of measures against them (Kumar, 2021). The monitoring of the load factor in trucks owned or commissioned by the company with sensors ensures the efficient utilization of truck's capacities (Baumgartner et al., 2008).

MA3: According to research, top management commitment is a significant driver of maritime green supply chain management initiatives and positively correlates to the reduction of emissions in the technology and transport aspects of manufacturers (Ali et al., 2021; Jasmi and Fernando, 2018).

4.9.2. Reduction potential

Although there seems to be a consensus on the importance of management-related factors in emission mitigation, statements about the amount of savings potential are relatively rare in the literature. Only one figure in *MA2* was observed, mentioning a reduction of 1.16% when environmental performance monitoring is applied in the shipping industry (Sames and Köpke, 2012). A considerably higher reduction between 41.42% and 43.42% was found in a simulation study investigating the potential of horizontal collaboration between suppliers, thus assigned to the framework category *MA1* (Aloui et al., 2021).

4.9.3. Discussion

Research tends to assume that logistics managers have a low priority for reducing emissions because companies are inherently profit-oriented constructs, and their managers are, therefore, dependent on financial success (Harris et al., 2018). Furthermore, external pressures to reduce emissions exist but have only weak impacts on the top management's desire to implement measures. Above all, customers' pressure to ensure environmental transport is missing in the industrial sector, not only in the developing world (Ali et al., 2021; Cichosz and Pluta-Zaremba, 2019). Additionally, research reports that practitioners of green freight transport often face problems in prioritizing measures and assessing or estimating the impact of those (Kumar, 2021), pointing to missing know-how in technologies and strategies.

5. Discussion

In this study, a total number of 81 papers was reviewed to first, list and categorize all measures a manufacturer can adopt to mitigate GHG emissions in its transport operations related to manufacturing, and, second, to estimate to what extent a manufacturer can expect those measures to reduce the GHG emissions. All in all, 27 different categories within nine clusters were formed from the 215 measures retrieved from literature screening.

5.1. Addressing the possibilities of manufacturers

In Fig. 6 (a), the number of identified measures from those 27 categories are visualized and sorted by, first, the number in the respective cluster and, second, the number in the respective category. The red color represents measures that were collected from papers directly found during the database search, and the grey ones represent measures that were collected from the backward search. The categories *VS2 Drivetrain technology* and *FS1 Fuel selection* were mentioned remarkably often. Other measures found in the categories from the cluster *VS Vehicle Selection* make it the most frequently mentioned cluster, reflecting the technical discussion of emission reduction to be the most relevant for current research on the decarbonization of transport. The lowest number of measures was found in the cluster *EM (Shippers' Employees)*, highlighting the need to further investigate the impact of employee knowledge and motivation on decarbonization. Similarly low was the number of measures included in the cluster *MA (Shippers' Management)*. On the one hand, top-management commitment is reported to be a critical necessity to succeed in sustainable initiatives, but is, on the other hand, rarely mentioned in the analyzed literature. Having said that, we can derive the basic need to focus more deeply on the human aspects when researching the decarbonization of transport. The necessity to use a transdisciplinary approach, e.g., by integrating more social science research, in supply chain management to gather a different perspective on problems than the traditional engineering-based approach is nothing new (Kaufman and Ülkü, 2018; Muduli et al., 2013; Wieland, 2021), but can be explicitly confirmed for the decarbonization of transport with the findings of the focal research. Currently, the discussion mainly focuses on technological and operational aspects, which will - out of a doubt - play a major role in future decarbonization, but alone not be capable of achieving the set goal of climate neutrality. Fundamentally rethinking supply networks beyond the tier 1 suppliers and thus minimizing the transportation demands globally will be a major and crucial task in achieving a zero-emission economy of the future.

In Fig. 6 (b), the number of measures identified for each mode of transport is visualized. For the sake of completeness, rail transport is also mentioned in this bar chart, but no measures were found to reduce

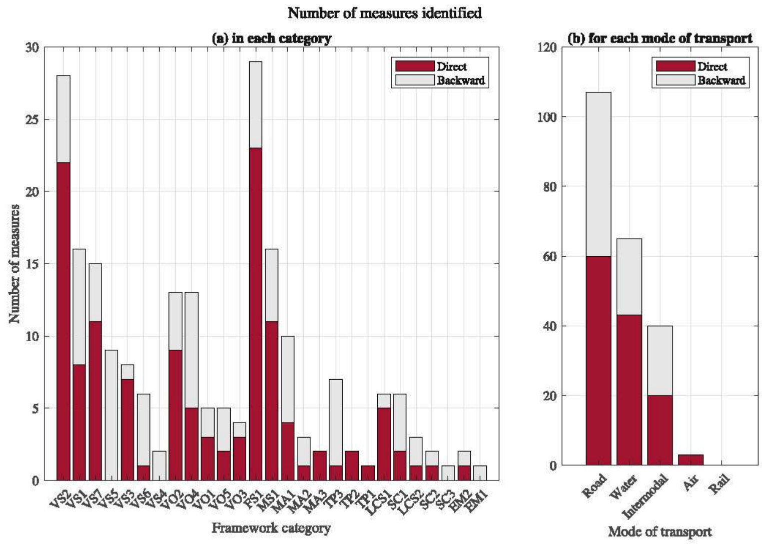

Fig. 6. Number of measures identified in each category (a) and for each mode of transport (b).

emissions in this mode of transport. Most of them deal with emission reduction in road transport, followed by shipping and intermodal transport. The high reference to measures regarding road transport might exist due to the large share of emissions accounted for road transport (Umweltbundesamt, 2019) and a high number of participating actors (Rodrigue et al., 2013). The astonishingly low number of measures found to reduce emissions from air transport should be investigated in future research.

The results of the categorization and clustering extend the current literature on this topic. Similar studies have been conducted to collect emission mitigation measures and their reduction potentials in the shipping industry, targeting shipping operations and ship's design and engineering and, thus, obviously do not include supply chain-, load carrier-, or transport planning-related measures (Bouman et al., 2017; Sames and Köpke, 2012). In contrast, Bjerkan and Seter (2019) present measures for sustainable ports, including a modal split in feeder and delivery services, as well as port dues and managerial policies. Piecyk and McKinnon (2010) conducted focus group interviews and a Delphi study elaborating on key variables, logistics factors, and their relationships, that determine the CO_2 emissions of road freight transport. Their explanatory theoretical model is split into structural, commercial, operational, functional, external, and product-related factors. In Fig. 7 the clusters defined in the focal paper are mapped to the decision levels at which decisions can be made on those factors (McKinnon, 2018; McKinnon and Woodburn, 1996). The mapping was done using empirically defined key variables and their relations from the aforementioned study by Piecyk and McKinnon. The description of the decision levels is presented in Section 2.

It can be seen that three clusters are not included in the existing framework that is visualized in the first row. Weight reduction is mentioned in the framework but was not considered as logistics-related decision due to the focus on the product itself. However, to reduce the total weight of the load, the current study found measures to reduce the weight of the load carrier, which in most cases are the responsibility of logistics. Since the classification into the existing decision-making levels is not possible in a meaningful way, a new level, that of technical logistics, is introduced for this purpose, as it can be seen in the second row of Fig. 7 in red. Technical decisions thereby relate to decisions made in the planning of the material flow before the operation, e.g., deciding on load carrier designs or improving the transshipment process and thereby reducing idle time. Shippers' employees and management were not included in the framework at all, again confirming the need to deepen social sciences among supply chain scholars. To include these clusters, the framework was extended to include decisions that are related to the management system, e.g., human resource management or KPI monitoring. Furthermore, the decision levels were modified to distinguish between manufacturing companies (MC) that do carry out transport on their own, i.e., with their fleet - and those, that do not carry out transport on their own and outsource their transportation demands to LSPs. Shippers are - in both cases - able to exert influence on all the clusters, but the influencing factor may be found on a different decision level, depending on the executing party.

5.1.1. Addressing the reduction potential to be expected

The reported emission reduction potentials of the measures were presented in Fig. 4 and further discussed in detail in the sections describing the categories. For 21 out of 27 categories, figures were found in literature, whereby only in 10 categories were more than three figures observed, and, thus, no robust statement can be made on 17 categories, presenting fewer than four data points each. Certainly, to aid decision-makers, these gaps have to be filled with reliable data, which is a task for further researchers.

The categories with the highest number of data points ($n = 17$) are the combination of *FS1* and *VS2*, which also show the greatest variance in the data, having its 75th percentile located at 73.25%, whereas the median is located at 32.6%. Therefore, the interquartile range (IQR) representing half of the figures stretches up to 60.58%, showing a low consensus between the studies. The category whose reduction potential can be estimated most confidently is *MS1*: nine out of 16 (56.25%) reported measures state reduction potentials, having an IQR of 18.2% ranging from 22.8% to 41%, and the median at 28.5%. Due to the need for high-quality information to reach a mature decision-making process (Adam, 1997; Ehrmann et al., 2021) and a greater willingness to implement measures if the potentials are better perceived (Pålsson and Johansson, 2016), this category is one of the most interesting for decision-makers. The data on this measure eliminates any doubt that it will reduce a significant amount of emissions and thus can be introduced without much uncertainty regarding emission mitigation. In comparison, data on the most researched categories, *VS1* and *FS1*, leave open a large space of potential reductions in the implementation of these measures, which negatively influences efficient decision-making processes.

5.2. Unexpected findings and limitations

On a positive note, there has been a trend in recent years toward more practice-oriented research. In this regard, case studies account for the second-most frequent methodological approach, as already shown in Fig. 2 (b), following mathematical models and simulations. Although the latter statement is in line with previous research findings, the observed trend toward practical experience in research could not be found in earlier reviews (Bjerkan and Seter, 2019), which indicates that research tends to develop toward being a bigger aid for practical decision-makers in the future.

Interestingly, aside from platooning and monitoring of indicators, no digital innovations and technologies are investigated in the literature

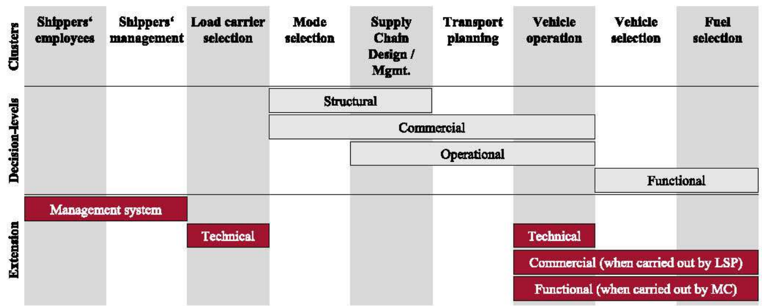

Fig. 7. Mapping of the findings to an existing framework.

regarding GHG emission reduction in freight transport. The adoption of developments from car manufacturers, e.g., the Traffic Light Information of Audi recommending driving speeds to "limit the number of red light hits" (AUDI, 2021), might be promising areas of research that are currently neglected in freight transport. Impacts of 5G-enabled Vehicle-to-Infrastructure or even Vehicle-to-Everything technologies on driving behavior, fuel consumption, and finally GHG emissions should be investigated in freight transport operations.

To critically reflect on the current paper it has to be denoted, that the robustness of the findings regarding the reduction potentials is limited due to a low number of widespread data points, which, first, implies a low reporting of figures on certain measures and, second, indicates a low consensus on figures of specific measures. To address the first issue, future research is proposed to provide more figures regarding the reduction of GHG emissions when specific measures are adopted and separate from the mere presentation and conceptualization of measures. Regarding the second point and also addressing the aforementioned limitation of sound reduction potentials to one single measure, we derive the requirement to develop a standardized set of rules or methodology to ensure comparability, representativeness, and completeness when scientifically reporting on emission mitigation measures in transport. A clear definition of the baseline situation, the breakdown of all assumptions made and argumentations for those, as well as sources for used figures (e.g., engine efficiencies, carbon intensities, …) must be included in such a framework to ensure comparability and reproducibility. Additionally, the scope (e.g., cradle-to-gate, well-to-wheel, …) of each of the objects under study and the investigated environmental impact indicator (e.g., CO_2 or GHG) must be pointed out, which is, considering the analyzed studies in this review, not always the case as of now. Furthermore, the reduction potentials need to be extended by empirical or desk research on the state of the art in practice, conducting, e.g., expert interviews, conducting surveys, or systematically analyzing sustainability reports.

6. Conclusion

In this paper, a comprehensive literature review on measures to mitigate GHG emissions in the transport operations of manufacturers was conducted. All in all, 215 measures were assigned to 27 categories and nine clusters, contributing to literature by, first, providing an up-to-date comprehensive collection and categorization of measures for all levels of logistics decision-making in manufacturing companies and, second, estimating the reduction potentials of the measures and categories that were found by screening literature systematically.

This literature analysis deepens the general understanding of which levels and with which decisions manufacturing companies can exert an influence on GHG emissions that originate from the transportation activities related to their production processes. Depending on their role, acting as a shipper and outsourcing all their transportation activities to LSPs, or as a carrier themselves and executing transportation with their vehicles, the measures in the clusters can be influenced by different decision levels. Companies that outsource transportation can exert influence on operational aspects, just not at the functional level, but at the commercial level. An existing framework that defines four decision levels, i.e., structural, commercial, operational, and functional decisions, was therefore specified for manufacturing companies and the two aforementioned cases of the freight-carrying party. Furthermore, it was extended to also include decisions related to technical logistics and the management system.

Besides the mere categorization of measures that are currently researched, a meta-analysis of their respective potential emission reductions was carried out during the research. On the one hand, the analysis has shown that a sound estimation of emission reductions by shifting road transport to rail is possible, and on the other hand, that it is hardly possible to make a general statement regarding the potentials of other measures, among them the switch to alternative drivetrains and fuels. Given the fact that valid information is the basis for efficient decision-making, this study outlines that managers currently receive meaningful support from science on only one measure. But having in mind the need to reduce emissions to zero, shifting road transport to rail can reduce a significant portion of emissions, but it is far from sufficient to eliminate emissions. This implies the necessity to establish a stronger scientific consensus on the reduction potential of various measures under certain conditions to enable managers to compare different alternatives evidence-based. Therefore, the need to develop a standardized methodology to scientifically report on such measures is raised due to tremendously different baseline scenarios and assumptions that are used as of now and lead to partially incomparable results.

Furthermore, the current focus of the discussion on emission reduction is very technical, leaving out the role of human employees and managers. This article is not the first to reach this conclusion, raising the need to incorporate more social research into the discussion of reducing emissions. Technological developments and research will be a major part of emission mitigation, but will not be able to sufficiently reduce emissions on their own. What will be necessary is a rethinking of supply networks to tremendously reduce transportation demands. To conclude, this paper highlights one more time that the decarbonization of freight transport will only be possible if strategic, operational, and technical decisions will be aligned so that every potential, no matter how small, can be exploited.

CRediT authorship contribution statement

Philipp Miklautsch: Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Manuel Woschank:** Supervision, Methodology, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The research was funded by 'Amt der Steiermärkischen Landesregierung', grant number ABT08-247910/2021.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.132883 and https://doi.org/10.17632/t3p2nv66wm.2.

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9.2. Paper 2

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Identifying a Country's Freight Transport-Intensive Economic Sectors and Their Logistics Emissions—Method Development and Exemplary Evaluation with Austria

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Abstract: It is unequivocal that global greenhouse gas emissions must be reduced drastically. One opportunity to quickly achieve deep emission reductions is by investigating the largest emitters first. This can be based on countries but also on the underlying sectors of local economies. Focusing on the latter, the transport and industry sectors stand out, as well as their overlap, which is reflected in the emissions from freight transport. To enable legislators and researchers to focus on the major emitters in freight transport and to develop tailored sectoral measures, we present a method to identify the transport-intensive sectors of a country. A two-part approach thereby makes it possible to identify these sectors and their value chains and to analyze the different emission structures of companies between the sectors. This suggests the relevance of decarbonizing transport from a company's perspective and helps to understand the entrenched situation. Finally, the methodology is applied to the Austrian transport industry as an example to demonstrate its applicability. As applied research in this area has lagged somewhat, our results can provide managers in transport-intensive economic sectors with new motivation to decarbonize logistics, as well as guide policymakers and researchers on which sectors to focus first.

Keywords: greenhouse gas emissions; climate change; transportation; logistics; transport-intensive sectors; transport-intensive value chain; reporting

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1. Introduction

With the contribution of the first working group on the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), the harmonization of thousands of sound scientific findings enhanced the understanding of the physical science basis of climate change and established confidence that the warming of the earth's surface temperature can be attributed to anthropogenic greenhouse gas (GHG) emissions [1]. Following this report, the second IPCC working group deals with consequences arising from this climate change and points to nothing less than a serious climate crisis, including extreme weather events, climate-caused refugee movements, biodiversity loss, and mental health challenges if GHG emissions are not profoundly reduced in the near-term [2]. Those findings, again, highlight the need to reduce emissions significantly as soon as possible. To do so, a prominent strategy is a top-down approach, focusing on the top emitters first and implementing carbon-neutral or carbon-free practices among them. This can be performed on the country level, concentrating, first, on the nations that emit most of the emissions. Having a look at the top-emitting countries, China has been leading this list since about 2006, when it passed the United States of America [3]. However, this perspective on prioritizing decarbonization poses some problems. First, it enters the discussion of emissions accountability since "China emitted considerable amounts of carbon dioxide on behalf of foreign consumers in the years from 2000 to 2014" [4]. Thus, the question arises of how to deal with and allocate emissions embodied in global trade [5], resulting in a dilemma between "production-based" and "consumption-based" responsibility [6]. Additionally, secondly, new estimations and datasets show that ranking by country no longer reflects the real situation since the inequality of income inside countries is overwhelming, and the top 10% of the earth's population emits 48% of the global GHG emissions, while the bottom half of the population emits 12% [7]. Therefore, the concentration on the top-emitting countries does not seem to be appropriate anymore.

Another perspective to focus on top emitters first is the division of global emissions by economic sectors. Although small differences in the concrete figures among different reports exist, the energy sector is undoubtedly the top emitter, contributing 25 to 42% of the global anthropogenic GHG emissions [8–10]. Subsequently, emissions from the industrial sector amount to 21–23% and from the transport sector 14–23% [9,10], awarding them silver and bronze in the ranking of top-emitting economic sectors, respectively. The emissions from industry will further rise when indirect emissions are accounted to this sector. Following the Greenhouse Gas Protocol's logic, not only direct emissions created by production processes, so-called "Scope 1" emissions, are to be allocated to the industry, but also indirect emissions that emerge in the generation of energy used by the companies ("Scope 2"), as well as emissions from the companies' value chains ("Scope 3") [11,12]. Considering also Scope 2 emissions, the emissions of the industrial sector increased by another 11% [10]. Similarly, certain emissions from the transport sector can be attributed to the industry—which are the up- and downstream Scope 3 emissions from transportation purchases. Those originate from the need of industrial companies to transport raw, auxiliary, and operating materials, as well as intermediate and end products [13], and are originally accounted for as freight transport emissions. In total, freight transport accounts for around 30% of the transport sectors' emissions [14], resulting in 4 and 7% of the worldwide GHG emissions. Accounting for those in the industrial sector leads to an increase in the industry's emissions by 4–7%, pushing it to the pole position of global GHG emitters. Although emission reduction initiatives in the Scope 1 manufacturing processes are slowly starting to take effect, measures in logistics that are mainly accounted for in Scope 3 do not yet reach their expected potential [15].

Therefore, current research should have a serious interest in examining more closely the emissions arising from the up-and downstream transportation activities of shippers. Splitting up the industry into smaller industrial sectors producing and handling specific goods allows for tightening the aforementioned top-down approach, focusing first on the sectors with the highest transportation demands and, thus, the highest emissions from transportation. Therefore, the structure of a country's freight transport system needs to be known so that macroeconomic decarbonization initiatives can be steered to have their effect first in transport-intensive sectors.

Whereas the extant literature on decarbonization measures in logistics exists [16], research on the transport-intensiveness of different sectors is scarce. Only a few articles dealing with this could be found when screening the pertinent literature on this topic. A survey aiming at transport-intensive industries in Sweden was sent to companies in nine different sectors, namely agriculture/forestry; chemical; food and drinks; manufacturing; manufacturing other; ore/metal; pulp, paper and paper articles; wholesale trade; and logistics service providers. The selection of those sectors is thereby argued by the statement that "the span of logistical demands in these industries covers a variety of requirements in terms of costs, flexibility, delivery time and quality" [17]. At least the selection of forest products can be validated by another study from a Scandinavian country, mentioning that about 14% of the tonne kilometers in the domestic freight transport of Norway originate from the forest sector [18]. Swiss authors elaborate on the transport-intensive sectors of Switzerland based on official statistics [19]. The primary industries identified were the chemical and plastics industry, metal industry, mechanical engineering, electrical and precision engineering, construction industry, food and beverage industry, and mineral oil industry. These were expanded to include the two cross-sectional sectors of retail and wholesale and waste and recycling. The authors thereby discuss their methodology in detail and combine economic data with transportation volumes. For China, economic data from the China Statistical Yearbook 2000 are used in [20] to derive the transport intensity of different sectors. Those are composed similarly to the Swiss but account for significantly more transportation services to the agricultural sector [20]. Although some other papers exist that use the term "transport-intensive" in some form [21,22], to the authors' surprise, no further papers could be found that define the term or elaborate on other countries' sectors. All in all, this leads to the assumption that the transport-intensive sectors differ country-wise, based on the unique composition and characteristics of economic activities in the countries, but that no general methodology to identify those sectors exists.

To close this gap, we develop a methodology on how to identify the transport-intensive sectors of a country generically. We base our method on the methodology used in the aforementioned Swiss study [19] and extend it with data and methods from the EcoTransIT World emission calculation tool [23]. In this way, we define a methodology that has minimum requirements for official statistics and, at the same time, is close to reality and thus finds applicability in as many countries as possible. For evaluation, we use Austria as an example because the country is comparable to Switzerland in terms of being a landlocked, middle-European, developed country, with a hilly surface and access to important European inland waterways.

Providing a methodology that identifies transport-intensive sectors allows researchers and policymakers to easily compare countries and provides an initial indication of which macroeconomic sectors to focus on first when aiming at emission reduction in freight transportation.

With this knowledge, legislators, for example, can develop sector-specific incentives to promote the implementation of decarbonization measures for a set of companies. To do this, however, it is essential to understand which companies operate in these sectors and how logistics emissions are relevant to them. Of particular interest is the share of logistics emissions in a company's total emissions, which determines how relevant the decarbonization of logistics is for the overall decarbonization efforts of the company. Manufacturing companies, e.g., are reported to perceive larger emission reduction potentials in their core operations than in logistics and therefore tend to focus on those areas first [24]. Little data on the numbers of companies' emissions attributable to logistics are presented in the literature [24]. Individual figures suggest that the share of emissions attributable to logistics among manufacturers is about 8% [25], having outliers such as the fashion industry accounting for up to 35% of the Corporate Carbon Footprint to logistics [26]. To provide a guideline on how to identify this share in a sound and comparable way, we extend our methodology by a second part. With this part, we aim to provide an answer to the question of what percentage of a transport-intensive company's total emissions is attributable to logistics and whether this share differs between the transport-intensive economic sectors. Again, we use Austria as an example to evaluate the methodology and analyze non-financial reports of Austrian companies that belong to the transport-intensive industry sectors.

Based on these considerations, the two overarching research questions of the focal paper were formulated and answered throughout the research:

- How to identify transport-intensive sectors of a country with minimal requirements to official statistics in a realistic manner?
- How to identify the percentage of a transport-intensive company's total emissions that are attributable to logistics and compare this share among the transport-intensive economic sectors?

The remainder of this paper is structured as follows: Section 2 presents the methodology and is split up into two subchapters, each describing the methodology used to answer one research question. Section 3 is similarly structured, presenting the results of the methodology. Section 4 discusses the results and Section 5 comprises a brief conclusion.

2. Research Methodology

As described in Section 1, we present a twofold methodological approach in this paper. First, a top-down analysis of transportation statistics reveals the transport-intensive sectors of the country under study. Second, a bottom-up approach enables the researchers to gain deeper insights into the structure of the identified sectors.

2.1. Transport-Intensive Economic Sectors

To identify a country's transport-intensive economic sectors, we adopt and modify a research approach taken by Swiss authors [19] aimed at understanding the Swiss freight transportation system. As discussed above, this study was selected as a methodological starting point because it is one of the few scientific publications in this field, and it ensures the comparability and verification of the results of the developed methodology.

The underlying data of the methodology and, thus, the starting point are official transport statistics of the country under study. From this, solely the transport volume in tons denoted as M, grouped according to the types of goods is used. We suggest using the goods classification defined in the classification system for transport statistics (NST 2007) on the division level and the modes of road freight, rail freight, as well as freight transported on inland waterways to cover all domestic modes of transport.

However, if only the mass of transported goods is used as an indicator of transport intensity, the picture is distorted because high-volume, low-density goods are neglected. The Swiss authors, therefore, use economic data of the sectors (value of goods, gross value added) as well as data on transport performance (tonne kilometers) to conclude the transported goods. However, since we strongly doubt the availability of these data in other countries and thus the generic applicability of the methodology, we have modified it at this point. To account for the influence of volume, we include an approach used by the EcoTransIT World emissions calculation tool [23] (p. 32). Therein, the transported mass M is adjusted by the average vehicle capacity utilization CU_{NC}, which depends on the goods category. Calculating $M_{adj} = \frac{M}{CU_{NC}}$ additionally includes the consideration of empty runs in the analysis. EcoTransIT was consulted due to its clear documentation and its broad acceptance in academia and practice. To consider different values for CU_{NC} across different NST divisions, cargo types are allocated to the goods in accordance with the description of the cargo types and examples provided in the EcoTransIT World methodology [23] (p. 31). If no logical allocation can be found, we suggest allocating the cargo type "average" to ensure comparability.

Having calculated M_{adj}, we order the goods descending by their respective M_{adj} and calculate the share of the total M_{adj} for each goods division. Then, the cumulative share of each NST division was computed to identify the goods that account for 80% of the total M_{adj}, following [19]. Thereby, the economies of transport-intensive goods are identified.

To map those goods to related economic sectors, we consult the description of the goods presented in the NST 2007 classification [27]. The goods are then mapped to those economic sectors that are producers, processors, or manufacturers of the goods. To ensure the comparability of economic sectors between countries, we recommend following the Classification of Economic Activities in the European Community, briefly called NACE [28]. This step results in the list of the economies' transport-intensive economic sectors.

For a more concise presentation of the results, we further cluster the sectors and formulate transport-intensive value chains based on supplier–demander relationships among the transport-intensive sectors.

In the last step, we discuss the limitations that we faced when applying the methodology and challenge our results against the existing literature on the topic.

The methodological approach is visually summarized in the first line of Figure 1.

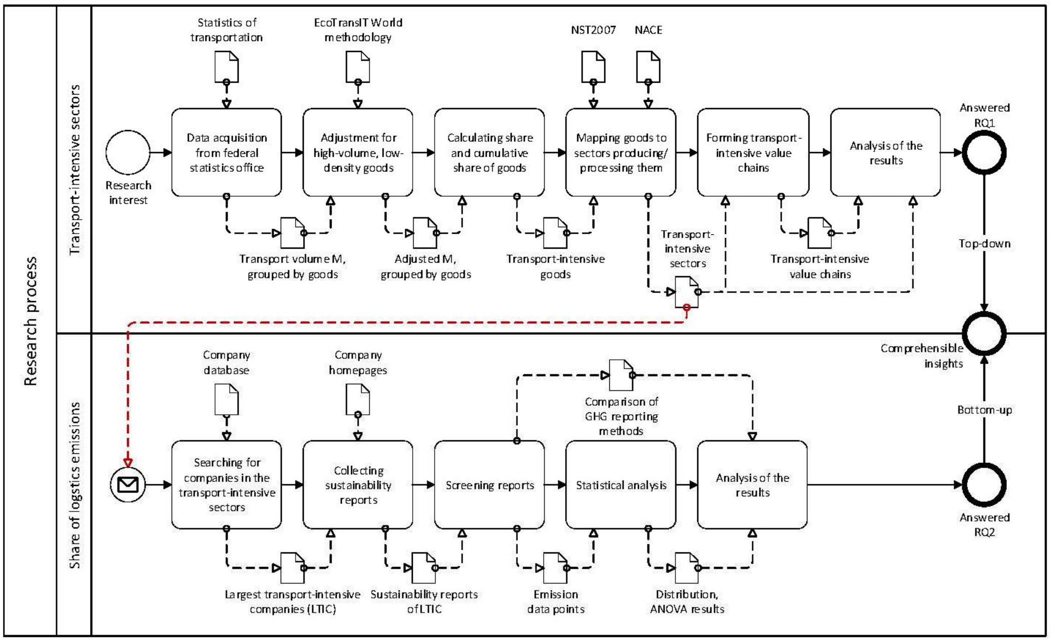

Figure 1. Research process.

2.2. *Logisitcs Emissions in the Transport-Intensive Economic Sectors*

To answer the second research question and identify the share of logistics emissions and sectoral differences, the transport-intensive economic sectors identified in the first part provide a starting point for a systematic search in a database that comprises company data for the country under study. Searching each of the sectors with predefined parameters filters the database according to the economic sector, number of employees, and turnover. To handle a high number of results, we propose to first select the top ten companies by turnover and then combine this with the top ten companies by the number of employees. This results in the set of the largest transport-intensive companies (LTIC).

Subsequently, as visualized in the second row of Figure 1, further desk research is conducted by analyzing the companies' homepages and trying to find published non-financial reports, which are referenced as Sustainability Reports (SR) in the further manuscript. All kinds of SR, no matter if they are compliant with specific standards such as the Global Reporting Initiative (GRI) or the Eco-Management and Audit Scheme (EMAS), are collected in this stage. If companies are part of a group and the group publishes an SR, the group SR is taken for the analysis. Therefore, companies of the same group are assigned the same SR, which lowers the sample size of the subsequent statistical analysis. We only consider SR, in which figures regarding the absolute GHG emissions in the timespan 2017–2020 are reported.

Screening the SR is accompanied by analyzing and comparing them regarding the method of emission reporting, the reported scopes, and the reported emission units. The main goal of this step is the extraction of data points from the reports, whereby one data point represents the emissions of one company in one year, which can be further split up into emission categories.

To make a generalized statement about the share of logistics emissions in the total emissions of transport-intensive companies, the distribution underlying the data is examined. We suggest doing this by fitting the data points with a Maximum Likelihood

Estimation to all 98 continuous distributions listed in scipy.stats [29] and check the Goodness of Fit by performing a Kolmogorov–Smirnov test. A commonly used distribution with an appropriate *p*-value (we suggest $\alpha = 0.05$) then describes the data points. Besides this distribution, the differences in emissions shares across the investigated value chains are examined in this phase. Therefore, the impact of the value chain a company is in on a company's share of logistics emissions is assessed by conducting a one-way ANOVA. This test shows if statistically significant differences across the transport-intensive value chains exist.

Similar to the first part of the methodology, limitations and comparisons to the similar literature are discussed in the last phase.

3. Evaluation of the Methodology with Austria

Austria was selected as an example because it is, first, comparable to Switzerland, as described above, and second, no data on the transport-intensive sectors are available yet.

3.1. Transport-Intensive Economic Sectors

After applying the methodology described in Section 2.1 to the Austrian transportation system, using statistics from the Austrian Federal Statistics Office [30] (p. 28) as a basis, the results in the selection of Austria's transport-intensive goods, as well as their respective business sectors, are listed in Table 1. The used statistics include domestic traffic, cross-border receipts, and cross-border dispatch but exclude transit traffic. The divisions 18 "grouped goods", 19 "unidentifiable goods", and goods that cannot be assigned to any division were removed during the application of the methodology because they account for less than 4% of Austrian transport volume. Note that the sum of all shares presented in Table 1. is not 100%, which is because we only present the transport-intensive economic sectors in this paper. The full list is provided in the supplementary material.

Table 1. Transport-intensive goods and their respective transport-intensive economic sectors in Austria, resulting from the developed methodology (source: own calculations based on [30] and mapped based on [28]).

NST 2007 Division		NACE Division		M_{adj}	Share
3	Metal ores and other mining and quarrying products; peat; uranium and thorium	B5	Mining of coal and lignite	245,533	21.66%
		B6	Extraction of crude petroleum and natural gas		
		B7	Mining of metal ores		
		B8	Quarrying of stone, sand, and clay		
4	Food products, beverages, and tobacco	C10	Manufacture of food products	145,236	12.81%
		C11	Manufacture of beverages		
		C12	Manufacture of tobacco products		
9	Other non-metallic mineral products	C23	Manufacture of other non-metallic mineral products	142,288	12.55%
10	Basic metals; fabricated metal products, except machinery and equipment	C24	Manufacture of basic metals	113,574	10.02%
		C25	Manufacture of fabricated metal products, except machinery and equipment		
1	Products of agriculture, hunting, and forestry; fish and other fishing products	A1	Crop and animal production, hunting, and related service activities	107,371	9.47%
		A2	Forestry and logging		
		A3	Fishing and aquaculture		

Table 1. *Cont.*

NST 2007 Division		NACE Division		M_{adj}	Share
6	Wood and products of wood and cork (except furniture); articles of straw and plaiting materials; pulp, paper, and paper products; printed matter and recorded media	C16	Manufacture of wood and products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	75,394	6.65%
		C17	Manufacture of paper and paper products		
14	Secondary raw materials; municipal wastes and other wastes	E38	Waste collection, treatment, and disposal activities; materials recovery	68,150	6.01%
12	Transport equipment	C29	Manufacture of motor vehicles, trailers and semi-trailers	43,905	3.87%
		C30	Manufacture of other transport equipment		

The most transport-intensive goods are, by far, metal ores and other quarrying products, peat, uranium, and thorium. This is a plausible finding because companies manufacturing those goods are, among others, suppliers for the metalworking industry (NACE divisions C24 and C25), which represents a significant economic sector in Austria, alone generating about 4.4% of the total revenue of Austrian companies [31]. Therefore, it is also understandable that these divisions, as demanders and further processors of transport-intensive goods, are also found among the transport-intensive industries. These supplier–demander pairs can be summarized as the Metal Value Chain (VC), as visualized in Figure 2. Non-metal mining and quarrying products that are extracted (B5 and B8) and further processed to non-metallic mineral products (C23) form the Mineral VC. Another supplier–demander pair can be found in the identified sectors, which is the agricultural sector (A1–A3) that manufactures and supplies input materials for the food and beverages industry (C10–C12), forming the Food VC. The same accounts for the manufacturing of products from wood (C16 and C17), forming the Wood VC. The manufacturing of motor vehicles, trailers, semi-trailers (C29), and other transport equipment (C30) is somewhat exceptional in this way because this sector is usually supplied by the Metal, Mineral, and sometimes Wood VCs. A cross-sectoral transport-intensive sector is the collection and processing of waste (E38), as this is necessary for all the value chains described.

Comparing our results to the Swiss study that was used as a methodological reference lead to the conclusion that the sectors do relate to a great amount but differ in some details. Astonishingly, the chemical industry is missing in the Austrian transport-intensive sectors. This might be due to the chemical industry being significantly smaller in Austria, as measured by the relative number of employees in the chemical industry (NACE division C20) to those in total manufacturing (NACE category C), which accounts for 2.86% and 4.3% in Austria and Switzerland, respectively [32,33]. Given the similarity of the two countries' freight transport systems and the logical arguments for the differences, we conclude that our methodology leads to valid findings of the transport-intensive economic sectors.

Three limitations that we faced when applying the methodology should be discussed. As already mentioned above, the first limitation is the neglect of tonne kilometers in the calculation due to scarce data, which underestimates the impact of high-volume, low-density goods. This drawback was addressed by including the mean capacity utilization adopted from EcoTransIT. One indication that this approach in calculating M_{adj} is valid is the inclusion of companies manufacturing transport equipment (NACE divisions 29 and 30) in the transport-intensive economic sectors after consideration of CU_{NC}. This sector ranked fourth in average revenue per company and fifth in average employees per company in Austria in 2019 [33], thus representing an important sector of the economy, but was not included in the transport-intensive sectors when only considering M. This is because the transportation demand for those goods is mainly driven by their volumetric properties and not their weight [23]. Nevertheless, another validity check should be performed as soon as more granular data on tonne kilometers traveled is available at the NST level. A second debatable point of the focal methodology is the allocation of goods to the sectors that manufacture or produce them. In this respect, only the transport of already-finished goods is considered. This makes sense for raw materials but may distort the picture for producers who are closer to the end customer, as their inbound transports are not accounted to them. This limitation was eased by considering the entire value chain, including supplier–demander pairs and thus causing these allocation discussions to be obsolete. The third limitation may be specific to the application of the methodology with the Austrian statistics because it is not entirely clear if the goods for which the transportation volumes were considered originate from Austria. Therefore, it is hard to logically argue that the companies from the identified transport-intensive sectors are located exclusively in Austria.

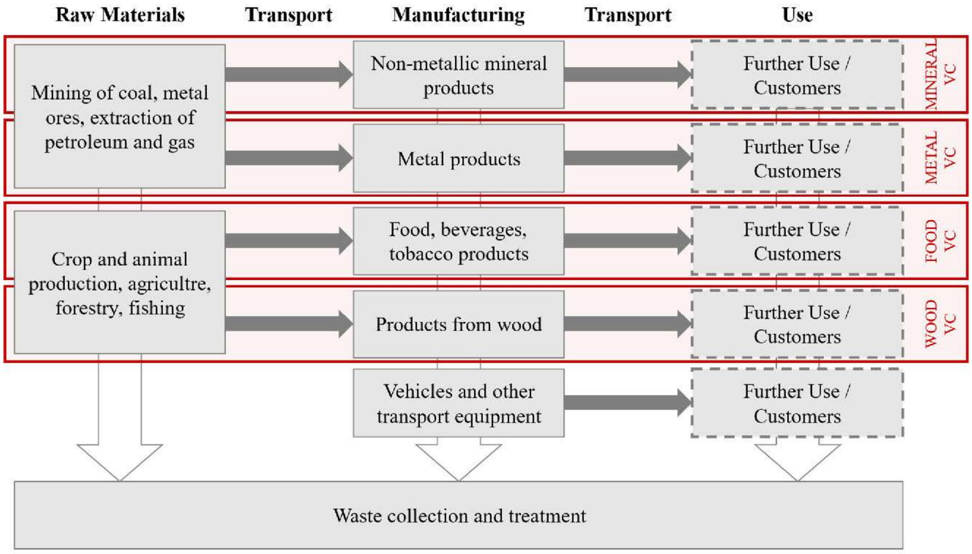

Figure 2. Visualization of the transport-intensive value chains in Austria.

3.2. Logistics Emissions in the Transport-Intensive Economic Sectors

3.2.1. Collecting Companies and Reports

To collect data on Austrian companies in the transport-intensive sectors, we use the Aurelia database [34]. Minimal values for the sorting parameters are a turnover of 10,000 EUR and ten employees. Except for NACE division B5, entries were found in all categories, thereby resulting in a total of 179 companies that, together, form the set of the LTIC in Austria.

For 108 of 179 companies (60.34%), no report could be found. For another eleven companies (6.15%), a report without figures on emissions could be found, and in the reports of five firms (2.79%), only specific emissions related to output or profit were reported. Thus, reports of 55 companies (30.73%) in the set of LTIC were considered. Since some companies belong to a parent group for which a central report is prepared, reports from a total of 38 business entities were analyzed.

3.2.2. Screening the Reports

All in all, we extracted 116 data points from the reports. Investigating the distribution of the data points over time on the left-hand side of Table 2 and Figure 3a, we see an inclination year by year, starting with 20 in 2017, rising to 29 in 2018, and reaching 33 and 34 in 2019 and 2020, respectively. This provides the first indication that although there has been a rise in emission reporting among companies in the considered period, saturation has been reached in the last two years. We observed most of the data points in the Wood and Food VCs. The existing data points were filtered once again, as only emission values that are further subdivided and for which logistics emissions are explicitly reported can be used to answer the research question. The remaining data points are shown on the right-hand side of Table 2 and Figure 3b.

Table 2. Distribution of data points over time and VC.

	All Data Points					Data Points Presenting Logistics Emissions				
	2017	2018	2019	2020	Total	2017	2018	2019	2020	Total
Food	8	8	7	8	31	3	3	2	5	13
Metal	2	4	4	4	14	1	1	1	2	5
Mineral	1	2	5	4	12	0	1	1	1	3
Other	1	2	2	2	7	0	0	0	0	0
Transport	1	4	6	7	18	1	1	1	2	5
Waste	2	3	3	3	11	2	3	3	3	11
Wood	5	6	6	6	23	1	1	2	2	6
Total	20	29	33	34	116	8	10	10	15	43

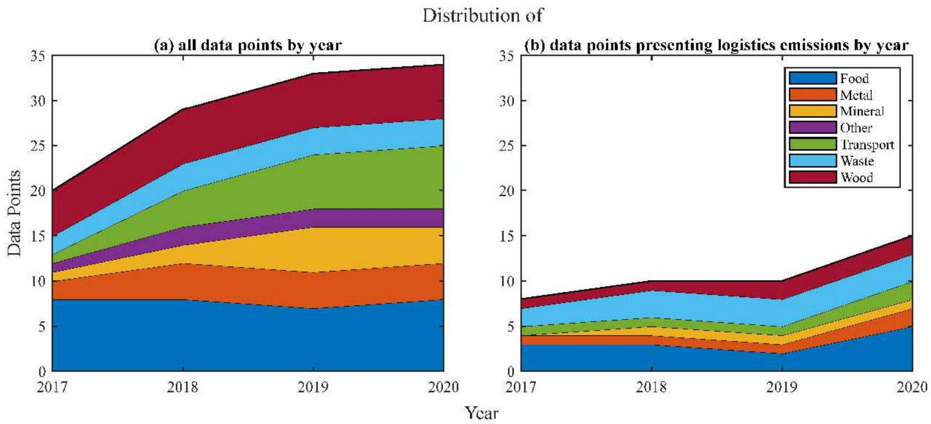

Figure 3. Number of data points over time and VC.

In total, only 43 of 116 data points (37.07%) separately present logistics emissions, but a rise in this share can be seen from 2019 to 2020, indicating a positive movement towards more solid logistics emission reporting. However, keeping in mind that the overall number of 116 data points was generated from reports of only 30.73% of companies in the set of LTIC, we can clearly state that reporting on logistics emissions is still in its infancy among the companies of the transport-intensive economic sectors in Austria, which is a call for action towards practitioners.

Investigating the reported emissions of logistics in more depth reveals another weakness in current reporting because the way these emissions are reported is extremely divergent. An overview of these ways of reporting is visualized in Table 3, employing a morphological box in descending order of detail, presenting each analyzed report together with its logistics emission categories. Thus, at the bottom row, the most detailed way of reporting is displayed. In there, the grey-colored boxes describe the different categories for which figures are presented in the SR. Only one company reports in the most detailed way, separately disclosing Scope 1, Scope 2, and Scope 3 emissions and further pointing out emissions from the transportation by vehicles that are owned by the companies (Scope 1 Logistics), as well as upstream and downstream transportation (Scope 3). Looking at the rows above the bottom one, companies start to aggregate their logistics emissions in different ways, i.e., summarizing all Scope 3 transportation emissions or even only reporting on emissions from logistics in general, but not describing what is meant in detail. All in all, this variety of ways in which emissions from logistics are reported leads to diminished meaningfulness of further analyses.

Table 3. Overview of the level of detail of reporting on logistics emissions in the analyzed SR.

Report(s)	Reporting on Logistics Emissions			Scope 1	Scope 2	Scope 3	Total Emissions
[35–38]	Transportation/Logistics in total						x
[39] [1]	Transportation/Logistics in total			x	x		
[40,41]	Scope 1 Log			x	x	x	
[42]	Scope 1 Log	Scope 3 Transport		x	x	x	
[43–45]		Scope 3 Transport		x	x	x	
[46]		Scope 3 Up		x	x	x	
[47]	Scope 1 Log	Scope 3 Up		x	x	x	
[48,49]		Scope 3 Up	Scope 3 Down	x	x	x	
[50]	Scope 1 Log	Scope 3 Up	Scope 3 Down	x	x	x	

[1] Although not specifically mentioned in the SR, logistics emissions from these SR were further considered to be Scope 1 emissions due to the absence of Scope 3 emission reporting.

3.2.3. Statistical Analysis

Due to the data describing different years and having different mean values over the observed years, we normalize the data by the mean value of the respective year $\tilde{x}_i = x_i/\bar{x}_i,\ i \in \{2017, 2018, 2019, 2022\}$ before the statistical analysis. Then, the data are fitted with a Maximum Likelihood Estimation to 98 continuous distributions listed in scipy.stats [29]. To check the Goodness of Fit, a Kolmogorov–Smirnov test is performed. The p-value leads to the rejection of 22 tested distributions ($\alpha = 0.05$), leaving 76 distributions not rejected. According to the residual sum of squares and the residual standard error (RSE), the three-parameter kappa distribution shows the best fit ($p = 0.9803,\ RSE = 0.0714$). However, when examining more common distributions, the log-normal distribution shows good results ($p = 0.8744,\ RSE = 0.0910$). The log-normal distribution was also shown to describe other data similarly well as the kappa distribution [51] and is suggested by different authors concerning emissions [52–56], but it is not generally observed [52]. Anyway, a modified version of the log-normal distribution, the power log-normal distribution, fits data even better ($p = 0.9132,\ RSE = 0.0857$), which is why we use it for further investigations. Figure 4 shows the probability density function (PDF), the cumulative distribution function (CDF), and the probability plot of the normalized empirical data $\tilde{x}_i$ and the fitted power log-normal distribution ($c = 176.69897614596493,\ s = 2.5642482494271484,\ location = -0.011826190254987191,\ scale = 669.729829463008$). Here, the unit length for the PDF representation of the theoretical distribution refers to the class width of the displayed histogram for better interpretability. The plots depict the close relation between the theoretical distribution and the empirical datapoints. This also shows the suitability of the distribution to represent the share of logistics emissions. The parameters and results of the Kolmogorov–Smirnov tests of all distributions are provided in the supplementary data.

Due to the limited sample size and the limited number of years considered, it is hardly possible to draw significant conclusions about the historical development of the logistics emission share. Nevertheless, to provide a first idea of the historical development of emission shares in the observed years, we present the share of total logistics emissions relative to the total emissions of the company using four box plots in Figure 5a. An enormous range of logistics emission shares is identified, thereby reaching from 1% to 95%. Although different interquartile ranges throughout the years, a similar median value of about 10% is identified in all years. The outlier on the upper end of each plot can be explained due to the type of business the company reporting these figures is doing—operating waste collection vehicles to collect waste from households and industrial customers. Thus, the main activity of this company is the transportation of waste and, therefore, the logistics emissions are correspondingly high. To avoid distortion of the results, this outlier is excluded from further analysis, leading to Table 4 and Figure 5b. In there, the mean share of logistics emissions relative to the total emissions $\overline{x}$ as well as their respective standard deviations (we use the standard deviation of a sample $s = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2}$), which are evaluated by year and value chain.

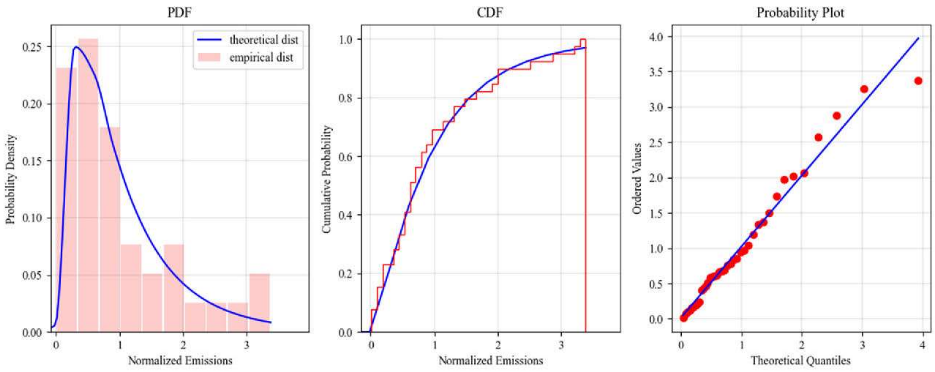

Figure 4. Representation of the fitted log-normal distribution compared with the empirical distribution.

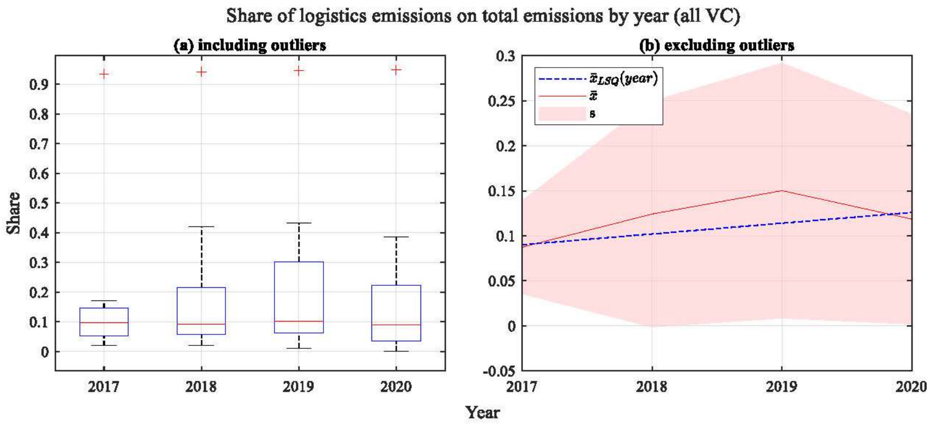

Figure 5. Evaluation of the share of logistics emissions in transport-intensive companies in Austria over time.

Table 4. Share of logistics emissions in transport-intensive companies in Austria over time.

	Total			Food VC			Metal VC			Mineral VC			Transport VC			Waste VC			Wood VC		
Year	$\overline{x}$	s	n	$\overline{x}$	s	n	$\overline{x}$	s	n	$\overline{x}$	s	n	$\overline{x}$	s	n	$\overline{x}$	s	n	$\overline{x}$	s	n
2017	0.0873	0.0517	7	0.082	0.0431	3	0.0685	-	1	-	-	-	0.0205	-	1	0.1719	-	1	0.1041	-	1
2018	0.1241	0.1253	9	0.0907	0.0254	3	0.0583	-	1	0.4195	-	1	0.0211	-	1	0.1198	0.1354	2	0.1061	-	1
2019	0.1501	0.1415	9	0.0937	0.0089	2	0.0636	-	1	0.433	-	1	0.0118	-	1	0.1243	0.1426	2	0.2033	0.1408	2
2020	0.1185	0.1166	14	0.0997	0.0347	5	0.0376	0.0327	2	0.3862	-	1	0.0063	0.0069	2	0.135	0.1548	2	0.2084	0.1361	2
Total	0.1215	0.1141	39	0.0926	0.0296	13	0.0532	0.0219	5	0.4129	0.0241	3	0.0132	0.0081	5	0.1329	0.1038	7	0.1723	0.1019	6

Investigating the share of logistics emissions for all relevant data points independent of the value chain in Figure 5b indicates a peak of relative emissions in 2019, which needs to be taken with caution due to a high standard deviation this year. The rising number of samples and a shrinking standard deviation in 2020 suggests more meaningful results for that year, presenting a share of $\overline{x}_{2020} = 11.85\%$ of emissions accounting for logistics, which is also quite close to the average across all years $\overline{x}_{Total} = 12.15\%$. Fitting the mean shares of each year to a first-order polynomial using least-squares (LSQ) approximation resulted in the equation $\overline{x}_{LSQ}(year) = k \times (2017 - year) + d$, which is evaluated by the dotted blue curve in Figure 5b. The regression indicates that the share of logistics emissions in the total emissions of Austrian transport-intensive companies has slightly increased in recent years by 1.19 percentage points per year, whereas the large uncertainty for the 2019 values might overestimate the real increase. Therefore, we raise the need to validate this further through empirical research in the future.

To conclude on the differences in emissions shares across the investigated value chains, we conducted a one-way ANOVA to assess the impact of the value chain a company is in on a company's share of logistics emissions. The results show that the share of emissions differs statistically and significantly for the different value chains, $F(5,\ 33) = 18{,}424,\ p < 0.001$. A detailed report is provided in the supplementary materials. To gain a better insight into this difference, we evaluated the data for each of the value chains by year and plotted it in Figure 6.

Similar mean shares between 4 and 10% are observed for the Food and Metal VC. The Waste and Wood VC also show similar mean shares of 10 to 20%. Somewhat exceptional are the Mineral VC, with high mean values of around 40%, as well as the Transport VC, presenting very small values of around 2%. The reason for the latter one is the reporting of emissions from the produced vehicles' use phase that is attributed to the Scope 3 emissions of vehicle manufacturers. By including those emissions in the corporate carbon footprint, the total amount of emissions soar, and the share of logistics emissions shrinks.

3.2.4. Analysis of the Results

Larger companies generally adhere to the consideration of the three scopes of the GHG Protocol, but smaller companies or single sites often simply report total emissions without describing which processes are considered in detail. However, differences can also be found in the reports based on the GHG protocol. To elaborate, 11 out of the 24 (45.8%) considered SR do not provide Scope 3 emissions and only one company reports to the full level of detail, as shown in Table 3. Furthermore, different gases were included in the emission reporting in the different SRs. From the 43 data points analyzed, 16 (37.21%) reported only CO_2 emissions, whereas 27 (62.79%) reported CO_2 equivalents, including other GHGs with relevant Global Warming Potentials. Although statistically significant differences across the value chains have been observed, more data would be needed to conclude developments over time. Therefore, Figures 5 and 6 show only initial estimates and should be treated with caution. Since the largest companies in the respective industries were examined and the smaller companies tend not to prepare SRs, we do not assume that an extension to further companies in the transport-intensive industries in Austria is more promising.

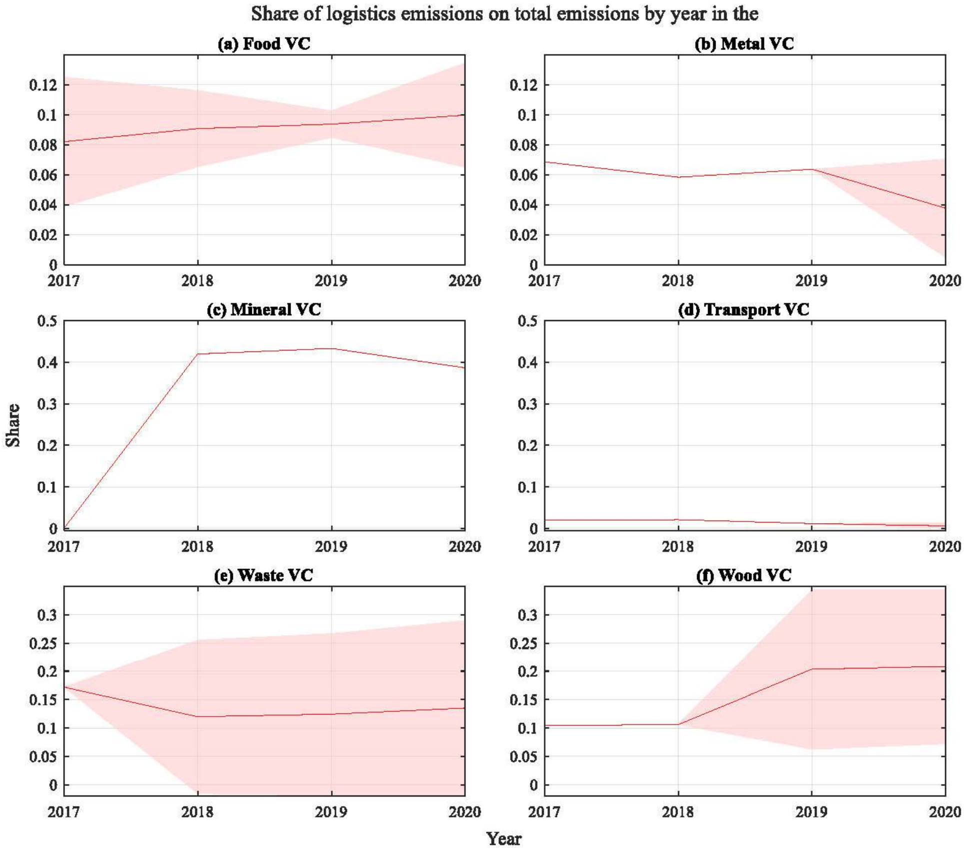

Figure 6. Share of logistics emissions by value chain and year.

As discussed earlier and evaluated in Figure 5, the majority of the data showing the share of logistics emissions lies between 9% and 30%, having the median at approximately 10% and the average across all years and sectors at 12.15%. This is higher than shares that have been reported earlier [24,25], which is plausible due to the population of this research being the transport-intensive business sectors. This finding highlights the validity of the methodology adopted in the first part because the sectors found seem to be more dependent on transport than others and can thus indeed be captioned as the transport-intensive sectors of the economy. Therefore, the answer to the second research question, in comparison to the existing literature, verifies the answer to the first research question.

4. Discussion

The aim of the current research paper was twofold. First, a methodology to identify a country's transport-intensive economic sectors was presented and validated by using Austria as an example. Second, a methodology to assess the amount of GHG emissions that account for logistics relative to a company's total emissions in these transport-intensive sectors was developed and evaluated against the Austrian transport-intensive sectors.

4.1. Identifying Transport-Intensive Sectors

The developed methodology for the first part combines official statistics with methods and data from the EcoTransIT emission calculation tool to provide a straightforward method that is easily applicable to different countries. Applying it to Austria highlighted four main value chains that can be considered transport-intensive value chains in Austria. First, the Metal VC with its raw materials suppliers (NACE divisions B5–B8), the transportation of raw materials (NST division 3), the manufacturers of metal products (NACE divisions C24 and C25), and the transportation of metal products (NST division 10). Statistically, the producers in this VC must share their suppliers with the producers in the Mineral VC (NACE division C23), which, in contrast to metallic ores, access non-metallic mining and quarrying products. The second group of suppliers is the companies from NACE group A, producing crops, animals, agricultural products, and fish for the manufacturers in the Food VC (NACE divisions C10–C12), as well as forestry products for manufacturers (NACE division C16 and C17) in the Wood VC. The finding that the Food VC is among the top GHG emitters underlines statements from other research mentioning that food systems are responsible for as much as one-third of global GHG emissions [57]. Additionally, companies that collect and treat waste (NACE division E38), supporting all the aforementioned sectors of the economy, were found to be major contributors to transport volumes by transporting waste and secondary raw materials (NST division 14). Furthermore, several mentioned value chains process pre-products for the automotive sector, which is why the manufacturing of transport equipment was also found to be a transportation-intensive industry sector. Considering all the demander–supplier relations and having in mind the urge to reduce emissions, a deeper focus on the value chains, i.e., the supplier–demander relationship, will be necessary for the future to reduce transportation demands as well as emissions from transportation. This needs to be elaborated, evaluated, and disseminated by researchers, as well as understood and implemented by practitioners. One possible measure to foster this supply chain-thinking in organizations might be the formation of an organizational unit in which responsibilities for procurement, transport, and production are combined instead of keeping alive separated procurement, logistics, and production divisions [58]. The need to investigate such organizational issues was already highlighted by other empirical research [15].

These discussions show that the application of the developed methodology can generate insights into the freight transportation sector of a country and enables the finding of high macroeconomic emission reduction potentials. Identifying the transport-intensive sectors and value chains of a country can thereby invite researchers and policymakers to lay focus on those sectors in a specific economy and promote emission mitigation research and actions. Applying this methodology to other countries in Europe and consolidating the results will bring indications for European policymakers.

4.2. Assessing the Share of Logistics Emissions

The methodology for the second part comprises the collection of companies in the transport-intensive sectors, the screening of their sustainability reports, and the analysis of their logistics emissions. Applying the method to Austria finds that the share of emissions significantly differs across the value chains and indicates the largest share of emissions in the Mineral value chain and the least in the Transport value chain. Two key findings can be drawn from the second part of the research process. First, potentially low attention paid by managers in the Transport VC to decarbonizing logistics can be explained by the very low share of logistics emissions in this VC. This underlines research indicating that manufacturing firms often concentrate on the decarbonization of their core processes instead of logistics due to higher potential in emission mitigation [24].

On the other hand, a focus to decarbonize transportation in the Mineral VC should be set by researchers and practitioners, as this value chain is, first, among the transport-intensive ones in Austria and decarbonization would have significant macroeconomic effects and, second, companies in this value chain have a significant share of logistics emissions, providing serious microeconomic mitigation potentials and thus larger incentives for managers to focus on logistics emissions. Therefore, companies in the non-metallic minerals sector, including the manufacturing of glass, clay building materials, cement, lime, concrete, and many other important raw materials, that are supported by research and policy could serve as frontrunners, adopting new ways to decarbonize logistics and showing other sectors how to do so.

In general, reporting logistics emissions must be expanded rapidly, as the share of about 30% of companies that report on carbon emissions is quite low. One possible explanation for this small share is the legislative situation in the European Union that excludes SMEs from the obligation of preparing an SR and only obliges public-interest entities with a minimum of 500 employees to prepare an SR [59]. With missing obligation comes missing motivation, it seems. Therefore, we raise the need to incentivize and financially support the creation of SR preparation in line with all three scopes of the GHG Protocol, also for SMEs. Furthermore, key figures of the reports should be made available online and in a computer-comprehensible form so that they can be processed and evaluated as automatically as possible. This can be done, for example, by making Excel spreadsheets available, as it is already being performed by some frontrunner companies [50].

The application of the second part of our proposed methodology thereby highlighted several insights into the structure of the companies in the transport-intensive sectors. By screening the sustainability reports, researchers acquire evidence on how heterogeneous the emission reporting methodology in those sectors is, which companies operate in those sectors and how relevant logistics emissions are for them. The combination of knowledge from the first and second parts of the methodology can be used in this respect to derive tailored recommendations for action for sectors. Companies from transport-intensive sectors, where logistics only account for a small share of total emissions, e.g., have no incentive on their own to reduce these logistics emissions. For such companies, the reporting of emissions should be critically scrutinized and targeted incentives should be developed. In this manner, a matrix of calls for action can be developed, entailing the dimensions "transport-intensiveness" and "share of logistics emissions".

The application of this methodology to other countries and the publication of the results further allows for companies in the transport-intensive economic sectors that did not assess their logistics emissions yet to estimate their share of logistics emissions based on the distribution presented. Companies that do already assess their logistics emissions can benchmark themselves against the mean of all transport-intensive sectors or their respective value chain.

5. Conclusions

The aim of this research was twofold. First, we develop a methodology to identify a country's transport-intensive economic sectors and elaborate on it by using Austria as an example. Second, we present the share of emissions that can be allocated to logistics activities in an average company of those sectors.

The novelty of the methodology presented in the first part is its generic applicability with countries having minimal official transport statistics and the interdisciplinary combination of methodological guidelines from similar studies and the EcoTransIT World emission calculation tool. The transport-intensive sectors are thereby defined as those that produce transport-intensive goods. Further, transport-intensive value chains are defined as supplier–demander pairs among the transport-intensive sectors. For the Austrian case, the Metal, Food, Wood, and Fossil value chains were found to be transport-intensive.

The second part of the presented methodology allows for bottom-up insights into the transport-intensive sectors by suggesting collecting and analyzing sustainability reports of companies in those sectors. Descriptive and statistical analysis, thereby, ensure comparability and validity of the generated findings. For the Austrian case, 71 reports from 179 companies were collected and screened for logistics emission data. Analysis of the reporting methodologies thereby highlights the vast heterogeneity of the reports and suggests more comprehensive and obligatory guidelines.

During the statistical analysis, 97 different distributions were fitted and tested to the emission data and the log-normal distribution was found to be one of the most appropriate ones to describe the statistical distribution of logistics emissions among Austrian transport-intensive companies. The average share of logistics emissions was found to be in the range of 8.7% to 15.01%. To assess sectoral differences, we conducted a one-way ANOVA that shows statistically significant differences in the share of logistics emissions across different value chains.

Regarding the developed methodology, researchers are called to apply it to more countries and, at best, consolidate the results to derive meaningful recommendations for action for policymakers.

For the Austrian case, this study shows a new way to focus on specific sectors of the economy when creating policies for decarbonization and shows the structure of companies in these sectors. Further research will be necessary to investigate temporal trends and more specific sectoral characteristics across transport-intensive value chains.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su142215050/s1, ANOVA.

Author Contributions: P.M.: Conceptualization, Methodology, Investigation, Writing—Original Draft, Writing—Review and Editing, Visualization; A.K.: Investigation, Writing—Original Draft, Writing—Review and Editing, Visualization; M.W.: Supervision, Methodology, Writing—Review and Editing. All authors have read and agreed to the published version of the manuscript.

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The adoption of industrial logistics decarbonization practices: Evidence from Austria

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ABSTRACT

Considering the increasing awareness of customers, shareholders, and employees for climate change, European firms face a changing institutional environment and increased pressures to decarbonize their operations. Although this is already common practice in many areas, the emissions of in- and outbound logistics are still not shrinking. To develop effective novel measures, researchers and practitioners need a clear picture of the state-of-the-art. Currently, a scattered landscape of studies researching the utilization of green logistics practices in Europe exists. By surveying Austrian practitioners, we contribute to this landscape and enhance knowledge on the utilization of green measures, experts' perceptions of them, and discriminating factors for their implementation. Results indicate that the writing is on the wall for emission reductions in the near future due to several aspects. We elaborate on these, provide benchmarking possibilities for Austrian practitioners and indicate which managerial factors to concentrate on when aiming at decarbonizing logistics. For researchers, the presentation of the state-of-the-art and its discussion highlights future research directions and questions, among them the question of why the perceived potentials of measures differ from scientifically validated potentials and how to align this knowledge gap.

Introduction

In recent years, rising awareness regarding environmental protection has been observed in Europe (Bacsi, 2020). Considering the perception of 80% of European citizens that "big companies and industry" are not doing enough to protect the environment (European Union, 2020, p. 61), this, over time, inevitably leads to a change in the institutional environment of firms operating in Europe. Firms are predicted to adapt to rising customer and employee pressure, environmentally conscious investors, and new regulations by reducing the environmental burdens of their services and products and communicating this to their organizational environment (Latif et al., 2020; Neri et al., 2018; Collins et al., 2010; Merli et al., 2015).

Inbound and outbound logistics, as primary activities of industrial firms (Porter, 1985), contribute significantly to those environmental impacts. First, logistics consumes provisioning services from the ecosystem, i.e., using energy, raw materials, water, air and land, and second, returns emissions in the form of pollutants, greenhouse gases, waste and noise (Deckert, 2016, p. 17; World Resources Institute, 2003). Albeit all those impacts are considered in green logistics (GL) initiatives (Centobelli et al., 2017), greenhouse gas (GHG) emissions from burning fossil fuels have become established as a target and measurement parameter (Lohre and Gotthardt, 2016, p. 48) in inbound and outbound logistics.

As the urge to reduce emissions across all sectors and parts of the supply chain is now scientifically undoubted (Gulev et al., 2021), transportation must also contribute its part. Indeed, transportation accounts for 15 % of global GHG emissions (Dhakal et al., 2022), of which about one-third stem from freight transportation (Ritchie and Roser, 2020). Largely, these can be allocated to Scope 3 emissions of industrial companies, who request transportation services to transport raw materials, intermediate, and end products throughout their supply chains (Rodrigue, 2020).

Although decarbonizing logistics seems to be old news, European emissions from transportation – in contrast to total emissions – are not shrinking yet (EEA, 2022a; EEA, 2022b). The analogy of this macroscopic trend was observed in industrial companies, highlighting that – in contrast to product design and manufacturing – the emission reduction

Abbreviations: GL, Green logistics; GHG, Greenhouse Gas.

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potential of logistics is not yet fully exploited (de Sousa et al., 2021).

Especially in Europe, which is globally among the regions with the highest awareness of climate change (Lee et al., 2015), knowledge of the currently implemented measures is of utmost importance to prevent pointless research activities and direct the focus on the yet unexploited potentials. Thereby, preceding studies from, e.g., Sweden (Pålsson and Johansson, 2016; Pålsson and Kovács, 2014), Lithuania (Vienažindienė et al., 2021), Slovakia (Richnák and Gubová, 2021) and Croatia (Petljak et al., 2018) show an ambivalent picture, indicating that some practices have already reached broad application. However, it is not easy to deduce from the findings from the individual countries to the pan-European level. For example, evidence from Sweden might overestimate green practices utilization because Scandinavian countries were shown to stand out regarding environmental awareness (Bacsi, 2020). Meanwhile, recent newspaper articles from Lithuania indicate a high level of willingness to implement green practices on the part of individual companies (Girteka, 2022), which could distort the picture of the economy as a whole. Therefore, we aim to add further evidence from Central Europe to this scattered landscape of studies to close the gap to a pan-European picture.

Austria, thereby, is a good example of a small and landlocked country, having an outstanding share of 27% of all freight transport performance accomplished by rail (Statistik Austria, 2022, p. 23), which is recognizably higher than the European mean of 12% (European Union, 2021, p. 36). Furthermore, Austria's performance in various economic and social dimensions differs from that of the countries already studied and thus complements the overall European picture well. For example, although scoring similarly to Sweden in GDP per capita and R&D expenditures, the renewable energy share and environmental awareness are more similar to Lithuania, Croatia, and Slovakia, respectively (Bacsi, 2020; Schwab, 2019). Furthermore, to the best of the author's knowledge, no such study for Austria exists yet. Therefore, in this study, we aim to extend the knowledge of the current state-of-the-art in decarbonizing European freight transportation by shedding light on the Austrian practitioners.

Besides presenting the implementation level of green logistics, this study aims to explain this level through several discriminating factors in recent literature. First, studies predict the managerial anchoring and embedding of sustainability in an organization to drive sustainable growth (Martin-Rios et al., 2022; Huge-Brodin et al., 2020), which is why we hypothesize that the anchoring of green logistics correlates positively to the level of green logistics' implementation. Second, the practitioners' perception of the financial (Li et al., 2020; Schaltenbrand et al., 2018) and environmental (Pålsson and Johansson, 2016) effect of measures were proven to influence the adoption of the measures in preceding studies. Due to this, we survey the practitioners' perception of different measures and hypothesize that adoption negatively correlates with perceived barriers – and positively correlates with perceived potentials. Third, several studies explain the upstream diffusion of environmental consciousness and practices across the supply chain (Mir et al., 2021; Meinlschmidt et al., 2018; McFarland et al., 2008). The end of the stream is the end customer, who drives the initiatives according to this reasoning. Since the proximity to this customer differs across the industry sectors, we hypothesize that the degree of implementation of green measures in logistics also differs between the sectors of the Austrian economy. Summarizing, the focal study aims to answer the following two research questions:

- RQ1: What are the prevalent practices implemented in Austria to decarbonize freight transport?
- RQ2: How do organizational anchoring, practitioners' perception, and the industry sector affect the level of implementation of decarbonization measures in Austria?

To do so, we developed and conducted a survey aimed at Austrian logistics practitioners. Therefore, we sample from the 500 companies with the highest revenue among the transport-intensive and non-transport-intensive manufacturing sectors and the 200 companies with the highest revenue in the logistics sectors.

For logistics practitioners in Austria, this study clarifies what practices other companies already utilize and indicates which factors are essential to consider when aiming at emission reductions in logistics. Besides solely investigating the Austrian logistics landscape, the study enriches European research and contributes to creating a pan-European picture of transport decarbonization. Scientifically, the results of this study contribute to the body of knowledge in the field by, first, challenging existing theories and studies regarding discriminating factors of green practices, and second, extending the knowledge on practitioners' perceptions of emissions reduction potentials and implementation barriers. Finally, key implications for further research and advancements in the field are presented, which need to be considered to effectively mitigate logistics carbon emissions.

The paper is structured as follows: Section 2 comprises the results of a literature review, thereby presenting the body of knowledge on the field and developing the hypotheses for RQ2. Section 3 informs on the research methodology; Section 4 presents the results – separated into descriptive analysis to answer RQ1 and statistical tests to answer RQ2. Section 5 interprets the results, and Section 6 concludes the article.

Background and hypotheses development

Potential decarbonization measures

In the current literature, a vast number of technologies and practices to reduce GHG emissions from transportation are developed, presented, and discussed. For example, Churchman and Longhurst, 2022 divide measures to decarbonize into motive and non-motive technologies. In this regard, motive technologies include opportunities in the vehicle drivetrains, comprising electric vehicles, hybrid vehicles, or internal combustion engine vehicles with alternative fuels. Non-motive technologies transcend the vehicle drivetrain and concern measures in the network, measures in the vehicle, or the change to other modes of transport. The first category includes freight consolidation, platooning, and traffic management, the second includes, for example, technical support for eco-driving or improved aerodynamics, and proposed alternative modes include rail or water.

McKinnon and Woodburn, 1993 classify the variety of such measures based on the management decisions related to their implementation in a four-layered hierarchical framework, categorizing them into structural, commercial, operational, and functional decisions. Decisions made on the structural level define the nodes and links of the supply chain and thus the basic demand for transportation. Commercial decisions determine the companies' supplier and customer base and thus the parties from which or to which goods and services are bought and sold, respectively. One level below, operational decisions in the short-term planning define how the business will be executed in detail, e.g., production scheduling or transport dispatching. On the lowest level, the functional decisions determine logistics assets and other technical details. Miklautsch and Woschank, 2022b extended this framework by adding two categories on the top and bottom level, including decisions made in the management system, e.g., motivation of employees and collection of KPIs, and those on the technical level, e.g., load carrier design. Furthermore, they elaborate on the different parties that can decide on measures at the respective levels. These are, depending on the contractual and operational design, shippers or logistics service providers (LSP). In descending order of hierarchical levels, the planning horizon becomes shorter, and the decision frame becomes narrower, as upper-level decisions lay down the boundaries for decisions on the lower levels (Liu, 2005; Riopel et al., 2005). This implicates, that decisions on the upper levels must be made before decisions on the lower levels to effectively reduce emissions. Typically, shippers decide on the upper levels and thus lay the basis for any structural changes in the logistics network, and LSPs carry out transports and thus decide on the lower levels.

Similar to the idea of hierarchical levels is the well-known Avoid-Shift-Improve (ASI) approach introduced by Dalkmann and Brannigan, 2007. To reduce emissions from public transportation, they proposed first avoiding transport as much as possible, shifting the remaining transport to less emission-intensive modes, and then improving the emission intensity of the remaining transport. To date, this approach has become widely applied in the whole transport sector, including freight transportation, as several researchers use it to find and categorize emission reduction measures (Jaramillo et al., 2022; Zhang and Hanaoka, 2022), citing it as a "fundamental optimization framework" (Dhawan et al., 2022).

In search for a way to survey emission reduction measures in freight transport, we, therefore, utilized the ASI approach and clustered all relevant measures found in a preceding Systematic Literature Review (Miklautsch and Woschank, 2022b) according to it. In Table 1, the categorized measures are displayed.

Current decarbonization practices

Although a vast majority of the aforementioned measures and different ways to categorize them have been discussed for years, no reductions in emissions from transportation can be observed in historical data (IEA, 2022) or current studies (de Sousa et al., 2021), nor is expected in the next years with existing measures (EEA, 2022a).

To efficiently support practitioners in implementing new measures, empirical studies have already been carried out in various countries, analyzing the status quo of implementation and obstacles to further measures.

For example, Vienažindienė et al., 2021 research the application of green logistics practices among Lithuanian transport and logistics companies by conducting a quantitative survey. They split up the questionnaire into five fields of green logistics, namely green transportation, green warehousing, green packaging, green administration and logistics data management, and sustainable waste management. Investigating green transportation, they find that eco-driving and the optimization of transport routes are the practices that scored highest. A survey conducted in Sweden highlighted one measure that stands out regarding the likelihood to be implemented – which is transport planning. Following are the intentions to implement cleaner vehicle technologies and eco-driving. The highest potential effects were reported for shifting transports away from the road, using non-fossil fuels, and enhance transport planning (Pålsson and Johansson, 2016). However, there is not much intention to use alternative fuels – a finding that is supported by findings from various other studies (Froio and Bezerra, 2021; Vienažindienė et al., 2021; Martins et al., 2019; Zhang et al., 2014), except for Sureeyatanapas et al., 2018. Investigating common measures to protect the environment in Thailand, they find eco-driving, the use of alternative energy, a modal shift, and vehicle routing to be the prevalent measures. Modal choice and green routing have also been found to be the dominant measures of green transportation in Brazil, but only a little share of 27% of the companies utilize them (Martins et al., 2019). Focusing on Brazilian LSPs, another study highlighted shipment consolidation and re-positioning distribution centers to be the initiatives practiced most often with success (Froio and Bezerra, 2021). Besides the scientific papers on this topic, a recent survey conducted by a logistics interest group showed that transport optimization and route optimization are currently the practices conducted most often among German practitioners (BVL, 2022).

Table 1
Measures to reduce emissions from freight transport (Source: own illustration based on Miklautsch and Woschank, 2022b).

Category	Measure	
Avoid	*M1*	Reduction of the volume or weight of load carriers or packages
	M2	Reduction of the necessary distance during transport
	M3	Reduction of necessary transport frequency
	M4	Increased collaboration with other carriers and companies
	M5	Selection of the route with the lowest emissions
Shift	*M6*	Shifting transports to rail
	M7	Shifting transports to inland waterways or coastal short-sea connections
Improve	*M8*	Motivating vehicle operators to drive in an energy-saving manner (Eco-driving)
	M9	Reducing the age and improving the condition of vehicles
	M10	Use of alternative fuels in conventional combustion engines
	M11	Use of alternative drives

A summary of empirical studies investigating the current state of adoption and the barriers and motivations behind it is shown in Table 2. Although several studies for central European countries exist, to the best of the author's knowledge, no studies for Austria are available yet. Since Huge-Brodin et al., 2020 find that an LSPs' country of origin has an effect on green logistics practices' implementation, we aim to close this knowledge gap in the focal study.

Factors influencing the decision to decarbonize

A comprehensive base of literature exists that researches the mechanisms behind the adoption of green practices in logistics and supply chain management. Findings are elaborated by qualitative (Mir et al., 2021; Dubey et al., 2017; Miklautsch and Woschank, 2022c) or quantitative (Pålsson and Johansson, 2016; Philipp and Militaru, 2011; Li et al., 2020) research methods and are mostly based on organizational and behavioral theories (Sarkis et al., 2011; Touboulic and Walker, 2015). Thereby, barriers are often related to specific measures, e.g., higher costs, reduced flexibility, or reduced service levels, or located on the strategic level, e.g., lacking management support or missing customers' pressure. In the following paragraphs, we summarize some of the main findings and thereof formulate hypotheses that will be tested for Austrian logistics.

The customer's influence

From a theoretical perspective, practices diverge across supply chains based on the imitation of dyadic relationships. This phenomenon is called supply chain contagion, describing that the way firm A treats firm B influences the way firm B treats firm C (McFarland et al., 2008). Extending this with the finding that downstream actors are more likely to persuade upstream actors to implement green measures (Meinlschmidt et al., 2018), sustainable supply chain contagion is supposed to let environmental consciousness and green measures diverge upstream in a supply chain (Mir et al., 2021). This accounts for end customers and shippers, as well as shippers and their LSPs. Thus, companies that are closer to the end customer are supposed to have a higher motivation to reduce emissions, which should also lead to higher adoption of green practices.

Proximity to the end customer thereby depends on the companies' products and, thus, on the company's industry. However, from an empirical perspective, findings are ambivalent. Although Pålsson and Johansson, 2016 find that the industry sector of freight owners does not have a significant influence on the implementation of measures in logistics, Maccarrone, 2009 mentions that the attitude towards corporate social responsibility is influenced by the sector of the company. Preceding this study, the authors conducted expert interviews regarding the decarbonization of industrial logistics (Miklautsch and Woschank, 2022c), which indicated that, for example, the white goods (i.e., washing machines, dishwashers, fridges) and the automotive sector seem to be more conscious about their logistics emissions due to their increased proximity to end customers.

From those considerations, we derived the following hypotheses:

Table 2
Overview of related empirical studies.

Reference	No. of firms	Method(s)	Sector/Focus	Country/ Region	Main findings
Froio and Bezerra, 2021	32	No specific statistical analysis	Logistics service providers	Brazil	The utilization of "routing systems", "shipment consolidation", and "position of distribution center" are the initiatives practiced most often with success. "Alternative vehicles" and "alternative fuels" are used least often.
Richnák and Gubová, 2021	165	Chi-square test	Automotive, Engineering, Electrical Engineering, Chemical, Glass	Slovakia	Warehousing and storage are the prevailing logistics processes that are affected by environmental policies in the investigated companies, followed by packaging and transportation.
Vienažindienė et al., 2021	292	Descriptive statistics, correlation, regression analyses	Transport and logistics companies	Lithuania	"Eco-driving", "optimization of transport routes" and "optimization of cargo distribution" are the predominant practices but have only medium relevance to the firms. The need for subsidies and other benefits was identified to be the most relevant influence on green transportation.
Trivellas et al., 2020	134	Structural equation modeling (SEM)	Agri-food companies	Greece	Logistics networking and information sharing are the only items that influence all "green performance" dimensions.
Li et al., 2020	210	SEM	Large and medium-sized coal enterprise groups	China	Perception of the general benefits of green measures and green logistics efficiency drives the willingness to implement them, whereas internal motivation, external factors, and external support do not. Costs are the prevailing driving force.
Martins et al., 2019	30	Content analysis of sustainability reports, descriptive statistics	Companies that are representative of the Brazilian economy	Brazil	Modal choice and green routing are the dominant measures of green transportation, but only 27% of the investigated companies utilize them. 7% use electric vehicles and 10% perform "mapping of the energy and/or fuel consumption of the vehicle". Including sustainable criteria in purchasing is the prevailing measure, 57% of companies use it.
Petljak et al., 2018	190	SEM	Food retail	Croatia	The implementation of green logistics measures drives environmental performance, but not directly economic performance. Indirectly, environmental performance drives economic performance. Water and energy management drives green logistics.
Sureeyatanapas et al., 2018	311	Statistical analysis	Logistics service providers	Thailand	The prevalent measure regarding cost reduction and environmental protection is "eco-driving", followed by "alternative energy", "modal shift", and "vehicle routing".
Pålsson and Johansson, 2016	172	Statistical analysis	Transport-intensive companies	Sweden	Measures with the highest potential effects are "Shifting away from the road", "non-fossil fuels", and "transport planning". The later also has the highest intention to be implemented.
Zhang et al., 2014	104	Descriptive analysis, SEM	Road freight transportation industry	Nanjing (China)	The prevalent green transportation practices are "choosing the right mode of transport", "optimizing transport routes" and "monitoring vehicle driving mileage", whereas "use of alternative energy or new energy vehicles", "establishing alternative energy plans of companies" and "reducing the number of used vehicles" are the least popular.
Philipp and Militaru, 2011	172	bivariate correlation, ANOVA	Shipper's economic buying behavior of logistics services	France	The "perception that the quality of logistics services" is equal after "implementing green measures", as well as a "proactive ecological strategy at the corporate level" are significant predictors regarding "ecological buying behavior". Only a moderate correlation between declared willingness and real buying behavior was observed.
Murphy and Poist, 2003	188	Chi-square test	Manufacturing, Merchandising	US, Canada, EU	No significant difference regarding the use of green measures between US and non-US firms was found. Strategies used frequently are the "reduction of consumption" and "reuse and recycle of material whenever possible". About half of the respondents try to redesign their logistical system, increase the education and training of company personnel, or conduct environmental audits.
BVL, 2022	117 (total) 56–99 (tools)	Descriptive statistics	Transport & Logistics, Manufacturing, Wholesale & Retail Trade	BVL network	"Transport optimization" and "route optimization" are used most often among survey participants.

- H_0: There is a significant difference in the level of implementation of green logistics measures between different industry sectors.

Organizational anchoring

Discussing how to embed sustainability in service firms, Martin-Rios et al., 2022 define three key anchoring managerial mechanisms that must be utilized to transform their business towards environmentally and socially friendliness. Those three dimensions are the external disclosure and reporting, the business model innovation for sustainability, and the accountability and management control. The first dimension aims at reducing information asymmetry between the firm and external stake- and shareholders through disclosing information on corporate social responsibility affairs. However, empirical evidence shows that reporting alone does not contribute to the adoption of green practices, as "no relationship between the disclosure of sustainability and sustainability growth" was observed when studying European enterprises (Oprean-Stan et al., 2020). Thus, the development of a novel business model that does not deplete "the natural, economic, and social capital it relies on" (Schaltegger et al., 2016) is the second key anchoring managerial mechanism. Third, the management control and governance over sustainability issues are key to establish sustainability in companies and influence the organization towards achieving sustainable development (Henri and Journeault, 2010), whereby three issues arise. First, the motivation of employees and managers to enhance sustainability is connected to the setting of challenging sustainable growth goals (Locke and Latham, 2002). Connected with this is the second issue, setting up measurable and controllable environmental performance measurement metrics. Introducing substantive metrics instead of symbolic ones thereby determines the impact on environmental performance (Flammer et al., 2019). Regarding climate change, the calculation of the prevalent metric, i.e., greenhouse gas (GHG) emissions, is standardized by the well-established Corporate Accounting and Reporting Standard (World Business Council for Sustainable Development and World Resources Institute, 2004), commonly known as the GHG protocol. Third, due to the multitude of levers and levels regarding environmental performance, tasks need to be distributed across all hierarchical levels (Martin-Rios, 2016). This includes strategic management, executive management, and all employees. A scarcity of resources thereby rises the need to make trade-offs regarding long-term environmental goals and short-term financial goals (Cai et al., 2011). To prevent the pursuit of exclusively financial goals, other goals and objectives must be explicitly set.

Because of those considerations, we suggest that there is a relationship between the establishment of green logistics in an organization and the environmental performance of the organization's logistics. We operationalize the anchoring of green logistics by four indicators, namely the reporting on logistics emissions, the allocation of a budget to decarbonization, the implementation of green agendas in logistics employees' role descriptions, and the setting of reduction targets. As a proxy for environmental performance, we see the level of implementation of green measures, which is why we hypothesize the following:

- H_1: There is a significant relationship between the anchoring of green logistics in the organization and the level of implementation of green logistics measures.

The perception's influence

Studying green logistics practices among Chinese coal companies, Li et al., 2020 find that "there is a significant positive correlation between green logistics benefits and willingness to implement green coal logistics". Benefits, in this case, are meant to positively influence the financial performance of the firms – indicating that greening logistics is a "nice-to-have" side effect. Thus, when a practice is believed to reduce costs, its implementation is more likely because it reduces the aversion to spend money for greening measures that solely help tackle climate change or other environmental risks (Schaltenbrand et al., 2018). However, studies have also already shown that the prospect of nonfinancial benefits drives the implementation of measures. For example, a discriminating factor influencing the adoption of decarbonization measures among freight owners in Sweden was found to be the perception of a measure's potential to reduce emissions (Pålsson and Johansson, 2016).

From these considerations, we hypothesize that measures that are perceived to contribute more to emission reduction are adopted significantly more. Considering the positive influence of perceived potentials, we further elaborate on this relationship and hypothesize that barriers have the opposite effect, correlating negatively with the implementation.

- H_2: There is a significant relationship between the perceived potential of a measure and its implementation.
- H_3: There is a significant relationship between the perceived barrier of a measure and its implementation.

Methodology

Survey development

To test the developed hypotheses and reveal the status quo, we developed a survey by applying recommendations from modern literature (Moosbrugger and Kelava, 2011; Blanz, 2021) that have been used in highly ranked research recently (Dallasega et al., 2022). Starting in December 2021 with an initial literature review and hypothesis development, the first instance of the survey was set up by the authors. In this version, 19 measures were included that have been derived from a systematic literature review conducted previously (Miklautsch and Woschank, 2022b). The survey was then discussed in detail with two independent practitioners to ensure proper wording, whereof some questions and answers were rephrased to increase the understanding and provide more comprehensive answers. Continuing that, in January 2022, the survey was evaluated by two independent researchers that are experienced in survey developmet. From this discussion, the structure and design of the survey were adopted, some questions of minor importance were dropped, and several answers were reformulated. In March 2022, the survey was implemented in LimeSurvey and sent out to participants of the 'Zero Emission Green Deal' working group of the BVL Austria (WEKA Industrie Medien GmbH, 2021) for pilot testing. The collected feedback improved the survey significantly and reduced the survey time to approximately 15 min.

Final survey structure

The final survey was split into two parts. The first part comprises socio-economic questions on the respondent and the organization, surveying the experts' industry experience (*O1*) and position (*O2*), as well as the industry sector for the firms' main economic activity (*O5*), and the company size (*O3* and *O4*). Furthermore, questions on how well GL is incorporated in the company complete the first part, asking respondents on whether emissions from logistics are being reported (*O6*), whether goals for logistics emissions exist (*O7*), whether GL is anchored in certain roles in the company (*O8*), and whether a budget is allocated to green measures (*O9*). The second part of the survey deals with questions on eleven specific GL measures, which are presented in Table 1. For each of those measures, the experts had to fill out the perceived emission savings potential of the measure *(Mx,p; very low – very high)*, the perceived implementation barriers of the measure *(Mx,b; very low – very high)*, and the level of implementation of the measure in the company *(Mx,i; not pursued – established)*. Likert scales were used because of their ease of use, high reliability, and broad acceptance in modern studies (Stekelorum et al., 2021; Bortz and Döring, 2016). The full survey (in German) can be found in the dataset (Miklautsch, 2023).

Sampling

The selection of appropriate key informants is seen as crucial for the validity of the research results (Kumar et al., 1993). Thus, we aimed at reaching out to experts that are well informed about the utilization of green logistics measures in the company, which are logistics managers, general managers, or sustainability managers. Distribution of the survey was done by random sampling via e-mail to make the findings generalizable to the industrial logistics context (Zhu et al., 2008). From a large database containing data on Austrian companies (Bureau van Dijk Electronic Publishing Inc., 2022), we identified three categories of companies as our target group: those in the transport-intensive and non-transport-intensive manufacturing sectors, and those in freight transport sectors. From the first two sets, we selected the top 500 companies regarding revenue, and from the last one the top 200 companies. In July 2022, we sent out emails with a compact invitation to the survey to the addresses provided by the database. Not all the addresses were up to date, which lead to a mail-delivery-error-rate of about 10%. As we sent out the invitation without prior consent of the informants, many non-respondents stated that they will not respond due to corporate policy or limited time. By the end of August 2022, the number of respondents did not change anymore and we closed the survey, which has been started by 190 respondents, of which 94 completed the first part, and 69 completed also the second part. This lead to a response rate of about 6.4%, as depicted in Table 3.

Table 3
Calculation of response rate.

Mailings to transport-intensive companies	500
Mailings to non-transport-intensive manufacturing companies	500
Mailings to freight transport companies	200
Total number of contacted companies	1,200
Mail addresses resulting in a mail delivery error (approx. 10%)	120
Delivered mails	1,080
Number of respondents starting the survey	190
Number of respondents completing the first part	94
Number of respondents completing the first and second part	69
Response rate	6.39%

Results

In the following subsection, we present the results of the survey. Section 4.1 presents the descriptive analysis of the responses, and section 4.2 analyzes the statistical procedure results to test the hypotheses. The data can be found in the corresponding dataset (Miklautsch, 2023).

Descriptive analysis

Socio-economic aspects

Table 4 presents the socio-economic details of the responding firms and experts. Most respondents have at least five years of industry experience. Together with the respondents' positions, of which nearly 90% are logistics, supply chain, or sustainability managers, this indicates a high validity of the survey results (Kumar et al., 1993), as our survey reached our key informants and targeted respondents who could answer the questions reliably. Predominantly, the respondents work for large companies having more than 250 employees and a yearly revenue of more than 50 Mio. €, which fits the aims of the study. Regarding the firms' role in freight transport, most respondents classify their companies as shippers, which is confirmed when considering the predominant main economic activity of the companies, manufacturing.

Approximately 75% of the companies do not, or only partially, report logistics emissions internally or externally. Nearly the same share of firms does not have emission reduction goals set for logistics activities and does not add green logistics or decarbonization agendas in logistics employees' role descriptions. Thus, only 25% of companies proactively advise their logistics employees to monitor logistics emissions. The share of companies that allocate a budget for logistics decarbonization is even less – only 8.82% of respondents report that a budget exists.

To further test the validity of the results, we tested the socio-economic responses against results from a preceding study in which we investigated transport-intensive firms in Austria and their logistics emissions reporting (Miklautsch et al., 2022). Thereby, we found that 30.73% of the largest transport-intensive companies in Austria report on logistics emissions in their nonfinancial reports. Among the responses to the focal survey, 33 firms allocate to the transport-intensive economic sectors. All of them generate more than 10 Mio. € of yearly revenue. Of those 33, 10 firms state that they report on logistics emissions, which is a share of 30.30%. This result aligns with the preceding findings, so we can conclude that our survey results are valid and infer the population of transport-intensive companies from the sample.

When extending the sample from the transport-intensive companies to companies of all sectors, we expect the share of companies reporting logistics emissions to shrink slightly as smaller companies without obligation to report on their sustainability initiatives become included. These firms account for about 6% of the responses, approximately the amount we expect the share to shrink. Investigating Table 4, we find the share to be 25%, which indicates that we can infer all sectors from the transport-intensive ones.

Therefore, we conclude that the results of this survey for transport-intensive sectors are consistent with those of previous studies and that we can infer the population of all sectors from the sample. Nevertheless, we cannot guarantee the generalizability for companies having a yearly revenue of less than 10 Mio. € – which was not the purpose of this study. Further research is asked to investigate those firms' anchoring and adoption of green logistics.

Table 4
Descriptive statistics for the socio-economic aspects.

Respondent's position		
Logistics planning	4	5.88%
Dispatching	3	4.41%
Logistics management/SCM	53	77.94%
Other	8	11.76%
Respondents' experience		
1–2 years	10	14.71%
2–5 years	8	11.76%
>5 years	28	41.18%
n.a.	22	32.35%
Company size – Number of employees		
<10	1	1.47%
11–49	2	2.94%
50–249	19	27.94%
250–999	31	45.59%
>1000	15	22.06%
Company size – Yearly revenue		
<2 Mio. €	1	1.47%
2–10 Mio. €	3	4.41%
11–50 Mio. €	19	27.94%
>50 Mio. €	45	66.18%
Role of the company in freight transport		
LSP	11	16.18%
Shipper	45	66.18%
Shipper with own vehicles	12	17.65%
Are logistics emissions being reported?		
Yes	17	25.00%
No	46	67.65%
Partially	5	7.35%
Is there an emissions reduction target in logistics?		
Yes	17	25.00%
No	51	75.00%
Is green logistics anchored in role descriptions?		
Yes	18	26.47%
No	50	73.53%
Is a budget for decarbonization available?		
Yes	6	8.82%
No	62	91.18%
NACE group of the companies' main economic activity		
n.a.	2	2.94%
A – Agriculture, forestry, and fishing	2	2.94%
C – Manufacturing	51	75.00%
E – Water supply; sewerage; waste management and remediation activities	2	2.94%
H – Transporting and storage	8	11.76%
N – Administrative and support service activities	3	4.41%

Measure-specific questions

Table 5 displays the respondents' answers regarding the decarbonization measures grouped by firm type. For each measure, the mean ($\overline{x}$), the median ($\tilde{x}$), the standard deviation (SD), the Interquartile Range (IQR) and the number of responses (n) are displayed for the perceived potential, the perceived barriers, and the level of implementation. To

Table 5
Descriptive statistics for the level of implementation, perceived potential, and perceived barrier of the surveyed measures.

	Total					LSP					Shipper					Shipper with own vehicle				
	$\bar{x}$	$\tilde{x}$	*IQR*	*SD*	*n*	$\bar{x}$	$\tilde{x}$	*IQR*	*SD*	*n*	$\bar{x}$	$\tilde{x}$	*IQR*	*SD*	*n*	$\bar{x}$	$\tilde{x}$	*IQR*	*SD*	*n*
M1,i	2.62	2	4.00	1.67	61	3.18	3	3.50	1.64	11	2.41	2	3.50	1.63	39	3.82	2	3.50	1.70	11
M2,i	3.04	3	4.00	1.75	55	3.70	2	3.75	1.73	10	3.00	3	4.00	1.68	34	3.45	5	4.00	1.88	11
M3,i	3.40	4	3.00	1.66	60	3.00	2	4.00	1.86	11	3.54	5	3.00	1.61	39	3.30	3.5	2.50	1.49	10
M4,i	2.98	3	4.00	1.76	59	2.50	2	3.25	1.69	10	2.66	2	4.00	1.71	38	4.55**	5**	–	0.99	11
M5,i	2.37	2	3.00	1.61	52	2.67	2	4.00	1.70	9	2.06	1	1.25	1.52	32	3.00	2	2.50	1.54	11
M6,i	2.54	2	3.50	1.66	63	2.18*	2*	1.00	1.40	11	2.62	2	4.00	1.79	42	2.60	2	1.75	1.28	10
M7,i	1.53*	1*	1.00	1.03	47	1.29**	1**	0.50	0.45	7	1.65*	1*	1.00	1.21	31	1.33**	1**	1.00	0.47	9
M8,i	2.59	2	4.00	1.72	54	3.18	2	3.00	1.70	11	2.13	1	1.50	1.62	31	3.25	3	3.00	1.59	12
M9,i	3.06	2	4.00	1.76	53	3.45	5	3.00	1.72	11	2.90	2	4.00	1.78	30	3.08	2.5	3.25	1.71	12
M10,i	1.96*	1*	1.00	1.39	50	2.27	1	2.50	1.71	11	1.7*	1*	1.00	1.18	27	2.25	2	1.25	1.36	12
M11,i	2.42	2	2.00	1.40	50	2.27	2	2.00	1.29	11	2.54	2	3.00	1.57	28	2.27**	2**	–	0.96	11
M1,p	2.46	2	2.00	1.16	68	3.27	4	1.50	1.14	11	2.38	2	2.00	1.10	45	2*	2*	2.00	1.00	12
M2,p	2.94	3	2.00	1.29	68	3.09*	3*	1.50	1.00	11	2.96	3	2.00	1.28	45	2.75	2.5	3.00	1.53	12
M3,p	3.25	4	1.25	1.17	68	3.64**	4**	1.00	0.77	11	3.20	3	2.00	1.17	45	3.08	4	2.25	1.38	12
M4,p	3.06	3	2.00	1.17	68	3*	3*	1.50	0.95	11	3.04	3	2.00	1.25	45	3.17*	3.5*	1.00	1.07	12
M5,p	2.64	3	2.00	1.16	67	2.91*	3*	2.00	1.00	11	2.64	3	2.25	1.21	44	2.42	2.5	1.25	1.04	12
M6,p	3.03	3	2.00	1.17	67	2.91**	3**	0.50	0.67	11	3.09	3	2.00	1.21	45	2.91	3	2.00	1.38	11
M7,p	2.22	2	2.00	1.09	63	2.2**	2**	1.00	0.75	10	2.23	2	2.00	1.07	43	2.20	1.5	2.00	1.40	10
M8,p	2.58*	2.5*	1.00	1.03	66	3.09**	3**	1.00	0.90	11	2.3**	2**	1.00	0.98	43	3.08*	3*	2.00	0.95	12
M9,p	3.33*	3*	1.00	1.08	66	3.27**	3**	1.00	0.86	11	3.33*	3*	1.00	1.18	43	3.42**	3**	1.00	0.86	12
M10,p	2.82*	3*	1.00	1.07	65	2.91**	3**	–	0.79	11	2.83	3	2.00	1.19	42	2.67**	3**	1.00	0.75	12
M11,p	3.00	3	2.00	1.15	65	3.18**	3**	0.50	0.57	11	3.12	3	2.00	1.20	43	2.36	2	2.00	1.15	11
M1,b	3.16*	3*	1.00	1.15	61	3**	3**	1.00	0.74	11	3.31*	3*	1.00	1.16	39	2.82	3	2.50	1.34	11
M2,b	3.31*	3*	1.00	1.17	54	3.5**	3.5**	1.00	0.81	10	3.41*	3*	1.00	1.06	34	2.80	3	3.00	1.60	10
M3,b	3.16**	3**	1.00	0.98	61	3.45**	3**	1.00	0.66	11	3.13*	3*	1.25	0.93	40	3.00	2.5	2.00	1.34	10
M4,b	3.24	3	2.00	1.09	59	3.3**	3**	1.00	0.90	10	3.32	3	1.75	1.08	38	2.91	3	1.50	1.24	11
M5,b	3.06	3	1.25	1.03	52	3.33**	3**	1.00	0.67	9	3.19*	3*	1.00	1.01	32	2.45	3	1.50	1.08	11
M6,b	3.87	4	2.00	1.13	63	3.82**	4**	0.50	0.83	11	4.00	4	2.00	1.07	42	3.40	3.5	3.00	1.50	10
M7,b	3.64	4	2.00	1.34	47	3.71	4	1.50	1.03	7	3.90	4	2.00	1.17	31	2.67	3	3.00	1.63	9
M8,b	2.78*	3*	1.00	1.07	51	3.18**	3**	0.50	0.83	11	2.66*	3*	1.00	1.09	29	2.73	2	1.50	1.14	11
M9,b	2.82*	3*	1.00	1.19	49	2.55**	3**	1.00	0.66	11	2.85	3	1.50	1.21	27	3.00	3	2.50	1.48	11
M10,b	3.54*	3.5*	1.00	1.08	48	3.64*	3*	1.50	0.98	11	3.69	4	1.75	1.07	26	3.09	3	1.50	1.08	11
M11,b	3.56	4	1.75	1.19	50	3.36*	3*	1.00	1.07	11	3.75	4	2.00	1.18	28	3.27	3	1.50	1.21	11

investigate the answers, we highlighted all values with the respective $SD < 1$ and $IQR < 1$ with **. In line, the mean of answers having $SD < 1$ or $IQR < 1$ are highlighted by *. Answers marked with ** or * thereby show a low distribution, thus a high consensus among the respondents, and are considered reliable.

Investigating the different measures' levels of implementation, we find reliable answers for *M7* (Shifting transports to inland waterways or coastal short-sea connections) for all three firm types, whereby the mean ranges from $\overline{x} = 1.29$ to $\overline{x} = 1.65$ and the median is uniformly $\widetilde{x} = 1$. This highlights the subordinate role of waterborne transport to Austrian companies, which can be explained by Austria's limited access to inland waterways and lack of access to the sea.

All other reliable levels of implementation are limited to one firm type. *M*4 (Increased collaboration with other carriers and companies) shows the highest level of implementation by shippers with their own vehicles. The mean of $\overline{x} = 4.55$, the median of $\widetilde{x} = 5$, and the low *SD* and *IRQ* show that cooperation in the supply chain is an established practice for Austrian freight owners that operate their own fleets. In addition, shippers with their own vehicles show at least a common interest in switching to alternatively powered vehicles. The mean level of implementation of *M*11 is $\overline{x} = 2.27$ and the median $\widetilde{x} = 2$. The use of alternative fuels (*M*10) by shippers without their own vehicles is currently uniformly low ($\overline{x} = 1.70, \widetilde{x} = 1$), which is probably because shippers see themselves to have little influence on the fuel chosen by the carrier – or little interest in it.

In contrast, neither alternative vehicles nor alternative fuels are utilized evenly among LSPs ($SD > 1 \cap IQR > 1$ for *M*10 and *M*11). For those firms, the shift to rail seems to be of more common interest due to *M*6 showing reliable values regarding the implementation ($\overline{x} = 2.18, \widetilde{x} = 2$).

Regarding measures' emission reduction potentials (the second 11 rows in Table 5) and the implementation barriers (the last 11 rows in Table 5), LSPs seem to be the most consent group. Ten of eleven measures present reliable means for the perceived potential and the perceived barrier. LSPs assign the highest potential to *M*3 (Reduction of necessary transport frequency/frequency, $\overline{x} = 3.64, \widetilde{x} = 4$) and the second highest to *M*9 (Reducing the age and improving the condition of vehicles, $\overline{x} = 3.27, \widetilde{x} = 3$). Other promising ways to decarbonize, having $\overline{x} > 3$, are utilizing alternative drives, reducing the necessary distance during transport, and training vehicle operators towards eco-driving. The biggest hurdles are seen in implementing *M*6 (Shifting transports to rail, $\overline{x} = 3.82, \widetilde{x} = 4$) and *M*2 (Reduction of the necessary distance during transport, $\overline{x} = 3.50, \widetilde{x} = 3.5$). Except for *M*9, the barriers of all measures are higher than moderate, which is in line with the little levels of implementation of the measures. Recent findings explain this by arguing that incentives to decarbonize are missing for LSPs, mainly because of a lack of pressure from the LSP's customers, i.e., the shippers (Huge-Brodin et al., 2020).

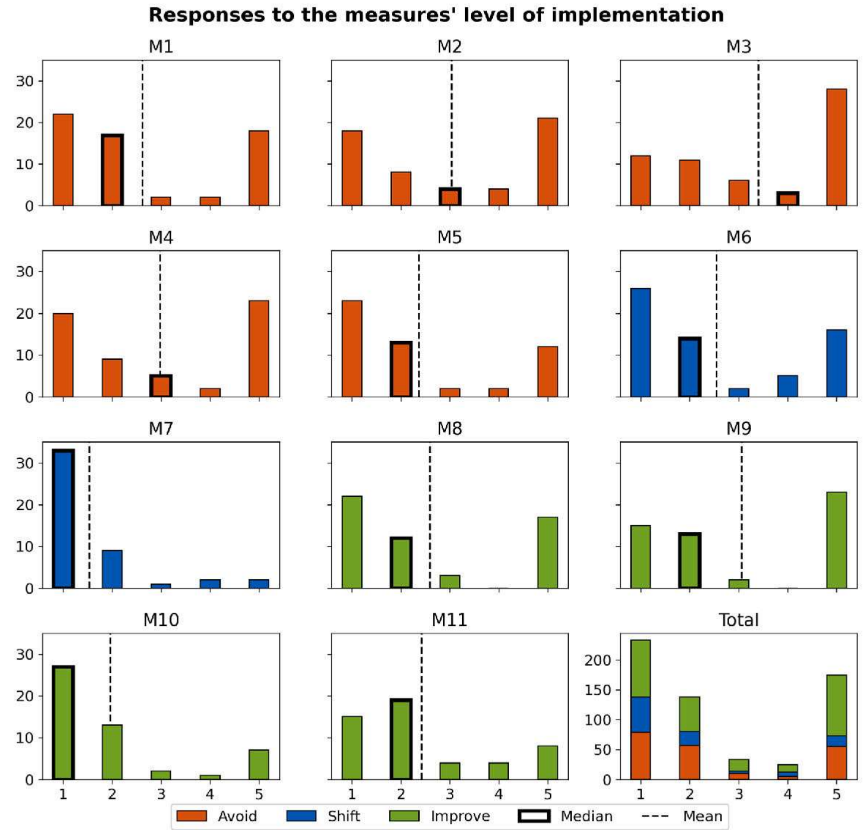

Fig. 1. Distribution of the answers regarding the level of implementation.

Investigating what shippers perceive regarding decarbonization measures, we see that they consent with LSPs in eco-driving's high emission reduction potentials ($M8$) and the utilization of newer vehicles ($M9$). For both shippers with and without freight vehicles, the most promising measure is the latter one. Unlike LSPs, all shippers with their own vehicles do not expect emission savings from optimized packaging or load carriers ($M1$ Reduction of the volume or weight of load carriers or packages, $\overline{x} = 2, \widetilde{x} = 2$).

Interestingly, no reliable figures can be observed regarding the barriers of measures from the perspective of shippers with their own vehicles. Shippers without their own vehicles consent about the barriers of five from 11 measures. Thereby, the measure with the highest barrier is the reduction of necessary transport distance ($M2$), which aligns with the LSP's perspective.

Fig. 1 plots the distribution of answers regarding the measures' implementation level against the measure category. The highest bar is the leftmost one, presenting how often "not pursued" was selected by the companies. The second-highest bar is the fifth one, showing the number of "pursued" measures. For some other measures, interest exists, but no implementation or pilot is planned (bar 2). The bars reporting on measures for which pilots are planned or conducted are lowest for most measures. This is an alarming finding because firms are more likely to adopt a practice when another firm with a similar structure has already implemented it (Mir et al., 2021), e.g., in a pilot project. Furthermore, conducting pilot studies reduces the concerns of employees and managers towards the measures (Miklautsch and Woschank, 2022c) and can transfer knowledge to and from other supply chain members (Siems and Seuring, 2021). Nevertheless, Fig. 1 also reveals that, for nearly all measures, some exemplar organization exist that already implemented the measures.

Hypotheses testing

In the following paragraphs, the authors describe the statistical analysis performed to test the hypotheses. We first tested the variables for normal distribution to select the statistical tests. A Kolmogorov-Smirnov and a Shapiro-Wilk test showed that the variables do not follow a normal distribution (Miklautsch, 2023), an expected finding as other studies incorporating Likert-scales show similar results (Woschank, 2018). Thus, we selected the nonparametric Kruskal-Wallis test instead of ANOVA to compare the mean of more than two groups, the Mann-Whitney U test as the counterpart of the t-test for the comparison of two groups, and Spearman's rank correlation instead of Pearson's correlation coefficient (Najmi et al., 2021). Table 8 presents a summary of the research findings.

The influence of the industry sector

To test differences and correlations between organizational factors and measures' implementation, we create a scale representing the overall level of green logistics practices implementation in a company, i, consisting of all eleven measures' levels of implementation ($M1, i - M11, i$). We tested the internal consistency of the scale by calculating the value for Cronbach's Alpha, resulting in $\alpha = .852$. Although no generally valid terminology or thresholds exist (Taber, 2018), several authors propose that, as a rule of thumb, values for $\alpha > .700$ indicate an acceptable internal consistency (Blanz, 2021; Hair et al., 2010; Heath and Martin, 1997).

To test the hypotheses related to the industry sector, we grouped the responses by their NACE industry sector, e.g., "A 01", "C 10", or "E 38". A Kruskal-Wallis test was used to test whether there is a significant difference in measures' implementation i among different NACE sectors ($O5$), whereby no statistically significant difference was found between at least two groups ,$H(20) = 21.500, p = .368$). Thus, we cannot support H_0.

The influence of organizational anchoring

To get evidence on the anchoring of green logistics in a company, we surveyed four items ($O6 - O9$) and built a scale on the level of green logistics anchoring, a, by calculating the four items' average. Again, Cronbach's Alpha $\alpha = .748$ highlighted validity and led to the acceptance of the scale.

Spearman's rank correlation coefficient was computed to assess the relationship between green logistics' anchoring in a company a and green measures' implementation i in the company. There was a moderate positive correlation between the two variables, $R_s(66) = .421$, $p < .001$. Due to the statistical significance, we can accept H_1. The results are evaluated in Fig. 2, where a is plotted against i, and a best least-squares linear fit is further visualized to highlight the positive correlation. Through the regression analysis, the coefficient of determination $R^2 = 0.182$ was calculated. In other words, the implementation of measures can be explained to an extent of 18.2% by organizational anchoring.

The influence of perceived potential

To test the influence of the perceived emission reduction potential on the implementation, we calculate eleven independent Spearman rank correlations to assess the correlation between a measure's perceived potential Mx, p, and a measure's implementation $Mx, i; 1 \leq x \leq 11$. Results of the calculation indicate a positive correlation with a statistical significance at the 0.01 level for five measures and a positive correlation with a statistical significance at the 0.05 level for four other measures. For those eight measures, H_2 is supported. All R_s- and p-values as well as the degrees of freedom (df) are displayed in Table 6, wherein the significance at the 0.01 level is marked by ** and at the 0.05 level by *.

The influence of perceived barriers

Similarly, eleven Spearman correlation coefficients were computed to assess the linear relationship between a measure's perceived barrier Mx, b and a measure's implementation $Mx, i; 1 \leq x \leq 11$. Investigating the results shows that there is a strong statistical significance that the H_3 can be accepted for two measures, and less significance that it can be accepted for five other measures. For four measures it cannot be supported by our data. Again, the R_s- and p-values as well as df for each measure are displayed in Table 7, wherein the significance at the 0.01 level is marked by ** and at the 0.05 level by *.

Discussion

This paper determines the status quo of Austrian industrial logistics practitioners in decarbonizing their transportation activities. Therefore, the authors survey shippers and logistics service providers to capture their perceptions of the emission reduction potential, the barriers, and the level of implementation of eleven different measures. Besides this, socio-economic factors have been surveyed, to first, test for nonresponse bias by subjective estimates and second test for four hypotheses that aim

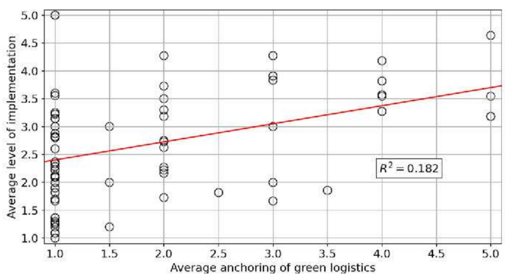

Fig. 2. Results of testing H_1

Table 6
Spearman's rank correlation coefficient and statistical significance for the correlation between a measure's perceived potential and its implementation.

	M1*	M2**	M3*	M4*	M5**	M6*	M7**	M8**	M9	M10**	M11
R_s	.30	.48	.33	.30	.49	.29	.47	.54	.21	.38	.27
p	.018	< .001	.011	.023	< .001	.020	.001	< .001	.118	.007	.062
df	59	53	58	57	50	61	44	52	51	48	47

Table 7
Spearman's rank correlation coefficient and statistical significance for the correlation between a measure's perceived barrier and its implementation.

	M1*	M2	M3	M4*	M5	M6*	M7*	M8**	M9*	M10	M11**
r	−.32	.01	−.14	−.26	−.26	−.30	−.33	−.38	−.35	−.24	−.43
p	.011	.930	.275	.047	.067	.018	.024	.004	.011	.089	.002
df	59	53	58	57	50	61	45	52	51	48	48

To sum up, there is a strong statistical significance that the hypothesis can be accepted for two measures and less significance that it can be accepted for five other measures. For four measures it cannot be supported by our data.

Table 8
Summary of hypotheses' testing.

Hypothesis: There is a significant…					Test	Proposed direction	Supported (p-value)
—	Organizational factors						
	$i_{01} = 1.73$	$i_{20} = 2.56$	$i_{25} = 2.90$	$i_{38} = 3.42$			
H_0	… difference in the level of implementation i_s of green logistics measures between NACE industry sectors s.	Kruskal-Wallis	n.a.	No ($p = .368$)			
	$i_{10} = 2.69$	$i_{21} = 1.70$	$i_{27} = 1.43$	$i_{49} = 3.48$			
	$i_{15} = 2.43$	$i_{22} = 2.63$	$i_{28} = 2.31$	$i_{51} = 2.60$			
	$i_{16} = 3.91$	$i_{23} = 3.27$	$i_{29} = 2.87$	$i_{52} = 2.64$			
	$i_{17} = 3.43$	$i_{24} = 1.43$	$i_{32} = 3.18$	$i_{82} = 2.47$			
H_1	… relationship between the anchoring of green logistics a in the organization and the level of implementation i of green logistics measures.				Spearman's rank correlation	+	Yes ($p < .001$)
	$\overline{a} = 1.89$	$\overline{i} = 2.66$					
	Perception of measures						
H_2	… relationship between the perceived potential Mx,p of a measure Mx and its implementation Mx,i.				Spearman's rank correlation	+	
	$\overline{M1,p} = 2.46$		$\overline{M1,i} = 2.62$				Yes ($p = .018$)
	$\overline{M2,p} = 2.94$		$\overline{M2,i} = 3.04$				Yes ($p < .001$)
	$\overline{M3,p} = 3.25$		$\overline{M3,i} = 3.40$				Yes ($p = .011$)
	$\overline{M4,p} = 3.06$		$\overline{M4,i} = 2.98$				Yes ($p = .023$)
	$\overline{M5,p} = 2.64$		$\overline{M5,i} = 2.37$				Yes ($p < .001$)
	$\overline{M6,p} = 3.03$		$\overline{M6,i} = 2.54$				Yes ($p = .020$)
	$\overline{M7,p} = 2.22$		$\overline{M7,i} = 1.53$				Yes ($p = .001$)
	$\overline{M8,p} = 2.58$		$\overline{M8,i} = 2.59$				Yes ($p < .001$)
	$\overline{M9,p} = 3.33$		$\overline{M9,i} = 3.06$				No ($p = .118$)
	$\overline{M10,p} = 2.82$		$\overline{M10,i} = 1.96$				Yes ($p = .007$)
	$\overline{M11,p} = 3.00$		$\overline{M11,i} = 2.42$				No ($p = .062$)
H_3	… relationship between the perceived barrier Mx,b of a measure Mx and its implementation Mx,i.				Spearman's rank correlation	−	
	$\overline{M1,b} = 3.16$		$\overline{M1,i} = 2.62$				Yes ($p = .011$)
	$\overline{M2,b} = 3.31$		$\overline{M2,i} = 3.04$				No ($p = .930$)
	$\overline{M3,b} = 3.16$		$\overline{M3,i} = 3.40$				No ($p = .275$)
	$\overline{M4,b} = 3.24$		$\overline{M4,i} = 2.98$				Yes ($p = .047$)
	$\overline{M5,b} = 3.06$		$\overline{M5,i} = 2.37$				No ($p = .067$)
	$\overline{M6,b} = 3.87$		$\overline{M6,i} = 2.54$				Yes ($p = .018$)
	$\overline{M7,b} = 3.64$		$\overline{M7,i} = 1.53$				Yes ($p = .024$)
	$\overline{M8,b} = 2.78$		$\overline{M8,i} = 2.59$				Yes ($p = .004$)
	$\overline{M9,b} = 2.82$		$\overline{M9,i} = 3.06$				Yes ($p = .011$)
	$\overline{M10,b} = 3.54$		$\overline{M10,i} = 1.96$				No ($p = .089$)
	$\overline{M11,b} = 3.56$		$\overline{M11,i} = 2.42$				Yes ($p = .002$)

to explain the implementation level and clarify the discriminating factors. The considerations regarding the nonresponse bias in section 4.1.1 led to the conclusion that the findings are generalizable to Austrian companies having a yearly revenue of at least 10 Mio. €.

In those companies, the amount of green practices adopted in logistics to some extent depends on how firmly green logistics is anchored in the company and how the logistics managers perceive the measures' GHG reduction potential and the implementation barriers. In more detail, H_1 proves that anchoring is a determining factor but only explains the implementation by 18%. One hint for the other part of the implementation is provided by H_2 and H_3, as significant correlations between the measures' level of implementation and the perceived potentials and barriers were shown, respectively. This means that the implementation of a measure in a firm is more likely when the logistics management sees the potential as high and the barriers as low – whereby the intensity of the correlations shows that perceived potentials drive implementation more than perceived barriers hinder it.

Comparing results of Table 5 with other scientific findings sheds light on a fundamental problem: the perceived GHG reduction potentials diverge from scientifically validated potentials. For example, the respondents see eco-driving as a high-potential measure, whereas most emission reduction potentials reported in the scientific literature are below 10% (Miklautsch and Woschank, 2022b). Moreover, driver training courses are already integral to driver education in Austria, which is why further significant reductions cannot be expected. Another example is $M9$ (Reducing the age and improving the condition of vehicles). Although the potential for decarbonization is perceived as high, scientific evidence for emission-saving potentials – especially in high-developed countries – is low (Miklautsch and Woschank, 2022a). This discrepancy between practitioners' perceptions and scientific evidence is dangerous for two reasons. First, under- or overestimating the potential might lead to ignoring high-potential measures in strategy development or frustration during strategy operationalization. Such expectation gaps drive divestment (Huangfu et al., 2021), are negatively correlated to innovation (Hammarfjord and Roxenhall, 2017), and might thus lead to the omission of further measures. Second, communicating supposedly green measures could lead to public criticism of their impact and creates the image that the company is being portrayed to the outside world as more environmentally friendly than it actually is and wants to mislead the uninformed market participant. This unintentionally or unknowingly created 'discrepancy between [the] green talk and [the] green walk' (Walker and Wan, 2012, p. 231) could lead to accusations of greenwashing, which is negatively related to financial performance (Walker and Wan, 2012, p. 237).

However, the estimates of practitioners and scientists agree on one point – both are ambivalent about the potential of alternative drives. A high mean potential of $M11$ is accompanied by a high standard deviation and interquartile range. Other empirical studies conclude with similar findings (Vienažindienė et al., 2021). A review of studies investigating measures to decarbonize freight transport leads to the same conclusion for scientific papers, reporting that the range of emission reduction potentials by implementing alternatively powered vehicles spans from nearly 0% to nearly 100% (Miklautsch and Woschank, 2022b). Regarding alternative drive utilization, several firms report on implementing such vehicles in their processes. Nevertheless, the future outlook is weak as further use is hardly planned among respondents. Interestingly, the median and mean values for the use of alternative fuels is significantly lower than for the use of alternative drives, showing that most of the companies do not pursue the use of fuel from renewable sources. Although fuels from renewable sources are frequently criticized because of their productions' energy consumption or their competition with food production, their utilization could lead to significant near-term emission reductions (Miklautsch and Woschank, 2022b) without investments in novel vehicles or infrastructure. Thus, low-carbon or zero-carbon fuels are essential to bridge the gap until alternative drives are scaled (Jaramillo et al., 2022). However, without being requested by freight owners or fleet operators, their distribution will not exceed the minimum required by law. This attitude of companies in Austria will torpedo emission reduction goals in the short- and medium-term – which is a finding that should be a wake-up call for the industry to make alternative fuels an accepted transition technology.

Another promising measure consistently showing solid savings potential in the scientific literature is shifting traffic to rail (Miklautsch and Woschank, 2022b). Nevertheless, our study shows that it is also the measure with the highest barriers, according to Austrian LSPs. The reasons might be the low flexibility of current rail services, missing infrastructure, and longer delivery times (Pencheva et al., 2022; Pålsson and Johansson, 2016). In contrast to the LSPs, no consensus on the potentials and barriers could be found among shippers. As shippers' transportation requirements are a major contributor to the mode choice, increased promotion of potential emission savings and innovations in the rail freight domain could increase demand for rail.

Regarding the hypotheses raised, the results were ambivalent. Contingencies were assumed to differ across sectors, which our data could not support. As mentioned, another empirical study leads to the same conclusion (Pålsson and Johansson, 2016), indicating that sectoral differences are not pivotal for adopting measures. The correlation between the mean organizational anchoring of green logistics and the mean level of implementation was strong, positive, and significant. However, anchoring solely explains 18.2 % of the successful implementation – indicating the need to investigate several other factors to explain the adoption of green practices fully. Nevertheless, due to the high α value and the positive correlations among the indicators of the anchoring scale, an obligation for reporting logistics emissions is predicted to raise the average anchoring scale $\overline{a}$. Because this scale correlates positively to the implementation of measures, this is expected to increase the implementation of GL measures. Thus, initiatives to foster emission reporting in general, particularly logistics emission reporting, are considered to promote GHG mitigation.

The study results further allow us to speculate about the future of emission mitigation in Austrian freight transport. From Fig. 1, we see that only a small number of companies currently pilot or implement measures. Thus, we cannot expect a broad-scale implementation of measures in the coming years from our data. This finding is alarming concerning tackling climate change, as the IPCC highlights that decarbonization progress in the coming decade will decide on the severity of the impacts of climate change (IPCC, 2022). One explanation might be the high variability regarding the barriers and potentials observed in Table 5, which indicates uncertainty among practitioners. Uncertainty regarding technological choices, practical implementations, or emission mitigation potentials hinders decision–makers in enterprises and policy design (Heal and Millner, 2013) from effectively deciding.

To summarize, the results of this study help to explain why transportation emissions are not decreasing in Austria – showing that, except for "cooperation with other companies" by shippers with their own vehicles, even the highest-rated measures in terms of implementation show mean values below 2.5 on a Likert scale of 1 to 5. This is very similar to recent findings from Lithuania (Vienažindienė et al., 2021). Furthermore, summarizing the preceding studies in Table 2 shows that common measures in other countries seem to be eco-driving, route optimization, and different kinds of transportation planning, e.g., locating distribution centres or shipment consolidation. Categorizing those measures to the ASI-approach reveals that the prevalent measures in other countries are from the category "Avoid" – a finding we can support for Austria. An explanation for the uniformly higher adoption of those measures might be that most of them predominantly reduce logistics costs, with emission reduction as a side effect.

From the above considerations, we can derive four critical implications that address the future agendas of researchers and practitioners in the field:

- Our research has identified exemplar organizations that have successfully implemented decarbonization practices on a large scale. By studying these companies and delving into their drivers, motivations, and experiences, we can uncover valuable insights that have meaningful implications for other practitioners. This includes identifying best practices, understanding how to establish a culture of innovation, and inspiring other firms to set higher goals. Thus, we encourage to put the investigation of exemplar organizations regarding emission mitigation on the future research agenda.
- The existence of a gap between scientifically validated GHG mitigation potentials and how these potentials are perceived in practice emphasizes the need for effective dissemination of research findings. Establishing realistic expectations regarding barriers and potentials for effective large-scale emission reduction measures is crucial. To prevent distortion of the reality by interest groups or lobbyists, scientists must take a proactive role in promoting their research findings to technology users. Future research agendas should prioritize a detailed examination of this expectation gap and the development of countermeasures. This includes exploring new forms of dissemination and providing information to key stakeholders in the freight domain. Addressing these challenges can bridge the gap between scientific knowledge and practical implementation, fostering more informed decision-making and impactful actions towards GHG reduction.
- Our data reveals that LSPs have a higher level of agreement on the potentials and barriers of measures compared to shippers. This raises the important question of why such a discrepancy exists and how the shippers' uncertainty can be addressed. Unfortunately, our current data does not answer this question, highlighting the need for future research in this area. Potential solutions could involve improving education and information for shippers' logistics managers regarding green measures and advocating for better access to information. By exploring these avenues, we can work towards reducing uncertainty and enhancing collaboration between LSPs and shippers in implementing environmentally friendly practices.
- In light of the urgent need to address climate change, it is crucial to investigate, promote, and utilize short-term reduction measures. This requires action from all involved parties, with researchers playing a key role in providing the necessary information for informed decision-making. Two promising measures were discussed in this regard: shift to rail and low-carbon or zero-carbon fuels. However, the low interest shown by logistics practitioners in alternative fuels is concerning and calls for further investigation by researchers, as well as financial incentives provided by legislators to encourage their use. Shippers can also play a role by requiring logistics service providers to use higher blends of these fuels. Furthermore, the high barriers to the shift to rail underline the need for innovation in the rail freight sector, requiring further research and development. This is just as much a task for rail freight operators as for legislators and researchers. In summary, promoting and utilizing short-term emission mitigation measures is crucial in addressing climate change. Collaboration between researchers, legislators, shippers, and logistics practitioners is essential in achieving this goal.

Nevertheless, our study encompasses some limitations that need to be mentioned. First of all, the target group of our study consisted of industrial logistics practitioners in Austria. To obtain a comprehensive understanding, future research should explore additional economic sectors, encompass public transportation, and target transnational groups. By doing so, a broader perspective on Europe can be achieved, allowing for insights into frontrunner and laggard countries. Furthermore, our investigation of alternative drives and fuels was conducted at a high level. A more detailed examination of these aspects is necessary to provide deeper insights into the acceptance and perception of different technologies. Lastly, our study provides only rudimentary explanations for the observed results, suggesting the potential for further exploration through qualitative studies. Such research can offer a more nuanced understanding and interpretation of the findings.

Conclusion

The focal study sheds light on the prevalent measures that are adopted in Austria to decarbonize industrial logistics and the discriminating factors that influence their implementation. Regarding the first research question, all firm types show at most a moderate level of implementation. The only exception are shippers with their own vehicles that broadly utilize collaboration with other carriers and companies. In general, measures that aim at avoiding transport are utilized more often than shifting transports to other modes or improving the carbon intensity of the modes. Regarding the future emission path, the outlook towards near-term mitigation looks grim. Promising measures like the shift to rail or the utilization of alternative fuels face high barriers or are not being pursued by firms, respectively.

Investigating the second research question, two aspects were highlighted. First, the organizational anchoring of green logistics, i.e., reporting logistics emissions, setting reduction goals, and allocating resources, significantly influences the adoption of practices among the surveyed firms. Second, the perception of measures was found to correlate with the level of implementation, which is a mixed blessing. On the one side, this means that reports of positive use cases can advance green practices diffusion in the industry. At the same time, an expectation gap regarding the emission reduction potential of several measures seems to exist. Practitioners' perception of reduction potentials thereby differs from scientific findings, which is a call for action towards researchers to disseminate their findings more broadly and proactively.

In 2003, Murphy and Poist conducted one of the first empirical studies on green perspectives and practices among US and non-US firms. They conclude that "green concerns will broaden the scope of logistics as well as influence the way logistics managers do their jobs". Our study shows that several green practices have already been established in logistics, but the way to broad decarbonization is still long. Considering the urge to reduce greenhouse gas emissions from the atmosphere, results highlight that logistics practitioners need to make a U-turn in the coming years.

CRediT authorship contribution statement

Miklautsch Philipp: Conceptualization, Methodology, Formal analysis, Investigation, Visualization, Data curation, Funding acquisition, Writing – original draft, Writing – review & editing. **Woschank Manuel:** Supervision, Methodology, Formal analysis, Conceptualization, Writing – review & editing.

Declaration of Competing Interest

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

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9.4. Paper 4

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Decarbonizing Industrial Logistics

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Abstract—*Transport decarbonization is a major climate change mitigation challenge. Transportation is an industry that takes significant effort to change. It is the basis of every person's daily life. People's mobility and freedom are central to their quality of life. Global goods transport also ensures that the supply chains can source raw materials, intermediate, and end products. Freight transport is a complex interaction between multiple actors and stakeholders. Using interviewed expert insights, we provide insights for managers and organizations on factors influencing the decarbonization of transportation and industrial logistic. We map the interrelationships of those factors and create factors and enabler interrelationships visualizing the complex dependencies among them. We identify two major propositions on how to decarbonize industrial logistics on a broad scale—with the goal of future proofing this decarbonization.*

Key words: Climate change, decarbonization, logistics, technology

1. INTRODUCTION

INDUSTRIAL logistics is concerned with the planning, implementation, controlling, and continuous optimization of material flows and associated information flows [1]. Logistics' primary role is to align customer requirements with social and regulatory pressures. Central to this evolving pressure is the alignment of logistics to climate protection targets. Global freight transportation is central to managing greenhouse gases (GHG)—the scientific consensus of the major contributor to climate change [2].

Industrial shippers require transportation activities to move raw materials, by-products, and finished goods in their in- and outbound logistics. These industrial transportation and logistics activities are central to manmade consumption-based responsibility for GHG emissions. Initiatives to reduce these emissions are frequently marketed by companies, but these GHG emissions from the freight transport sector continue to grow as if no crisis exists.

Current evidence shows that logistics industry decarbonization practices have yet to reach their potential [3]. Some pioneers in low-carbon industrial logistics do exist. We explore the underlying mechanisms to understand what distinguishes these exemplary organizations from less aggressive organizations. We briefly introduce a broader background in Section 2 followed by some insight into how we captured the information. Our results are then presented in Section 3. We then provide interrelationships and what they mean to managers and organizations in Sections 4 and 5. Finally, Section 6 concludes this article.

2. BACKGROUND

According to institutional theory, greening industrial firms can occur from external pressures and from various stakeholder groups. Powerful stakeholders put coercive pressures on organizations, such as when the government sets carbon taxes. Customers may put on competitive and normative pressures when they demand certain green actions through conscious buying behavior. Organizations may also face mimetic competitive pressures from other organizations [4], [5]. Thus, a variety of pressures and responses are likely to occur.

In order to understand industrial logistics decarbonization, we conducted a series of semistructured interviews with logistics experts from exemplar organizations in the automotive, metal, food, and materials sector. These exemplar organizations have implemented low-carbon practices in their logistics processes. We also interviewed consultants and academics to provide a broader view of the industry decarbonization.

The semistructured interview guideline was developed in collaboration with researchers and practitioners. Ten interviews were conducted with experts. We transcribed interviews and then analyzed them using content structuring content analysis [6]. Within this approach, a categorization is derived from the interview guideline followed by coding and text passage inclusion to help maintain the quality and validity of our findings [7].

3. RESULTS OF THE STUDY

The content structuring content analysis resulted in two sets of factors. The first set describes the positive and negative factors that affect willingness to adopt low-carbon industrial logistics practices. Those factors are further grouped into external and internal factors. The factors can also be viewed as barriers or motivators and are dependent on the industry sector, the company size, and the organizational culture.

These factors are fairly consistent with various institutional theoretic pressures [5]. This outcome highlights the validity of the results. Our discussion will focus on the *enablers*. Enablers are success factors that facilitate the broad adoption of low-carbon industrial logistics practices. The identified external and internal factors, as well as the enablers, are summarized in Table 1.

3.1. Factors Affecting the Willingness to Adopt Industrial Logistics Decarbonization Practices

A broad variety of factors were provided by our experts—each falling within the institutional pressure dimensions. We now provide some insights into the most predominant linkages to industrial logistics companies' willingness to adopt industrial logistics decarbonization practices from the broader set in Table 1.

The most often mentioned factor is that the costs of transportation will rise significantly when adopting low-carbon practices in logistics (*COSTS*). The prospect of rising costs is a barrier because the transport sector is a highly competitive cost-driven industry; charging premiums for offsetting the costs is not feasible.

The manufacturing industry—the shippers of the goods to be transported—is not willing to pay the carriers more for green transport services. This situation does not mean that the shippers are not ready to implement low-carbon practices, but they resist decarbonization initiatives that will result in higher transportation costs. Shippers are ready to implement practices when they are at cost neutral—one way of achieving cost neutrality is by reducing through a strategic reconfiguration of supply chain nodes.

Two other dominant factors closely connected with costs are based on regulatory forces. First, the existing internalization of external cost approaches, such as carbon emissions' taxes or requiring participation in an emission trading scheme (*INTER*), is too low to incentivize low-carbon technologies

Table 1. Factors and Enablers of Decarbonization in Industrial Logistics.

	Factors influencing the willingness to adopt practices		Internal enablers	
External	Shareholder value	SHARE	Strategic positioning regarding the investment in future technologies	STRAT
	Internalization of external costs and incentives to reduce GHG emissions	INTER	Key figures with appropriate responsibility and self-motivation	FIGURES
	Development of the energy market	ENERGY	Exchange and communication with stakeholders	COMM
	Market participants	PARTI	Use of software	DIGI
	Clear requirements for reporting and calculating GHG emissions	REQ_GHG	Transparency and knowledge of emissions and operational processes	TRANSP
	Legislation, permits, and subsidies	LEG	Pilot projects as test runners with low risk	PILOT
	Availability of necessary infrastructure and technology	INFRA	Logistics organizational structure	ORGA
	Citizens and regional policy	CITI	Awareness, motivation, and competence of employees	EMPL
Internal	Commitment of the owner or board of directors	MGMT	Level of control of transportation processes	CONTROL
	Marketing, image, and reputation	IMAGE	Definition and operationalization of goals	GOALS
	Costs and possibility of passing them on to customers	COSTS	Tendering and long-term contracts with service providers	LSP
	Operational efficiency and service level	EFF	Use of services and consulting as well as outsourcing	SERV
	Corporate culture and policy	CULTURE	Other	OTHER_SUC

and practices adoption. Second, uncertainty in regulations, as well as subsidies (*LEG*), discourages organizations from investing. New decarbonization supporting technologies may require significant investments in vehicles and infrastructure. Companies are not prepared to make these investments without the support of subsidies to lower potential technology risk. This risk arises from skepticism about regulatory strategies that may shift in the future. Another risk source is the volatile energy markets (*ENERGY*), which make cost estimates difficult and subject to significant uncertainty.

Managerial attitude and perception are crucial for any organizational investment. Therefore, management commitment is an important influencing factor for industrial logistics decarbonization (*MGMT*). This commitment has been found to be positively correlated to the size of the company. This issue may arise due to the larger visibility of and more resources available in larger companies.

We found that investments, costs, and management commitment are closely related to other factors, namely marketing, image, and reputation (*IMAGE*). The more a company is the focus of media attention, the more it is willing to invest in green measures—as long as the communication of the measures attracts customers or reassures shareholders.

Eventually, respondents made clear that further investments in green practices and their communication do not result in enough marketing and reputation-building value to be justified. Many initiatives are, thus, not pursued. This phenomenon—mentioned many times by experts—can be observed in many companies that started implementing battery electric vehicles (BEVs) or natural gas trucks in creating media attention for their green logistics initiatives. Many times these initiatives stopped prematurely after one or two vehicles were in operation and were never truly institutionalized into the company.

Lack of customer consciousness and marketing impact is not solely to blame for the lack of logistics decarbonization implementation. Another factor that arose from our interviews is a lack of infrastructure (*INFRA*). Infrastructure is needed to change logistics systems and start with the widespread availability of alternative energy vehicles, new charging and refueling infrastructure, as well as intermodal terminals and rail lines that are suitable for freight transport.

3.2. Enablers Affecting the Success of Industrial Logistics Decarbonization Practices The other set of identified factors comprise factors determining the success of industrial logistics low-carbon practices—it is for this reason, we identify these factors as enablers and go beyond just the willingness to adopt the practices. The full set of enablers appears in Table 1. In this section, we focus on specific enablers that were mentioned numerous times in different contexts throughout the interviews. Due to the frequency of mentions, we initially view these as the most important enabling factors.

The most frequently mentioned enabler is anchoring logistics decarbonization in the business strategy (*STRAT*). These strategies—when they exist in organizations—need to be sufficiently operationalized. The exemplar organizations identified two major reasons for the strategic importance of logistics decarbonization. The first reason is that fossil-free logistics is an unavoidable future scenario. By building on this strategic perspective, a strategic tradeoff between the logistics emissions and the short-term cost is completed. Much of this scenario is replete with uncertainty since many times the organizations are unlikely to be familiar with new technologies and practices to support this endeavor.

By investing in these decarbonization technologies, the organizations wanted to prepare now for the ultimate long-term scenario. They also felt that they could build competitive advantage when fossil-free logistics become mandatory or unavoidable. Currently, costs for those technologies are higher than costs for traditional technologies. Companies justify these higher costs for transportation by reducing risks of unacceptable future costs of transportation or even the unavailability of transportation services.

The second reason to accept an industrial logistics decarbonization strategy is to create security. Investments in green logistics and transportation solutions can reduce the dependency on volatile energy and carbon emission markets. Uncertainty in these markets is great. Decoupling from these uncertainties and contingencies creates security for the organization itself, as well as its customers and supply chain partners.

To integrate and execute the organizational strategy, human resources input and supporting values are necessary. A part of this is building a culture that supports these values, fosters awareness of climate risk, and creates innovative ideas on how to minimize those risks. The presence of key figures and champions with these perspectives is of utmost importance (*FIGURES*). Those supportive figures can exist at all employee levels. They need to be motivated to mitigate climate impacts and also need to be able to influence decisions made in the company—

either by being the decision makers themselves or by being recognized and consulted by the decision makers.

Many times these champions require stamina and persistence, the decision-making process for investments that will only pay off in the future is perceived as quite lengthy and may be fully discounted. Many of the respondents were key figures and mentioned that significant personal interest and spare time were invested in the development of ideas and knowledge on decarbonization topics.

Building knowledge includes reading specialist magazines, listening to pertinent podcasts, or participating in different advocacy groups or industry clusters. The importance of working and communicating with advocacy groups and industry associations was so frequently discussed that we categorized it as a separate enabler (*COMM*).

These groups of stakeholders can be industrial partners, logistics service providers (LSP), representatives of the authorities or regulators, or customers. Information and knowledge exchange on low-carbon technological or process innovations, funding opportunities, or the state of adoption across the industry were each seen as crucial for the success of logistics decarbonization solutions. These issues are, especially, pertinent as many parties are involved in transportation activities by nature.

Communication with LSP was important because the experts perceive smaller LSPs to have little knowledge about low-carbon measures and practices. Therefore, shipper experience gained in pilot projects conducted with larger LSP can be a valuable facilitator in driving the adoption of measures. This characteristic is seen as another important enabler to reduce manager, employee, and partner concerns with changes to old proven systems (*PILOT*).

Before any changes can be made to established systems, they must first be known and made transparent (*TRANSP*). The importance and difficulty in achieving holistic transparency in logistics systems exist because many parties are involved across multiple processes—many times the companies do not even have control of these processes. This situation highlights the difficulty to calculate carbon emissions in inbound and outbound transportation activities, hindering comparable and meaningful emission reporting. This lack of meaningful reporting and transparency lowers the managerial relevance of reducing emissions.

Holistic software systems implemented on a supply chain level for processing information from all partners (*DIGI*) is a dimension that can overcome transparency concerns. Digital systems cannot only provide transparency but also aid in calculating emissions and providing decision support for specific decarbonization implementation measures. But, it has also been observed that current software and digitization solutions are limited in how holistic they are; also observed is lagging disruptive innovations in this area.

4. Interrelationships and Implications of Identified Factors

In our discussions and analysis, we found that the factors and enablers are strongly connected and influence each other in multiple ways. We started documenting various interrelationships between the factors and enablers—the threads of a spiderweb of relationships—graphically summarizing them in Figure 1.

In this figure, the color of the link provides insight into the characteristic of the node and its influence. Blue nodes and links represent external

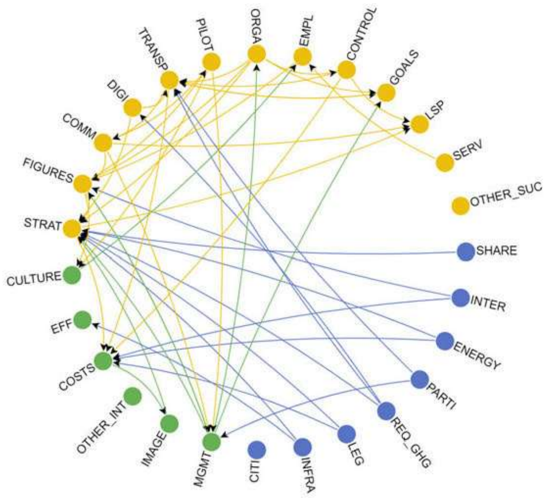

Figure 1. Interrelationships among factors and enablers for industrial logistic decarbonization.

factors, green ones are internal factors, and yellow ones are enablers. Note that no links have external factors as end nodes; in these cases, it is unlikely that these external nodes will be influenced from within a single organization.

The identifier terms used in Figure 1 are the same as the factor and enabler identifiers from Table 1. These interrelationships provide a systemic and deeper understanding of the underlying mechanisms for industrial logistics decarbonization.

When investigating the spiderweb, the first major observation is the many blue links that are connected to the enabler *STRAT*. This observation indicates a strong alignment of strategic positioning to external pressure, for example, from legislation or shareholders. Besides the strategic aspects, transparency and digitalization seem to be significantly influenced by the government and the communication to other stakeholders due to regulatory or mimetic pressure.

In general, many black arrows are directed toward the strategic factor, showing the vast amount of other factors and enablers that exert pressure on decision makers and influence far-reaching strategic decisions. Another prominent factor includes costs, which are found to be at the center of all decisions related to decarbonization. What is further eye-catching is the yellow connections among the yellow nodes. This within the group observation highlights the strong mutual dependence of the enablers. A reason for this observation is that institutionalizing some enablers results in the institutionalization of other enablers. An example of this interrelationship is the link between organizational structure and key figures' enablers. These factors are complementary as the existence of an appropriate organizational structure can establish the existence of motivated and influential key figures and vice versa.

From these links, we are able to draw two main propositions on a decarbonized and future-proof industrial logistics system for organizations and managers, which we will now discuss with an allusion to Figure 1. The first major proposition is that holistic systemic decisions are needed; the second major proposition is that energy management will be a central fundamental for decarbonization. We delve further into these general perspectives.

4.1. Importance of Holistic Decision Making in Industrial Logistics Logistics decisions can be made in a hierarchical structure across four levels where decisions at the upper levels determine the decision space of the lower levels. The levels comprise structural decisions that set the basic supply chain structure, commercial decisions that define the customer, supplier, and service provider base, operational decisions that determine which activities are carried out on a daily basis, as well as functional decisions that specify technical details on how those activities are carried out [8]. Rising costs of logistics activities that accompany new technologies and energy carriers are the most important factor facing companies seeking to be greener or decarbonized.

Technical details for manufacturers and customers of logistics and transportation usually occur at the lower levels of decision making in logistics—namely, the functional or operational level. These levels are usually outsourced to LSPs. LSPs can only operate within the agreed contractual provisions, which are determined by decision makers on the commercial level. This situation provides a first indication that organizations should make logistics-related decisions consistent across hierarchical decision-making levels and carefully consider changes in lower level decisions that are potentially outsourced.

Identifying and pursuing "win–win" outcomes through the mitigation of emissions and cost reductions are important goals. One common approach to achieve win–win outcomes that arise from a reduction of transportation demand and activities. Practices to operationalize this approach must be decided at the upper hierarchical level of decision makers because this approach necessitates structural or commercial decisions. Examples include changing the location of suppliers, warehouses, plants, or customers. These decisions are strategic, far-reaching, and affect more than just logistics functions. But minimizing transportation demand at the same time minimizes fuel demand and is an example, which is directly related to costs and emissions.

To exploit these potentials, one respondent recommends that a single "Supply Chain Department" of the organization, made up of multiple functions and levels, manages this process. The strategic decision maker is responsible for structural decisions, including facility location decisions, and commercial decisions, such as supplier selection, in addition to functional and operational decisions, such as scheduling of trucks for deliveries and dispatches. Establishing this type of cross-cutting function can ensure end-to-end responsibility for material flows—as well as associated emissions—throughout the entire company.

Holistic material flows control also means commensurate information flows—a crucial resource in establishing a broad-based assessment of emissions from logistics. Combining these decisions in one department means the need for a single source of truth and information—enabling higher transparency inside the organization.

Decisions on supplier selection can be linked to existing or new long-term contracts with LSP, fostering deeper collaboration and trust, which can be used to test new and innovative solutions to reduce emissions and costs.

The holistic perspective is understood on two levels. First, the consideration of all decision-making levels of logistics, even if these are outsourced to LSP; and second, material flow integration beginning with upstream suppliers, passing through the company, and ending at the customer. Allocating these perspectives to a cross-functional department can result in meaningful measures for industrial logistics decarbonization.

4.2. Introducing the Energy Management Perspective in Industrial Logistics

Discussions into the decarbonization of logistics quickly boil down to alternative energy sources and associated drive systems that will pave the way toward a decarbonized transport system. These technologies are yet to be fully used competitively.

Logistics experts tend to criticize or promote technological solutions depending on their perception and experience with a specific technology. For example, classical arguments against BEVs are the availability of renewable energy and charging infrastructure, short ranges of trucks, and questionable resource consumption in battery production. Alternatively, logistics managers who have adopted BEVs are enthusiastic about the vehicles.

The discussion on fuel-cell electric vehicles powered with hydrogen currently has similar issues, especially on the production and distribution of green hydrogen. Logistics experts are curious about the technology because of the potential long-range operations of these vehicles. High gas prices and new studies, showing smaller emission reduction potentials than expected, have caused interest in natural gas-powered trucks to level off. Most interest in this technology remains with companies that can produce biogas as fuel.

These examples highlight a phenomenon found in exemplar logistics decarbonizing companies—the technology used in the vehicles will likely be determined by the competitive availability of the appropriate form of renewable energy than by the operational characteristics of the vehicles themselves. This availability, in turn, will depend on how well logistics is integrated into the organizational energy management system and how well primary or secondary excess energy will be used for logistics.

With rising transportation costs—for example, because of rising carbon taxes or fossil fuel prices—the use of excess energy for logistics that are currently sold or used somewhere else can become economically beneficial relatively quickly. An illustrative example of this situation was described by an interviewee from a brewery: the organic waste from the brewing process is no longer sold as fertilizer but is fed to a biogas plant, the energy from which is used to fuel gas-powered trucks, reducing emissions as well as costs of transportation.

5. Concerns and Implications

We have observed a number of factors and enablers that are needed for industrial logistics decarbonization. There are many dimensions to this problem. There are also a variety of planning, design, and implementation concerns that cover the broader organization, partners, and multiple stakeholders. We mention some of these concerns and directions.

For companies relying on transportation, the question will be which of the new technologies to use and where and how to counteract potential additional costs. For example, introducing the energy management perspective in industrial logistics highlights the new potential to simultaneously reduce emissions and costs and ensure the future competitiveness and greenness of industrial logistics. To exploit any available potential, organizational structures, management systems, and employee motivation need to be established to provide a holistic picture of industrial logistics and its related emissions.

Win–win is difficult to find. Working with a multiplicity of stakeholders is required to get an effective holistic solution. Who to involve becomes a major concern—each stakeholder has a different motivation and pressure to address. We did not interview a broader set to determine whether behavior and personal individual values play a role and these may be just as critical as strategic and operational decisions.

The holistic perspective is also shifting. We only took a snapshot. The relationships are quite extensive among the various factors. Which practice or concern will have priority is something that will also evolve. Careful evaluation and evolution, including technological forecasting and scenario planning, will be needed. Organizations and their partners must lead or be involved in this strategic scenario planning.

Essentially, there will be internal and external initiatives and organizations and managers in industrial logistics need to be aware and proactive in these developments. Hiding from the inevitable will make society but also organizations unsustainable.

6. Conclusion

Decarbonization of industrial logistics and transportation is a complex issue. Even though we know the concerns, the environment remains dynamic, including organizational, technological, and external forces playing a multiplicity of roles. Central to the issues is that renewable energies and the associated drive technologies associated with mobility and transportation will shape the image of logistics in the future. In this regard, there will not be just one dominant technology but a mix of different ones.

Using expert interviews, we examined how exemplar organizations have already advanced decarbonization of industrial logistics practices in recent years. We found at least a couple of major conclusions that can be drawn from the insights offered. There is a spiderweb of interrelationships among factors affecting the willingness to and enablers fostering the success of the adoption of low-carbon logistics practices for industrial firms.

Before fully blowing away the cobwebs, it is necessary to spin them, which is why we see this article as one major step toward more empirical and quantitative studies to deepen the understanding of factor and enabler relevance and the strength of the observed interrelationships.

In addition to these questions, further research is also required to validate and quantify the propositions and implications drawn. We seek to help foster the understanding of why decarbonization practices are adopted in leading companies and, at the same time, provide a basis for logistics managers that aim at designing future-proof industrial logistics systems.

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9.5. Paper 5

At the time of writing, this paper is still under review at the Taylor & Francis Journal "Transportation Planning & Technology".

9.6. Paper 6

Due to copyright restrictions, we can only insert the title page of this contribution in the thesis. The full contribution is available at https://doi.org/10.5771/9783957104311-25.

Philipp Miklautsch, Manuel Woschank

The Missing Link

How to Bridge the Gap to Zero-Carbon Logistics

Summary: This research study addresses the increasing need to reduce greenhouse gas emissions in the transport sector, particularly in freight transport, to meet climate targets. The study focuses on short-term decarbonisation measures for industrial logistics, considering the heterogeneous challenges of transportation. The authors develop a multi-criteria decision analysis methodology by incorporating qualitative, quantitative, and secondary data-based studies. A comprehensive perspective is provided through collaboration with experts, enabling decision-makers to assess the most promising short-term decarbonisation actions for their respective companies. Preliminary results of an exemplary application highlight the rising significance of increased biofuel usage and combined rail-road transportation as interim solutions until zero-carbon technologies become broadly available. The contribution offers an easy-to-use decision-making tool for evaluating and ranking the most promising measures for short-term emission reduction until 2030 that are financially and operationally feasible. Thereby, it helps in the green logistics strategy development and contributes to the literature in elaborating on critical decision criteria and their characteristics.

Keywords: greenhouse gas emissions, freight transport, decarbonisation, multi-criteria decision analysis, industrial logistics.

9.7. Paper 7

Due to copyright restrictions, we can only insert the title page of this contribution in the thesis. The full contribution is available at https://doi.org/10.1007/978-3-031-44021-2_14.

Decarbonizing Construction Material Supply Chains: An Innovative Approach to Intermodal Transportation

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Abstract. The transportation of construction materials is a crucial part of the construction material supply chain and a major contributor to greenhouse gas emissions from transportation. In Austria, for example, around 11% of the goods transported in 2020 were mineral products, such as glass, cement, lime, and plaster - much of which are demanded by the construction industry. Some of those goods are bulk materials that are well suited for high-capacity means of transport, e.g., trains. However, several system characteristics of the railroad severely limit its use on the last mile to the customer. Here, materials need to be delivered in a timely and efficient manner to ensure that projects stay on schedule and within budget. An eligible solution for this is intermodal transportation, which couples the benefits of efficient rail haulage with flexible road haulage. Nevertheless, conventionally used 30-foot silo containers hinder high utilization of trains due to weight limit excess of trucks. Therefore, a novel 22.5-foot container design for the transportation of cement was introduced recently that enables a high-capacity utilization of trucks and trains. In this article, we present the environmental impact of its use in construction material transportation by quantifying greenhouse gas emissions of an exemplary use case in the Austrian construction industry. Results show emission mitigation potentials of 75% to 93%, depending on several parameters. This article contributes to the scientific literature by bringing evidence on emission reduction potentials in the construction material supply chain and elaborating on the determining factors.

Keywords: combined transport · construction material · industrial logistics · climate change · greenhouse gas emissions

9.8. Paper 8

Due to copyright restrictions, we can only insert the title page of this contribution in the thesis. The full contribution is available at https://doi.org/10.1007/978-3-031-38274-1_31.

Decarbonizing Industrial Logistics Through a GIS-Based Approach for Identifying Pareto-Optimal Combined Road-Rail Transport Routes

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Abstract. The urge to reduce greenhouse gas emissions is omnipresent in all sectors. Freight transport is responsible for approximately 14% of European emissions, of which 70% stem from road traffic. Since transportation demands are expected to rise in the upcoming years, and short-term broad-scale application of low-carbon truck technologies is unrealistic, the shift to rail freight offers a potential solution. However, block trains are no viable choice for many industrial firms due to operational and infrastructural hurdles. Still, combined transport offers promising opportunities by enabling flexible pre- and post-haulage, centralized transhipment, and an environmentally friendly main leg. However, deployment scenarios in logistics networks are challenging to find. Thus, we present a high-level GIS-based approach to suggest Pareto-optimal routes eligible for shifting to combined transports. This approach provides indications for decision-makers that strive to decarbonize their supply chain and serve as input for detailed assessments.

Keywords: combined transport · industrial logistics · geographic information system · rail

9.9. Paper 9

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applied sciences

MDPI

Article

A Novel Approach to Identify Industrial Logistics Decarbonization Opportunities: Method Development and Preliminary Validation

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Featured Application: This approach can assist industrial logistics professionals in obtaining a fresh viewpoint toward their decarbonization strategy.

Abstract: This article explores how different types of inventories affect the costs of decarbonizing transportation in manufacturing companies. For these companies, it is difficult to find affordable ways to reduce emissions from transportation given their resource scarcity. Additionally, they handle numerous inventory items that have varying transportation needs based on their order frequency and value, which necessitates the development of tailored inventory management strategies. One tool to do so efficiently is the ABC/XYZ analysis, which classifies items into nine different inventory categories. These groups have different economic importance and predictability, which impacts total logistics costs. Our literature analysis contends that lower-carbon transportation alternatives yield varying abatement costs contingent upon the specific inventory categories. Subsequently, we empirically validate this proposition through discrete-event simulations in two case studies involving Austrian manufacturing enterprises, employing combined road-rail transportation as an illustrative decarbonization measure. Statistical tests substantiate the significance of the XYZ dimension in influencing carbon emission abatement costs during the transition from road to rail transportation. In conclusion, our study offers a novel perspective on decarbonization efforts, underscoring the importance of leveraging established management tools to inform strategic decarbonization decisions. This research holds promise for catalyzing progress in overcoming entrenched challenges associated with decarbonization initiatives within industrial logistics.

Keywords: green logistics; decarbonization; climate change; industrial logistics; ABC analysis; XYZ analysis; simulation; transportation

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1. Introduction

Decarbonizing logistics is, from a scientific perspective, crucial for mitigating climate change [1], and from an institutional perspective, crucial for achieving net-zero pledges [2]. Systematic approaches to developing strategies for logistics decarbonization from a freight owners' perspective already exist. For example, the 10C approach by McKinnon [3] consists of ten activities and includes possible options to consider. The field of developing carbon mitigation measures for transportation is well researched, from discussing different drivetrain technologies [4] and alternative fuels [5] in technical terms to developing green routing algorithms [6]. Regarding the application of greening measures in practice, generic total cost of ownership studies exist, but often only distinguish between factors that are not tangible from the perspective of the freight owners, e.g., the application scenarios in urban logistics [7], factors on the national level [8], or barriers for the implementation of specific measures [9,10]. Although all these contributions are important for the decarbonization progress, efficient and effective guidelines that freight owners can use to select decarbonization measures are missing. Most studies only rank the different measures by abatement costs. Although this is a common instrument to evaluate the efficiency of decarbonization measures and is highly important in selecting decarbonization measures [11–13], abatement costs only provide limited support for firms in identifying appropriate alternatives that can be ranked and prioritized based on their respective situation.

The challenge is to select a decarbonization measure that minimizes expenses and avoids disrupting operations [14,15]. This problem is particularly difficult to overcome when dealing with diverse goods that have varying value and volume compositions, which is the case in most industrial companies. To the best of our knowledge, there is currently no way for industrial companies to increase the effectiveness and efficiency of the process of identifying and selecting transport decarbonization measures for further evaluation.

Nevertheless, one positive result is that parallels can be drawn with another area of industrial engineering and management, that is, inventory management, which deals with many items and must prioritize them to manage inventory levels [16]. Therefore, instead of investigating each item on its own, a common approach is to classify goods with similar characteristics or importance to the firm's success. Inventory control tools for these purposes have been in use for economic reasons for many years. One of the best-known inventory control tools is the ABC/XYZ analysis, which classifies inventory items along the two dimensions, "value" and "order frequency," into nine types. For each of these types, different replenishment strategies are commonly applied to efficiently and effectively manage inventory levels [17].

With regards to these parallels, in this study, we introduce a novel approach to identify industrial logistics decarbonization measures that differentiate the transportation requirements of the transported goods in line with the ABC/XYZ analysis. Simply put, we propose that different transportation requirements come with different costs for lower-carbon transportation. From the inventory management perspective, higher transportation costs can be borne for some inventory items, as their storage is as expensive as their transportation [16]. If shipments in which such goods are transported are to be decarbonized, high abatement costs may have to be expected. For shipments of lower value or shipments with a stable demand, cost-effective decarbonization measures might be an option, leading to negative abatement costs. In the first part of this paper, we delineate this novel perspective from literature and define our proposition.

In the second part, we present the results of two simulation case studies, exemplarily testing the proposition using a promising decarbonization option, i.e., the shift from road to rail. We develop a discrete-event simulation using Python that mirrors the behavior of a logistics system using combined road–rail transportation. We decided to use this measure for several reasons, which are elaborated on in Section 4.1.

To summarize, the overarching goal of this paper is to introduce a novel perspective on carbon management for industrial logistics and provide the first evidence for its effectiveness. For researchers, this adds fertile ground for further research on the entrenched field of applying decarbonization measures in industrial logistics. As for practitioners, this paper offers an efficient way of investigating decarbonization measures to reduce their logistics' impact on climate change. Chances are high that ABC/XYZ analysis has already been implemented in a manufacturing company, which is why this approach proves useful for efficiently evaluating alternative and environmentally friendly transportation methods.

The paper is structured as follows: Section 2 presents the research methodology applied in this paper. Section 3 presents the results of a literature review on the selection of logistics decarbonization measures from an industrial company's perspective, the parallels to inventory management and the developed theory. Section 4 presents the argumentation for using combined road–rail transportation to evaluate the proposition and the method to do so. Section 5 outlines the case studies for the exemplary validation, the assumptions, and scenarios, as well as the simulation results. The paper concludes with a discussion of the limitations and implications in Section 6 and a summary of the results in Section 7.

2. Research Methodology

As the title of this paper suggests, this research is split into two consecutive parts. In the first part, the proposition is formulated. The initial motivation to do so emerged from the preceding research of the authors and discussion on decarbonization practices with industry experts. Throughout these talks, the authors recognized a repeating pattern where logistics managers stated that a specific decarbonization measure is only competitive for a certain type of good, i.e., a small portion of the inventory. Starting with this observation, we have gradually developed our theory with findings from the literature in a back-and-forth manner between literature and practice; we present it in the first part of this paper. This method of theory development is suggested to build theory from case studies [18] and applied by other researchers in supply chain management [19].

The second part of the paper deals with the validation of the developed proposition. However, since this proposition is very generic, it is not possible to test it in all its facets. For this reason, we have chosen a specific decarbonization measure to test the proposition. This measure is the shift from road transport to combined transport. We quantify the carbon abatement costs through a discrete-event simulation using primary data from two Austrian industrial companies.

The research process is visualized in Figure 1.

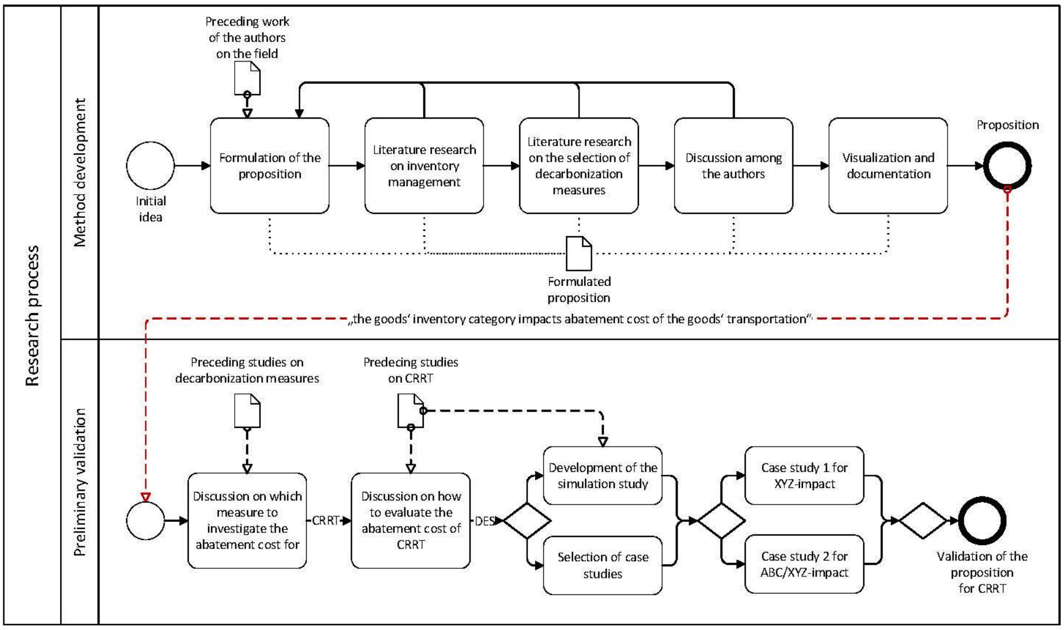

Figure 1. The research process of this study.

3. Theory Development

This section explains the challenges involved in selecting decarbonization measures from a manufacturing company's perspective and delineates our theory.

3.1. Selection of Decarbonization Measures

To decarbonize industrial logistics, researchers and practitioners discuss a vast number of different measures [20], which are commonly classified through the Avoid–Shift–Improve (ASI) approach [1,21,22]. As modern economic theories state [23], implementing all the measures is impossible in practice due to resource scarcity. As economic entities only have limited resources available, policymakers and managers who define decarbonization pathways need to prioritize decarbonization measures [24] for some criteria. On a macroeconomic level, policymakers may prioritize the highest-emitting economic sectors in their decision scope [25]. Delving deeper into the sectors, such as the building sector, scholars suggest prioritizing actions according to their decarbonization potential, respecting their detailed technical feasibility [26]. Other researchers promote prioritizing those technologies that are least invasive to the current environment, i.e., rooftop photovoltaics in combination with electric vehicles [27,28].

Although these prioritization efforts are all, from an environmentalist perspective, comprehensible, actual decarbonization decisions in the industry are rarely one-dimensional. For example, when investigating decisions on a microeconomic level, empirical research found that decarbonization alternatives in the building sector were evaluated and prioritized by 27 different criteria [29]. Similar research approaches are applied to other sectors, including energy generation. In one case, green hydrogen production alternatives were prioritized according to their efficiency and sustainability, considering the criteria capital cost, feedstock cost, operations and maintenance cost, hydrogen production, and CO_2 emission [30]. These criteria focus on cost, which already implies that prioritization based solely on the effectiveness of decarbonization is unlikely. Instead, decarbonization may only be possible economically, which is a theory supported by various authors (for instance, see [31,32]), not least for freight transport. Exemplarily, the factors hindering the adoption of electric trucks in the United States were researched, and the results indicated that the top causal factors are the business model and partnerships, product availability, and charging time [9]. A Delphi Study on factors affecting the adoption of alternative fuel-powered trucks in Germany found that cost and reliability factors are ranked highest among practitioners [10]. These criteria, in the end, all reflect the efficiency of electric trucks. Similarly, the chief impediments mentioned by industrial logistics experts when surveyed about green practices were mostly related to costs [14]. A study proposing a multi-criteria decision-making tool for industrial logistics practitioners defined eight criteria for evaluating decarbonization alternatives. The two criteria considered most relevant in the demonstration case study were "abatement cost" and "impact on logistics performance" [15].

In summary, the selection of decarbonization measures in industrial logistics practice prioritizes efficiency over effectiveness. As previously demonstrated in [15], the economic efficiency of decarbonization measures can thereby be well expressed in terms of the abatement costs AC. These are defined by:

$$AC_m = \frac{C_m - C_b}{G_m - G_b}, [C] = \text{EUR}, [G] = t\ CO_2\ e$$

describing the cost difference of a decarbonization measure m compared to a baseline situation b, concerning the greenhouse gas (GHG) emissions reduced by m. Simply put, AC indicates how much it costs to reduce one ton of GHG and, thus, to which extent that measure is competitive with other measures. Abatement costs are commonly reported in studies dealing with decarbonization pathways or options, for example, in the energy sector [11,12]. Nevertheless, AC starts to be frequently used in freight transport, as well. In a recent study by Chinese researchers, various decarbonization measures for sand and gravel transportation were analyzed using the ASI strategy. By calculating AC, it was found that switching to lower carbon modes of transport was the most competitive option [22]. The cross-sectoral study of Denmark's transition to fossil-free transportation revealed differences in abatement costs both within and between transport segments [13]. An analysis of American electric vehicle procurement incentives revealed that the utilization of electric vehicles influences the abatement costs related to them [33].

According to these studies, the efficiency of decarbonization measures, in terms of abatement costs, varies significantly between implementation scenarios characterized by, for example, weight, volume, frequency, origin, and destination. This emphasizes the challenge of identifying efficient decarbonization measures in the logistic network of a manufacturing company, which usually involves goods of varying priorities, suppliers, customers, and values. To the best of the authors' knowledge, it is still unknown how industrial firms, whose main competence lies outside the decarbonization of logistics, can identify efficient decarbonization measures effectively.

3.2. Inventory Management

Handling the above-mentioned challenge regarding the multiplicity of goods purchased, transported, and handled in a manufacturing company, is the responsibility of inventory management. Inventories frequently constitute a considerable portion of the total assets on the balance sheet of manufacturing companies; a 15–20% share is not uncommon [16]. Given that inventory holding costs can range up to 26%, inventories have a significant impact on a company's cost structure. The DuPont scheme incorporates inventories in the evaluation of the current asset in the return on investment (ROI) calculation and highlights the lever of inventory reductions: a 10% inventory reduction results in a 3.6% ROI increase [16].

Nevertheless, inventory management has been found to significantly affect both the economic success and sustainability of the company. Choices made on the inventory management level thereby influence a multitude of factors, e.g., the necessary distance, the frequency, or the mode of transportation. For instance, replenishment strategies establish the essential prerequisites for transportation processes in terms of frequency and volume, which, if optimized, can result in cost and environmental advantages [34]. Mode choice depends on lead time, volume, frequency, and costs [35]. Whereas fast modes enable priority shipments, they usually come with premiums. Slow modes enable efficient transportation of high volumes at one time and reduce the replenishment frequency but are less flexible [36]. Calibrating the inventory management strategy for the whole inventory is a complex task for a manufacturing company handling multiple products given the varying product requirements [37].

To effectively optimize inventory, organizations, therefore, commonly prioritize goods based on their relevance. One widely used tool for distinguishing highly relevant goods from less relevant ones is the ABC analysis. The analysis classifies articles, suppliers, or inventory movements according to their materiality for inventory management. The A category thereby comprises the highest-value elements that account for 70–80% of the value measured in monetary units. Usually, these elements only account for 5–10% of the number of elements, highlighting the most relevant ones for inventory management [38]. Regarding the inventory value, these elements are of utmost importance and provide the largest lever for improvements. Elements belonging to category B generally represent 25% in terms of quantity and 10–15% in terms of value. The rest of the elements, which are considered the least valuable, are categorized as C. These elements generally comprise 65% of the total quantity, but contribute only 10% to the overall value [38]. The ABC analysis is known for its ease of use and its clear graphical representation, making it a commonly used instrument among practitioners [16]. Nevertheless, it has been criticized frequently for its one-dimensionality, which is why researchers started to incorporate multi-criteria decision-making techniques in the field of inventory management [39]; they added, for example, non-financial criteria [40] and uncertainty [41] to the classical ABC analysis. One further dimension that has been used to detail the results of the ABC analysis is the demand fluctuation, which is investigated using the XYZ analysis [42]. Like ABC, XYZ classifies inventory elements into three categories but uses the coefficient of variation CV instead of the element's monetary value. X elements, thereby, have a stable demand and a $CV < 0.1$; Y elements show seasonal fluctuations having $0.1 \leq CV < 0.25$; and Z elements are identified by $CV \geq 0.25$, being vastly volatile and unpredictable [16].

3.3. The Developed Theory

As elaborated above, inventory management and its ABC/XYZ analysis is a crucial and extensively researched aspect of operations management. Manufacturing companies typically use distinct logistics strategies for each of the nine emerging cells [35], which differ by the transportation mode, the order frequency, and the lead time [43]. These factors thereby impact the transportation cost, inventory holding cost, and order cost, which, together, form the total logistics cost [35,44,45]. Thus, the ABC/XYZ category of an inventory item impacts the logistics strategy applied to it, which, in turn, impacts total logistics cost.

Thereby, a goods' ABC dimension primarily affects the inventory holding cost, as it represents the pecuniary value of the inventory item. The XYZ dimension, on the other side, impacts the required lead times, flexibility, and resulting vehicle utilization, as it represents the demand characteristics, thereby impacting transport and order costs.

Combining this with the findings of Section 3.1, that abatement costs for one decarbonization measure differ among transportation scenarios, we can, in turn, delineate that logistics strategies impact the abatement costs of specific measures.

Thereby, the abatement costs represent the total logistics cost difference between the conventional transportation technique and a lower-carbon alternative, divided by the mitigated carbon emissions. As the goods' category impacts the total logistics cost, we theorize that the goods' category also impacts the abatement costs of reducing carbon emissions from the goods' transport.

Figure 2 presents a graphical representation of the line of argumentation for this theory.

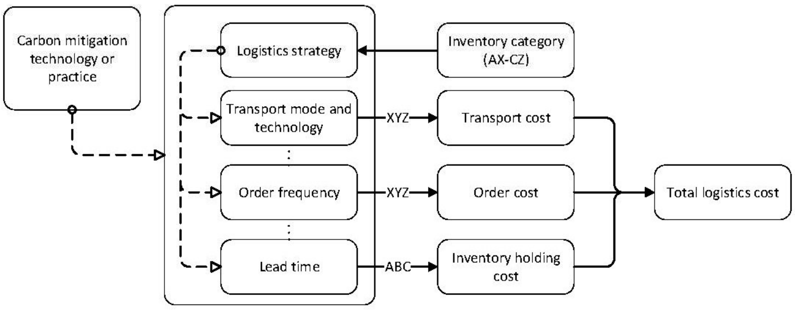

Figure 2. The impact of carbon mitigation practices on total logistics cost and the causal relationship with the inventory category.

This theory can be argued logically with different decarbonization measures, for example, vehicle selection. The truck class depends on several factors such as distance, speed, reliability, and flexibility. Items with a consistent demand (X items) may be transported in larger and slower trucks, while those with a volatile demand (Z items) require high-speed transportation in smaller trucks. A study by [13] found that abatement costs vary among various truck classes, which implies that the reduction of transportation emissions of X and Z items differ in this case. Additionally, there is evidence that the cost of reducing emissions for electric vehicles depends on their utilization [33], which suggests that the abatement costs for smaller, high-priority deliveries may be higher due to the need for low-utilization transport. Another example is the shift to lower-carbon modes of transportation, i.e., rail freight, which implies longer lead times. As elaborated above, these affect inventory holding costs. Thus, this measure is proposed to be more cost-effective for low-value goods (C) than for high-value goods (A), which implies different abatement costs for the transportation of A and Z items. The concept of differentiating abatement costs across inventory items is advocated by other researchers. For example, using different modes of transport for individual items across the entire range of products was found to identify products that are relatively cost-effective to abate, as well as more expensive-to-abate products [37].

To sum up, this theory leads us to our final proposition: The abatement costs of one carbon mitigation practice or technology differ significantly between the ABC/XYZ category of the good to which it is applied; simply put, "the goods' inventory category impacts abatement costs of the goods' transportation". Table 1 presents a conclusive summary of the literature on this topic, which is used to argue for this proposition.

Table 1. Literature summary.

Statement	References
Inventory management and its ABC/XYZ analysis are frequently applied in practice and well-researched	[16,34,35,37–41]
Inventory categories impact the selection of inventory strategies	[16,35]
Inventory strategies impact inventory cost	[16,35,43]
Inventory costs impact total logistics cost	[44,45]
Inventory strategies impact emissions	[46,47]
Implementing lower-carbon transportation technology, modes, or practices impacts total logistics cost	[13–15,20,33,48–50]
Selecting transport decarbonization measures on the product level can optimize total abatement cost	[37]
Transportation abatement costs differ across inventory categories	This study

Although our proposition has been carefully developed, it needs to be thoroughly evaluated. In the following section, we present an initial evaluation of the theory applied to one decarbonization measure, i.e., combined road–rail transportation.

4. The Methodology for the Proposition Validation

In-depth validation of the theory across all potential decarbonization measures exceeds the scope of a single article; therefore, in this study, we have opted to test the theory by way of exemplification using one specific decarbonization measure. In the upcoming sections, we present the rationale for opting for combined road–rail transportation (CRRT) as a model decarbonization measure, evaluating it through a discrete-event simulation approach. Additionally, we will highlight the critical facets of CRRT that are considered during the simulation, along with the description of the two case studies that were used for testing the proposition.

4.1. The Selection of Combined Road–Rail Transport as an Exemplary Decarbonization Measure

For the proposition validation, we selected CRRT as the exemplary measure, which is substantiated by several key factors. First, the emphasis on shifting towards lower carbon modes of transport as a central pillar of decarbonization literature [7] underscores the relevance and significance of rail transportation. As inland waterway transportation faces challenges regarding reliability [51,52], which is an important decisive factor for transportation users [53], rail transportation is the more common shifting alternative [21]. Since only a limited number of manufacturing firms have direct access to the rail network, intermodal transportation, particularly combined road–rail transport (CRRT), is promoted by various logistics service providers (see, e.g., [54–56]). The demonstrated cost-effectiveness of CRRT in mitigating emissions in China [22] and Europe [57,58] affirms its practicality and environmental viability.

Despite the potential advantages of CRRT, it presents significant challenges for shippers due to increased lead times and the involvement of multiple stakeholders in this type of transportation [59–62]. Therefore, this measure presents greater evaluation complexity compared to others, such as changing drivetrain technology. While the logistics system stays consistent with a change in drive technology, CRRT planning necessitates significantly extended replenishment times and consideration of rail network delays. For cost and emission assessments, it is necessary to consider two modes of transportation as well as load units and handling and storage procedures. This complexity creates challenges in conducting environmental and economic impact assessments. For these reasons, we opted to evaluate our proposition for CRRT, as it is a promising and hard-to-assess decarbonization measure. This selection aligns with the European Union's ambitious decarbonization goals, indicating that CRRT not only holds theoretical promise but also aligns with broader regional strategies for sustainable freight transport [63].

4.2. The Use of Discrete Event Simulation as the Evaluation Method

Because of the complexity of CRRT's impact assessment, simulation is a commonly applied methodology in researching intermodal transportation. Through simulation, researchers can gain a better understanding of mechanisms within the transportation system, reaching from the operations in transshipment hubs [64] to the utilization of transport corridors [65]. Simulation paradigms vary depending on the study's objective and encompass a multitude of possibilities, including agent-based [66], discrete-event [64], and system dynamics [67] approaches, as well as Monte Carlo simulation [49]. For the focal study, we developed a discrete-event simulation (DES) using Python and the Salabim library [68]. Within the simulation, the behavior of all elements and actors involved in CRRT, like consignees, shippers, hubs, trucks, trains, and load units, are modelled. We opted for DES because it is frequently applied to intermodal transportation [69–71] as well as the author's experience with DES.

4.3. The Case Studies Investigated for the Theory Validation

To validate our proposition, we use inbound shipment data from two Austrian industrial companies. The first case study is an Austrian electrical equipment manufacturer that provided us with nonfinancial data from its 2021 shipments over 11 months. Due to the attributes of the data, we cannot integrate the ABC part of the ABC/XYZ in this case study. For the validation of the ABC impact, we integrated a second case study, involving an Austrian cable manufacturer. The company provided us with shipment data from 2022, including the value of the goods.

For each case study, we combine all European inland road freight legs, including the final road leg for air or sea shipments, and road shipments as input for the DES. For each of the companies, we calculated costs and emissions from the status quo, i.e., road transportation, and compared it to two hypothetical shifting scenarios. Thereby, we were able to calculate hypothetical transportation abatement costs for each of the inventory categories.

Due to the numerous possibilities for planning, conducting, and controlling CRRT, we have made certain assumptions to ensure the simulation's effort is manageable. Therefore, the following constraints have been made:

- For competitive CRRT, the maximum number of transshipment operations during the main rail leg is set to one, i.e., no more than two rail services included in the main leg are allowed. The maximum allowed time for intermodal transportation is two days. To select the possible CRRT services, we search for the origin-destination pair on Routescanner.com (accessed on 11 September 2023) for each weekday and select the quickest connection that fulfils the requirements just mentioned. If there is no viable connection, we exclude the respective origin–destination pair from all scenarios. The rail services used are presented in the supplementary material.
- For pre- and post-haulage, we used the shortest possible routes from the suppliers to the origin terminal as well as from the destination terminal to the consignee. The distance and duration of these road haulages were acquired through the Openrouteservice.org (accessed on 11 September 2023) Distance API. We abstain from mentioning the precise addresses and distances due to confidentiality, but we can share that the average distances were 139 km and 169.5 km in the pre- and post-run for the first case, respectively, and 109.23 km and 193.82 km in the second case, respectively.

- The replenishment times differ between shipments from X, Y, and Z suppliers: X suppliers are given 7 calendar days replenishment time, Y shipments 5 days, and Z shipments 3 days. This reflects the predictability that is related to the different XYZ clusters. The replenishment time thereby determines how long before the planned arrival date the shipment is released by the supplier. For example, X suppliers are notified 7 calendar days in advance to send the shipment, either directly to the plant via road or to the first transshipment hub for intermediate storage.
- No further consolidation was considered. Shipment volumes and weights for intermodal shipments need to match the volumes and weights for the respective direct shipments that are given in the input data. It stands to reason that this is not the case with a real shift to rail as consolidation effects strengthen the business case for CRRT. However, we could not make any meaningful assumptions and would mix the evaluation with a second measure, which is why we decided against making any further assumptions on consolidation given the overall objective of the evaluation.
- To minimize cost, we aim to use 40-foot ISO containers. If the utilization of the 40-foot container is lower than 80% in terms of loading length, volume, or weight, we use 20-foot ISO containers instead. For competitive CRRT, each ILU utilization u_{ILU} needs to be larger than or equal to 80%.
- Combining the former two assumptions led us to discuss how to handle shipments that have $1 < u_{ILU} < 1.8$. Therefore, we introduced two dispatching modes for those shipments:
  a. In the first mode, we dispatch the whole shipment size to CRRT. This option constitutes the first shifting scenario, called "All ILUs on Rail" (ARA). In this scenario, the whole shipment, regardless of the shipment size, is dispatched to CRRT, meaning that one ILU is less utilized than 80%. This implies that some ILUs on rail are not well utilized, and the costs for renting, shipping, and handling the goods in this ILU are higher than for the better-utilized ones, but costs for direct road transport are obeyed. Before dispatching the ILUs via intermodal transportation, it is checked whether the ILU can reach the consignee on time with the available rail services. If this is not possible, the ILU is shipped directly by road transportation.
  b. This implies more cost for a low-utilized road transport. In this scenario, a minimum utilization of 80% is necessary for each load unit to be shipped via CRRT. If this utilization is not reached, the ILU is scheduled for direct road transportation. We call this scenario "Highly utilized ILUs on Rail" (URA).

Therefore, including the base case, three scenarios are presented for each case study, which are visualized in Figure 3.

Table 2 presents a summary of the input data that was used for the scenarios. The difference between the total and considered shipments is based on constraints 1 and 2 of the enumeration.

The emission data that is used is a combination of dynamic and static data. For the transportation legs, we use the EcoTransIT World (ETW) emission calculator as the shipments reflect real-world transports that have been conducted. ETW offers a comprehensive calculation methodology that accounts for real-world movements of ships and flights and integrates up-to-date emission factors, emission quantification standards, and traffic networks [72]. To address ILUs in the hubs, we use a static value of 30 kg CO_2e per transshipment activity, as suggested by the GLEC framework [73]. Emission intensities of transshipment activities differ between hubs and equipment used, but no detailed data was available to us regarding terminal-specific emission factors.

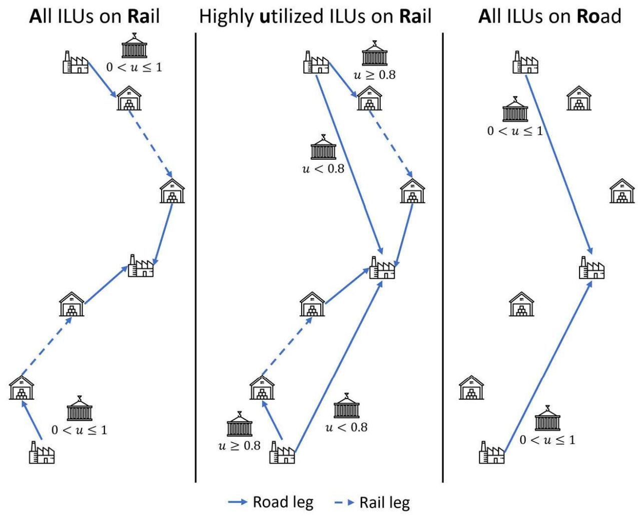

Figure 3. A schematic overview of the different dispatching mechanisms in the scenarios (from left to right the ARA, URA, and ARO scenarios).

Table 2. Descriptive statistics of the two cases under study.

	Case 1		Case 2	
	Total	*Considered*	*Total*	*Considered*
Number of suppliers	36	21	75	8
Number of products	n.a.	n.a.	359	10
Number of shipments	1215	275	1706	98
Shipment date range	February–December 2021	February–May 2021	January–December 2022	January–December 2022
Transport GHG emissions	548.51 t	247.25 t	305.60 t	153.01 t

4.4. Total Logistics Cost of Combined Road–Rail Transportation

Transportation costs generally comprise the cost components of each party involved in relocating goods [49]. Several studies have already defined the cost elements of intermodal transport and the comparison with unimodal transport. We use the cost functions defined in a recent case study on intermodal transportation [58] and detail them with other studies. The authors of [58] elaborate on the costs of intermodal transport services from a consignor's perspective and divide them into several parts. First, the pecuniary cost of transport PC includes the cost per kilometre and the cost of transshipment. Second, the monetary cost of transit time TT depends on the transport time, the value of the shipment, and the interest rate. Thirdly, the monetary cost of a delay D can be quantified, including fines and production downtime costs. Fourth, the cost of cargo loss C (i.e., damaged, expired, or stolen cargo) is a function of the value of the shipment, the fines, the production downtime costs, and the cost of reordering. Fifth, the study includes the cost of oversized cargo OC, which is highly dependent on the size of the cargo, and sixth, the social cost of transport SCT, the value of which depends on the method of quantification. Additional cost factors that have been considered in other studies are the expenses associated with storing a load unit at a terminal, the cost for the intermodal load units (ILU), incurred either as rent or depreciation, and the management and organization costs [74,75]. This study focuses on the perspective of the freight owner, which is why the total logistics costs are considered. Therefore, we have decomposed the aspects into six components that reflect the roles of all parties involved, including carriers, hub operators, railway operators, ILU owners, the organizing party, and the freight owner itself, including the transportation cost, order cost, and inventory holding cost. Respectively, these components are the cost for transport operations TC, the cost for hub operations HC, the cost for the ILU rent or depreciation $ILUC$, the cost for production downtime DC and the cost for capital CC, as well as the overhead cost for organizing the CRRT OC. TC includes cost for pre-, main, and post-haulage, and HC includes the cost of the origin and destination hub. Figure 4 illustrates the occurrence of these components in the transport chain. As the freight owner is the principal of the transport, the costs are borne directly or indirectly by the manufacturing company. As we are missing data on ILU thefts or damages, we neglect these cost components in the focal study.

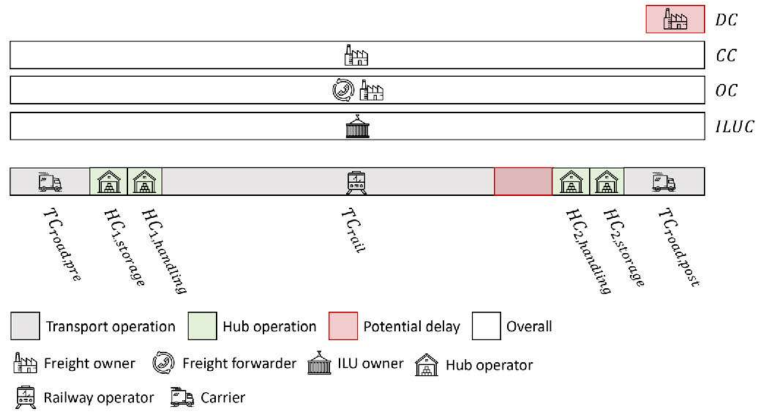

Figure 4. Cost structure of combined road–rail transportation from a freight owners' perspective (Icons from Freepik on Flaticon.com, accessed on 11 September 2023).

The cost data that was used in the simulation study is a combination of primary data and secondary data:

- TC_{road}: The input data from case study 1 were used to consider costs for direct truck transport. As a result, we developed a regressive function that depends on the truck utilization u to determine the freight charges per tonne-kilometre $TC_{road,direct,tkm}$. Specifically,

$$TC_{road,direct,tkm}(u) = 0.0582 + \frac{0.0244}{u} \frac{\text{EUR}}{\text{tkm}}$$

  Additional information on this can be found in Appendix A.
- TC_{rail}: To obtain pricing information for the main leg, we consulted the sales team at a railway operator for data related to a sample CRRT service. They provided us with a cost of 800 EUR for a single 60-foot wagon travelling an on-rail distance of 822 km and having a capacity of three 20-foot containers, which are commonly referred to as 20-foot equivalent units (TEU). Based on this information, we estimate the cost of transporting one 20-foot ILU per kilometre as:

$$TC_{rail,km} = \frac{800\text{EUR}}{3\text{TEU*}822\text{km}} = 0.32\frac{\text{EUR}}{\text{TEUkm}}$$

We are aware that rail transport pricing differs between operators, relations, and time, but regarding the efficiency of the research, we were not able to collect more detailed cost information empirically. Nevertheless, the 0.32 EUR/TEU used in this study is in the range of 0.46–1.35 EUR per forty-foot container provided by [75]. From this, we deduce that the exemplary price resulting from our research is representative of the European market.

- HC: For the hub cost, we use primary data from the involved terminals' homepages, if available. If not, the value of:

$$HC_{handling} = 48 \text{ EUR and } HC_{storage} = 0 \text{ EUR}$$

is used in line with [75]. For gateway movements, we use:

$$HC_{handling} = 27 \text{ EUR and } HC_{storage} = 0 \text{ EUR},$$

in line with [75] as no other data is available to us.
- $ILUC$: The ILU rental fee per day was retrieved from an Austrian container rental company, compared with data from [76,77], and set to

$$ILUC = 7.5\frac{\text{EUR}}{\text{day}}$$

- OC: Since actual road freight costs are included in the input data, the road OC is already included in the road freight charges.
- DC: As no data was available to us on the production delay, we initialized the simulation with:

$$DC = 500\frac{\text{EUR}}{\text{hour}}$$

- CC: In the first case, we cannot integrate CC in our evaluation due to the abundance of the shipment monetary values. For the second case, we compute the costs of capital by utilizing a literature-based interest of 12% from [62].

4.5. Distribution of Train Delay Times

Freight train delays negatively impact the reliability of intermodal freight networks and are an important, but under-researched element of combined transport [78]. Freight trains are typically less reliable regarding the planned arrival times than trucks, which is a planning challenge for freight owners. Reasons for freight train arrival delays can be grouped into two sets of factors [79]. The first set describes a deviation of the departure time from shunting yards or hubs. The distribution of these deviations in Swedish shunting yards has been investigated by [80]. In their paper, the authors find that the log-normal and the gamma distribution best approximate the departure delays and early departures, respectively. The second set describes delays during the journey of the train. Network capacity utilization, weather conditions, construction sites, and many more factors determine the actual arrival time of trains. To model the delays of freight trains in our simulation, we thus cannot rely on the departure time delays, as the influence of the journey would be neglected. As creating models that predict the arrival time by combining both sets of factors is its own body of research [79], we concentrate on approximating the actual arrival delay using a probability distribution. Some work in this field has already been done. For example, the delay time of arriving passenger trains was approximated for Chinese railway stations through exponential distribution [81]. Although passenger train punctuality is much higher than freight train punctuality in Europe (see, e.g., [82,83]), we argue that the nature of the factors influencing arrival delays are similar, and thus, the type of distribution approximating passenger train delays also approximates freight train delays. Therefore, we use the exponential distribution with the probability density function:

$$f(d) = \lambda e^{\lambda d}, d \in \mathbb{N}$$

to model the delay d of a freight train. For parameterizing, we use the punctuality information of the Austrian Railways, reporting that the share of combined wagonload traffic with less than 30-min delay in Austria in 2022 was 52% [82]. By calculating the cumulative distribution function:

$$F(d) = 1 - e^{-\lambda d}$$

we approximate $\lambda \approx 0.02531$ so that $F(29) \approx 0.52$. This results in a mean delay of $E = \frac{1}{\lambda} = 39.51$ min and a median delay of $m = \frac{\ln(2)}{\lambda} = 27.39$ min. In the simulation, we incorporate the delay by adding it to the scheduled lead time t_s, thereby defining the actual lead time t_a of a railway service as:

$$t_a = t_s + d$$

5. Validation Results

5.1. Results of the ABC/XYZ Analysis

In the first case study, the shipment data solely represents the supplier-level and not the product-level, which is why we conducted the XYZ analysis for the suppliers as suggested by [16]. The XYZ classification thresholds were set to $CV_{XY} = 0.3$ and to $CV_{YZ} = 0.6$. These values are in the range of the values presented by other literature, as elaborated in Table A1 in Appendix B. As values from the literature vary significantly, we established the thresholds to classify approximately 20% of suppliers as X, 50% as Y, and 30% as Z, as suggested by [16,38].

In the second case study, the shipment data contains weight and value data on the product-level. Thereby, each shipment represents the transport of a certain product from a supplier to the manufacturing plant. Due to the shipment data, we were able to conduct an ABC/XYZ analysis. Following the first case study, the XYZ thresholds were set to $CV_{XY} = 0.3$ and $CV_{YZ} = 0.6$. The ABC-thresholds were set to $s_{AB} = 0.8$ and $s_{BC} = 0.9$, whereby s is the share of the cumulative value, which aligns with other articles, as shown in Table A1.

Appendix B presents figures plotting the distribution curves of the XYZ and ABC/XYZ analysis of both case studies.

5.2. Results of the Simulation Study

The simulation of each scenario assessing the 275 shipments of the first case took about 5 min, and the scenarios of the second case about 1.8 min. The high-level results of the simulation study are comprehensively visualized in Table 3, outlining the total logistics cost of the scenarios for each case study along with the GHG emissions.

Table 3. Total logistics cost and GHG emissions resulting from the three scenarios for each case study.

	Case 1		Case 2	
	Total Logistics Cost EUR	*GHG Emissions t CO_2e*	*Total Logistics Cost EUR*	*GHG Emissions t CO_2e*
ARO	321,698.21	247.25	176,436.29	153.01
ARA	304,060.61	222.59	159,717.17	120.31
URA	308,854.52	224.32	166,241.26	131.04

In both cases, the ARA scenario is the best one from an economic and an environmental perspective. In the first case, costs are reduced by 5.8% and emissions by 9.97% when shifting all possible load units by rail. In the second case, this scenario mitigates cost by 9.48% and emissions by 21.37%. This is because the supplier structure in the second case is more consolidated. This can be seen from the statistics presented in Table 2, where indications for many small shipments are given, or in the ABC/XYZ visualization in Figure A3 in Appendix B, highlighting that, for example, a single product sourced by a single supplier accounts for more than 20% of the overall weight.

Interestingly, the URA scenarios result in slightly smaller cost and emission reductions, which was somehow surprising to us. For the first case, 3.99% cost and 9.27% emission reduction; and for the second case, 5.78% cost and 14.36% emission reduction are calculated.

Inventory holding costs were not included in the first case. Upon closer examination of the second case, these costs represent 1.23% of the total expenses in the ARO scenario, 8.25% in the ARA scenario, and 5.58% in the URA scenario. The differences between ARA and URA are due to a larger number of shipments routed via intermodal transport in the ARA scenario; this leads to longer overall lead times, which results in higher inventory holding costs.

According to a research project on the EU Combined Transport, as reported in 2015, the cost breakdown for a CRRT of a semitrailer from Germany to Italy with 435 km on the main rail leg is as follows: 3% from the cost of the load unit, 15% from road pre-haulage, 19% from road post-haulage, 3% from the exporting terminal, 6% from the importing terminal, and 55% from the rail leg [84]. The simulation in this study presents higher shares for pre- and post-haulages and a lower share for the rail leg due to the long pre- and post-carriage distances covered in our simulations. Specifically, in the URA scenario of Case 1, pre-haulage and post-haulage expenditures account for 33% and 32% of the total costs, respectively. As a result, rail transport expenses are comparatively low, at only 17%. Nevertheless, the expenses for terminals and ILU closely resemble those from the empirical report, implying the authenticity and comparability of our results.

To validate the proposition made in the first part of this article, we compare the costs and emissions of the ARA and URA scenarios to the ARO scenario by calculating abatement costs on the ABC/XYZ level available. Results are presented in Table 4.

Table 4. Transportation abatement cost (EUR per mitigated t CO_2e) on the ABC/XYZ levels for the evaluated scenarios, with cost savings in green and additional costs in red.

		Case 1			**Case 2**		
		X	***Y***	***Z***	***X***	***Y***	***Z***
ARA	*A*				−874.99	15.21	−891.09
	B				−989.48	−1169.40	−1251.47
	n.a.	−1510.92	−552.97	−1411.41			
URA	*A*				−849.64	−63.24	−892.56
	B						
	n.a.	−1514.00	−513.90	123.79			

On the left side of the table, the results of Case 1 are presented in the bottom lines of the ARA and URA scenarios as financial data was not available (*n.a.*). On the right side, the results of Case 2 are presented in rows separated according to the ABC category. The absence of C items in the study can be explained using the constraints mentioned in Section 4.3. Due to the small size of C-shipments, it is not possible to utilize a 20-foot container to a sufficient level. For the URA scenario, even the B shipments are too small, as only highly utilized load units are routed intermodally.

In Table 4, we have colored the cells according to their cost-effectiveness, with the green cells representing strongly negative abatement costs—cost savings accompanying emission savings—and the red cells representing positive abatement costs—cost increases associated with emission reductions.

In Case 1, abatement costs for X- and Z- shipments are similar, while AC for Y-shipments are still negative, but three times higher. The investigation of the URA scenario for the first case highlights the differences between the dispatching strategies. While the X- and Y-shipments evaluate to similar values, costs for Z-shipments significantly differ from the ARA scenario. If the utilization of load units on the train is focused, the Z shipments cause additional costs for badly utilized fallback road transportation, which impedes higher costs and emissions at a level that raises the abatement cost to a positive value. Comparing the results of Case 1 with Case 2, abatement costs at similar levels are observed. Interestingly, the abatement costs for the Y-shipments of Case 2 are higher in ARA than in URA. Despite the otherwise relatively similar values, the comparison of the cases shows that a generalization of the absolute abatement costs is hardly possible. However, this also shows that the abatement costs do differ between the ABC/XYZ classes, which supports our initial proposition and approach presented in Section 2.

To validate the proposition, we examined the results of the simulation runs of the second case study in more detail. Therefore, we conducted Kruskal–Wallis tests for three samples (shipments of the ARA scenario, the URA scenario, and both scenarios combined) and found that there is a significant difference in the abatement costs for at least two inventory groups in all samples. Delving deeper into the pairwise comparisons of the inventory categories' abatement costs, we found that abatement costs between the inventory groups BX-AY, AZ-AY, and AX-AY significantly differ for the ARA and Total samples, and between the AX-AY and AZ-AY groups for the URA sample. The methods used for the tests are described in Appendix C. Results show that, at least across the XYZ inventory groups, abatement costs differ significantly. Investigating the boxplots in Figure A4 shows that abatement costs are highest for the Y-shipments and similar for X and Z shipments. The influence of the ABC dimension was significant only in the ARA and total sample, indicating that the influence of inventory holding costs exists, but is not decisive in most cases.

To summarize, the high-level results of the simulated cases and scenarios indicate that abatement costs do pertain to the ABC/XYZ category. Further statistical examination of the second case study showed that there is a significant difference in the abatement costs of some inventory categories. These findings let us conclude that we can partially accept the developed proposition.

6. Discussion, Implications, and Limitations

This paper's approach is twofold. In the first part, the authors provide a novel perspective on industrial logistics' decarbonization measures by combining a well-known inventory management tool with transport decarbonization measures. From these considerations, it is proposed that transport abatement costs of a specific measure differ when it is applied across the nine different ABC/XYZ inventory categories. The second part of this research validates this proposition for an exemplary mitigation measure, combined road–rail transportation, while presenting some limitations. The following sections will discuss the implications and limitations of our findings for research as well as practice.

6.1. Implications for Practitioners from Simulating Combined Road–Rail Transportation

In the CRRT simulation, the rail scenarios denoted as ARA and URA, in both evaluated cases, yield an overall reduction in cost and emissions, resulting in negative carbon emission abatement costs. Consequently, despite being suboptimal due to extended pre- and post-carriage distances, the cost-effectiveness of CRRT was demonstrated. However, a more nuanced examination of the results by the ABC/XYZ classification unveils that certain inventory categories exhibit higher costs and/or emissions compared to the reference scenario.

Other research in this field finds that overall total logistics costs can be reduced when the transportation mode is not selected holistically, but product-wise [37]. This, in turn, supports our findings that total logistics costs for one carbon mitigation measure differ across inventory categories, which, in turn, leads to different abatement costs. Further, the costs associated with inventory holding significantly contribute to the total logistics expenses, comprising 1.23% in the reference scenario and escalating to a range of 5.58% to 8.25% in the rail scenarios. Nevertheless, this does not offset the cost savings realized from the rail segment. These two observations underscore the necessity of a comprehensive assessment encompassing total logistics costs, rather than focusing exclusively on transportation costs when evaluating mitigation strategies, which is a common practice. While transportation costs constitute the predominant component for freight owners, they do not comprise the entirety. Moreover, making overarching statements about the competitiveness of CRRT is unwarranted, underscoring the imperative to diligently scrutinize each CRRT application individually due to the intricate nature of the intermodal system. Differing shares of the cost elements in our study from preceding studies [84] highlight the presence of numerous parameters that influence the costs of the intermodal system. Our results also lead to the finding that the widely referenced break-even distance definition is not universally applicable to combined transport, which was also shown in other modelling studies [49].

In the ARA scenario, costs for direct road transportation are non-zero due to the incapacity of CRRT to deliver certain Z-shipments promptly to the consignee. This discrepancy arises from the stipulated replenishment time of three days for Z-shipments. In contrast, all Y-shipments, ordered five days in advance of their required delivery, can be feasibly transported via CRRT. This underscores the criticality of accurate production demand forecasting and the implementation of distinct dispatching strategies for varied inventory categories.

Despite the elevated abatement costs of AY inventory items in the ARA scenario of Case 2, the URA scenario registers higher total costs. This is attributed to the efficiencies achieved in B-shipments in the ARA scenario, which compensate for the inefficiencies in AY-shipments. This implies that, at least within Case 2, the 80% minimum utilization threshold may be set excessively high. If this level were lowered, the cost-effectiveness of CRRT could potentially be further enhanced.

Based on the insights derived from simulating CRRT, we posit that the marked disparities observed between cases, scenarios, and inventory categories underscore the imperative, first, to evaluate the total logistics costs holistically and, second, to optimize the dispatching strategy when transitioning to CRRT. Utilization levels and replenishment times emerge as pivotal determinants in total logistics costs when employing CRRT, potentially demarcating the boundary between cost savings and additional expenditures.

6.2. Implications for Practitioners from the Validation of the Approach

Regarding the proposition made, simulation results show that GHG abatement costs vary among different shipment categories (X, Y, and Z) in the URA scenario for Case 1, but less in the ARA scenario. For Case 2, a closer statistical investigation of the abatement costs on the shipment level showed that the abatement costs significantly differ between some inventory groups. Therefore, the more crucial ABC/XYZ dimension for the abatement costs was found to be the XYZ dimension.

The primary determinant in logistics is the logistics costs. When these costs vary among different alternatives, it implies that the likelihood of implementing certain alternatives is greater than others [14,15]. However, for decision-makers utilizing our developed method, the objective is not only to maximize economic savings but also to reduce emissions. To combine these two quantitative decision criteria, abatement costs can be calculated. We have demonstrated that the cost and emission impacts of shifting freight transport from road to combined road-rail transport differ depending on the transported goods. Briefly said, from a freight owners' perspective, GHG abatement costs for intermodal transportation vary, depending on the class of the inventory being transported. The most impactful variable, thereby, is the demand characteristics (order frequency and volume), described by the demand stability of the XYZ dimension. Therefore, we see that inventory holding costs, which are affected by the ABC dimension, are a less important criterion.

Nevertheless, our findings concurrently highlight the necessity for a nuanced assessment of the applicability of combined transport for different use cases to effectively exploit potential savings. The generalized assumption of break-even distances, dispatching strategies, or costs is not feasible, even within a single company. At the same time, the economic and environmental impact of a shift towards combined transport is difficult to evaluate in detail.

Since costs differ between some of the ABC/XYZ classes, and the ABC/XYZ analysis is a straightforward and well-known measure, this study provides practitioners with an efficient method for identifying potential promising use cases for combined transport. Even though the results differ between our simulation cases, a cost-effective reduction in emissions was demonstrated for the shift of X goods in every instance. For Y goods, the statistical tests showed a higher risk for positive abatement costs, and the Z goods varied across the case studies. This insight allows for minimal effort in identifying suitable goods for combined transport and provides a starting point for CRRT newcomers, decreasing the entry barrier to the intermodal system. Therefore, this approach aids industrial enterprises in efficiently decarbonizing their logistics.

6.3. Limitations and Further Research Directions

As with every research article, there are limitations to this study which create opportunities for further research. The main limitation of this study is the requirement of using only one decarbonization measure to validate the proposed method. The primary objective for future research is to evaluate the proposition for additional decarbonization strategies and suggest the most effective measures for each of the nine inventory categories. A large volume of literature is available that recommends and categorizes decarbonization techniques (see, e.g., [20] for a comprehensive list), which can be a useful starting point for future investigations. For example, a frequently discussed measure is the use of trucks with alternative drives. It would be interesting to investigate effective application scenarios and the differences in abatement costs among ABC/XYZ items. To test for these differences, we suggest collecting real-world data from case studies that have implemented GHG mitigation measures for a broad range of inventory items or conducting simulation-based studies. The first approach may be criticized for its comparability, while the second may be questioned for its validity. Nevertheless, data availability is a crucial issue for all approaches, which is why it is recommended that research institutions collaborate closely with industrial companies to obtain realistic data.

Due to missing data, we neglect costs for damaged or stolen cargo. These have been modelled in other studies [58] and might harm CRRT's competitiveness. Although prior research indicates that CRRT is cost-competitive only when the pre- and post-haul distances are less than 40 km and the primary rail haul is no less than 750 km [75], the scenarios evaluated in this simulation are beneficial in terms of cost. Further, we have not included external costs in our study, as these do not currently have to be paid. However, a recent European study shows how dramatically different the results could be if external costs had to be paid in transportation [75].

Regarding CRRT, many different parameters can be adjusted, and many different replenishment, order, dispatching, and routing strategies can be followed. As intermodal transportation is a highly complex system, we were not able to fully test all parameters but had to make some assumptions regarding how CRRT could be conducted. Although these assumptions were discussed with other researchers and practitioners, future studies might assess the impact of a change in load unit compositions, route selection, and many more operational aspects of CRRT.

We were not able to validate the calculated figures for the mean and median of the train delay for Austria due to an absence of data. An analysis of train delays for intermodal freight services departing in Luxembourg resulted in $E = 74.35$ min and $m = 12$ min [79]. Another study found the standard deviation of freight train delays on one Swedish railway line to be $\sigma = 64.19$ min [85]. Assuming the underlying data is subject to an exponential distribution means that $E = \sigma$. Comparing our computed results, $E = 39.51$ min and $m = 27.39$ min, and with these empirical data, we see that our approximation produces smaller delay times. On the other side, an older study utilizes an average anticipated delay time of $D = 30$ min [62]. To address the ambivalence in the results, the suitability of the exponential distribution should be further researched in future studies. During the literature review on train delay times, we found that the majority of studies dealt with real-time delay prediction for passenger trains, but almost no studies presented high-level metrics for freight trains [86]. Nevertheless, for simulations like ours and logistics network planning for shippers and logistics service providers, further research on this topic could be helpful.

7. Conclusions

Throughout this study, we delineated and preliminarily validated the proposition that the ABC/XYZ analysis can be used to cost-effectively diversify industrial logistics decarbonization measures. In detail, we propose that abatement costs of a specific low-carbon practice or technology differ when applied to transport goods of different ABC/XYZ categories. For the preliminary validation, we used two simulation case studies, assessing the impact of shifting goods from road to combined road-rail transportation. Results show that abatement costs differ between ABC/XYZ categories in some scenarios, but we could not determine a common pattern across the two studies, except that X-shipments were cost-efficient in all scenarios. For a more detailed examination, we conducted a Kruskal–Wallis test to compare the abatement costs from shipments of the nine inventory categories of the second case study. Results show that there is a significant difference in the resulting abatement costs across some inventory categories, which suggests that our proposition can be accepted partially for combined road–rail transportation. Thereby, the inventories' XYZ dimension impacts abatement costs more significantly than its ABC dimension. Nevertheless, the results of our tests refer to only two case studies, which is why more research is necessary to assess additional scenarios, supplier–consignee relationships, and industrial sectors. For researchers, this study provides a promising foundation for investigating abatement costs, which are a critical component of efforts to decarbonize transportation. For practitioners, the findings of this study indicate that the makeup of a company's inventory has a significant bearing on the costs of transporting goods in an ecologically responsible manner. This is vital for making knowledgeable choices in industrial logistics and harmonizing economic effectiveness with environmental responsibility.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app132212277/s1.

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Appendix A

To analyze the freight charges, we used visualizations to examine the input data. Our investigation revealed a clear non-linear correlation between truck utilization and freight charges per tonne-kilometre. Using scikit-learn, we created a Python script to fit our data to the regressive function $y(x) = a + \frac{b}{x}$. The code we used is accessible online at https://github.com/MUL-Chair-of-Industrial-Logistics/simple_regression (accessed on 11 September 2023) and outputs $a = 0.05816489075412676$ and $b = 0.02437902515302302$. The left subplot of visualizes the regression results.

Although we anticipated an association between transportation distance and freight charges per tonne-kilometre, we failed to identify a function that accurately models this relationship with acceptable residuals. The data point distribution is displayed in the right plot of Figure A1. This could be because the transportation data available to us primarily included long-distance shipments.

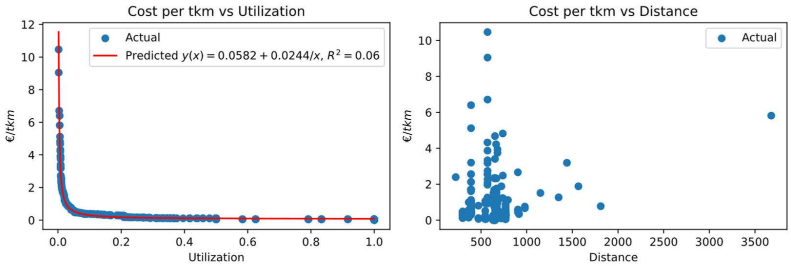

Figure A1. Graphical representation of the freight charges analysis.

Appendix B

The left plot of Figure A2 displays the characteristic curve of the XYZ-analysis plotted against the number of suppliers, while the right plot shows it against the cumulative weight.

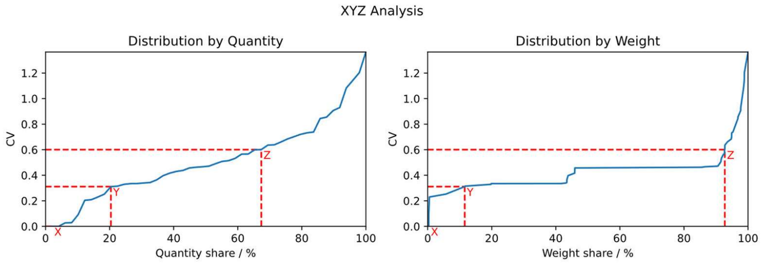

Figure A2. The characteristic curve of the XYZ analysis plotted against the number of suppliers (**left**) and the cumulative weight (**right**) for the first case study.

In Figure A3, the results of the ABC/XYZ analysis for the second case study are visualized.

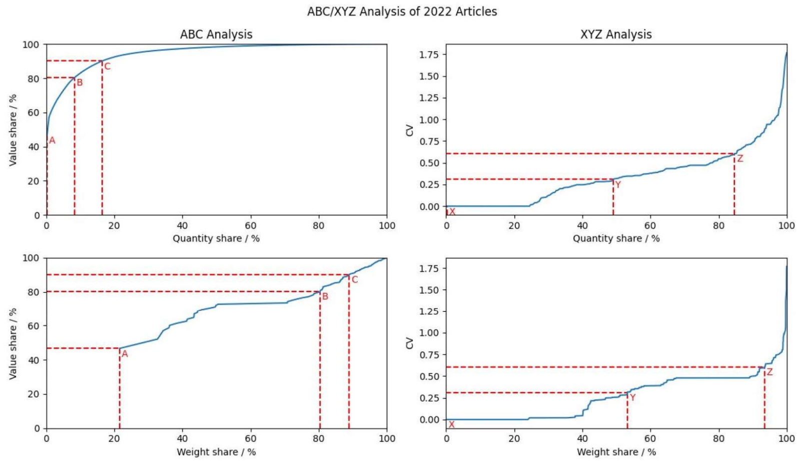

Figure A3. The characteristic curves of the ABC analysis (**left**) and the XYZ analysis (**right**) are plotted against the number of products (**top**) and the cumulative weight (**bottom**) for the second case study.

Table A1 presents the ABC/XYZ thresholds of this study in comparison to other references.

Table A1. Comparison of ABC/XYZ thresholds from the literature.

Reference	s_{AB}	s_{BC}	CV_{XY}	CV_{YZ}
This study	0.8	0.9	0.3	0.6
[16]	0.7–0.8	0.9–0.95	0.1	0.25
[38]	0.6–0.8	0.85–0.95		
[87]	0.8	0.95	0.5	1

Appendix C

To test the significance of the results, we calculated the abatement costs of each shipment shipped in the ARA and URA scenarios in the second case study. Then, we calculated the Kolmogorov–Smirnov and Shapiro–Wilk tests to test the abatement costs for normality using SPSS. We use an alpha value of $\alpha = 0.05$, which leads to a rejection of the hypothesis that the distribution of abatement costs is similar to a normal distribution. The results of the test for the shipments of the URA scenario, the ARA scenario, and both shipment data combined are presented in Table A2.

Table A2. Normality tests.

	Kolmogorov–Smirnov [a]			Shapiro–Wilk		
	Statistics	df	Sig	Statistics	df	Sig
abatement_cost_ara	0.209	55	<0.001	0.866	55	<0.001
abatement_cost_ura	0.267	32	<0.001	0.776	32	<0.001
abatement_cost_total	0.229	87	<0.001	0.852	87	<0.001

[a] Significance correction according to Lilliefors.

Due to the non-normality of the sample, we selected the Kruskal-Wallis – test for further investigation [88]. The test determines if all populations of one sample are identical [89]. In the focal case, the null hypothesis is that abatement costs are identical across the inventory categories, which implies that the alternative hypothesis is that abatement costs differ across inventory categories. Again, the alpha value was set to $\alpha = 0.05$. For all three samples (ARA shipments, URA shipments, and both shipments combined), the null hypothesis was rejected, and the alternative hypothesis was accepted, meaning that a statistically significant difference was found between at least two groups in all samples. Test results are displayed in Table A3.

Table A3. Kruskal–Wallis to test the null hypothesis.

	Kruskal–Wallis			
	Chi-Square	df	Sig	H
ARA	38.429	5	<0.001	reject
URA	19.176	2	<0.001	reject
Total	58.644	5	<0.001	reject

The pairwise group comparisons of the ARA and Total sample show significant differences ($sig < \alpha$) between the groups BX-AY, AZ-AY, and AX-AY. The group comparison of the URA scenario shows significant differences between the groups AX-AY and AZ-AY. These results are visualized in the boxplots shown in Figure A4, whereby SPSS visualizes outliers by circles (difference to 1st or 3rd quartile > 1.5 * interquartile range) and extreme outliers by asterisk (difference to 1st or 3rd quartile > 3 * interquartile range).

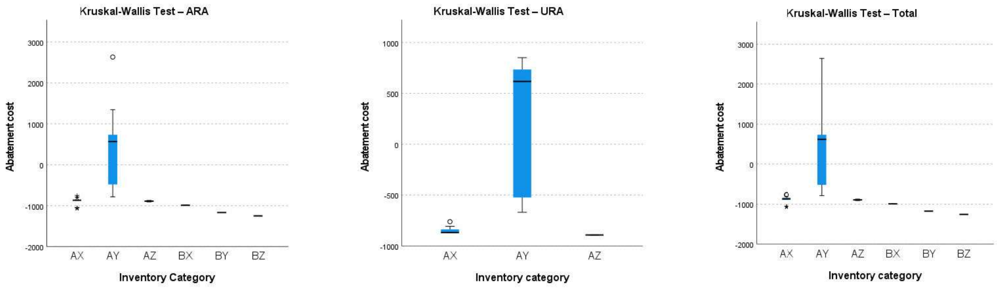

Figure A4. Boxplots of the abatement cost results for the ARA, URA and Total samples (left to right).

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9.10. CRediT Author statement

Table 2 clarifies the author contributions to the publications mentioned in Section 4 in line with CRediT. Further, Table 3 presents the authors' contribution to the bachelor and master theses which have been discussed in Section 5.

Table 2. CRediT author contribution statements of the publications (PM: Philipp Miklautsch, MW: Manuel Woschank, AK: Alexander König, JS: Joseph Sarkis, MH: Mario Hoffelner, BZ: Bernd M. Zunk, JH: Julia Heißenberger, NO: Nadine Olipp, GE: Gregor Enthaler)

CRediT term	CRediT definition	Paper 1	Paper 2	Paper 3	Paper 4	Paper 5	Paper 6	Paper 7	Paper 8	Paper 9
Conceptualization	Ideas; formulation or evolution of overarching research goals and aims	PM	PM, BZ	PM	PM, JS	PM	PM	PM, JH	PM	PM, MH
Methodology	Development or design of methodology; creation of models	PM, MW	PM, MW	PM, MW	PM, MW	PM, MW	PM	PM	PM	PM, MH
Software	Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components						PM	PM	PM	PM, MH
Validation	Verification, whether as a part of the activity or separate, of the overall replication/reproducibility of results/experiments and other research outputs						PM, ADW	PM, JH	PM	PM, MH
Formal analysis	Application of statistical, mathematical, computational, or other formal techniques to analyse or synthesize study data	PM	PM	PM, MW	PM	PM			PM	PM
Investigation	Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection	PM	PM, AK	PM	PM	PM, GE			PM	
Resources	Provision of study materials, reagents, materials, patients, laboratory samples, animals, instrumentation, computing resources, or other analysis tools							JH		
Data curation	Management activities to annotate (produce metadata), scrub data and maintain research data (including software code, where it is necessary for interpreting the data itself) for initial use and later re-use			PM					PM	PM, MH
Writing – original draft	Preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation)	PM	PM, AK	PM	PM	PM, JS	PM	PM	PM	PM
Writing – review and editing	Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre- or post-publication stages	PM, MW	PM, AK, MW	PM, MW	PM	tbd		PM	PM	PM, MW, MH, NO
Visualization	Preparation, creation and/or presentation of the published work, specifically visualization/data presentation	PM	PM, AK	PM	PM	PM	PM	PM	PM	PM
Supervision	Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team	MW	MW	MW	MW	MW, JS	MW	MW	MW	MW
Project administration	Management and coordination responsibility for the research activity planning and execution	PM	PM	PM	PM	PM	PM	PM	PM	PM
Funding acquisition	Acquisition of the financial support for the project leading to this publication	PM	PM	PM	PM	PM	PM	PM	PM	MW

Table 3. CRediT author contribution statements of the theses (PM: Philipp Miklautsch, MW: Manuel Woschank, MH: Mario Hoffelner, LJ: Lara Jöbstl, KD: Konstantin Karl Dallago, NO: Nadine Olipp, HK: Hana Kostolanska, JH: Julia Heißenberger (SiloRiedel), GE: Gregor Enthaler, CR: Chiara Raith, UR: Ulrike Elisabeth Roth)

CRediT term	**CRediT definition**	**BA Jöbstl**	**MA Pachteu**	**BA Lechmann**	**BA Dallago**	**MA Olipp**	**MA Kostolanska**	**MA Hoffelner**	**BA Enthaler**	**BA Roth**
Conceptualization	Ideas; formulation or evolution of overarching research goals and aims	PM	PM, SP	PM, ML	PM	PM, NO	PM, HK, MW, JH	PM, MH	PM, GE	PM, CR
Methodology	Development or design of methodology; creation of models	PM, LJ	PM, SP	PM, ML	PM, KD	PM, NO	PM, HK, MW	PM, MH	PM, GE	PM, CR, UR
Software	Programming, software development; designing computer programs; implementation of the computer code and supporting algorithms; testing of existing code components		PM, SP					PM, MH		
Validation	Verification, whether as a part of the activity or separate, of the overall replication/reproducibility of results/experiments and other research outputs		SP					MH		
Formal analysis	Application of statistical, mathematical, computational, or other formal techniques to analyse or synthesize study data									
Investigation	Conducting a research and investigation process, specifically performing the experiments, or data/evidence collection	LJ	PM, SP	ML	KD	NO	HK	MH	GE	UR

Table 3 (continued)

Resources	Provision of study materials, reagents, materials, patients, laboratory samples, animals, instrumentation, computing resources, or other analysis tools						JH	PM		
Data curation	Management activities to annotate (produce metadata), scrub data and maintain research data (including software code, where it is necessary for interpreting the data itself) for initial use and later re-use								GE	
Writing – original draft	Preparation, creation and/or presentation of the published work, specifically writing the initial draft (including substantive translation)	LJ	SP	ML	KD	NO	HK	MH	GE	UR
Writing – review and editing	Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre- or post-publication stages	LJ, PM	SP, PM	ML, PM	KD, PM	NO, PM	HK, PM, MW	MH, PM	GE, PM	UR, PM
Visualization	Preparation, creation and/or presentation of the published work, specifically visualization/data presentation	LJ	SP	ML	KD	NO		MH	GE	UR

Table 3 (continued)

Supervision	Oversight and leadership responsibility for the research activity planning and execution, including mentorship external to the core team	PM	PM, MW	PM	PM	PM, MW	PM, MW	PM, MW	PM	PM, CR
Project administration	Management and coordination responsibility for the research activity planning and execution		PM			PM	MW	PM		
Funding acquisition	Acquisition of the financial support for the project leading to this publication		PM			PM	MW	PM	PM	