1 Introduction

1.1 Motivation and Background

Logistics processes typically involve a high number of resources and activities which have a substantial impact on the sustainability performance of an organization. The most relevant logistics activity with the highest impact on sustainability is without a doubt transportation (Bretzke, 2011). As a matter of fact, the transport sector is one of the highest energy consuming and highest emission causing sectors (European Commission, 2011). However, the transport sector is key to delivering economic growth. Recent changes in customers' expectations have shown significant changes in consumer behavior. Services such as same-day-deliveries and free return of goods have become natural prerequisites in e-commerce (Morganti *et al.*, 2014). In B2B relations, just-in-time or even just-in-sequence deliveries have become common practice in specific industries such as automotive (Battini *et al.*, 2013). These developments result in growing freight volumes which have to be managed by logistics. Figure 1.1 shows the trend of increasing freight volumes. It can be seen that current freight volumes are considerably higher than two decades ago. Figure 1.1 also illustrates the modal split of freight transport at intra-EU level, where road transport has the highest share at slightly more than 50%, followed by a relatively high share of maritime transport (30%). In inland freight transport, the share of road transport is even higher, at around 75% (European Commission, 2019). This means that three quarters of the inland freight transport is carried out on roads, thus leaving a significant environmental footprint.

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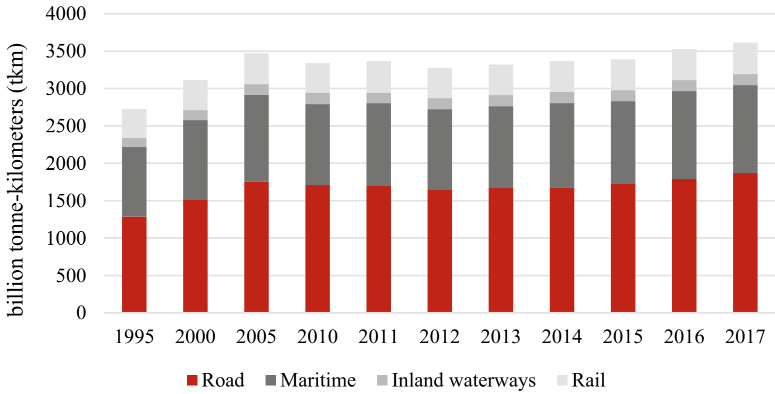

Figure 1.1 Freight transport volume and modal split within the EU. (data from European Environment Agency, 2019a)

It is projected that the environmental problems will even continue to grow within the next decades; in particular the share of road transport is predicted to rise further (McKinnon *et al.*, 2015). This is critical because road transport causes a lot of negative effects compared to other transport modes, not only emissions, but also other external costs such as noise, congestion or accidents. Figure 1.2 summarizes the external costs of road transport, rail transport and inland waterway transport. The external costs of road transport amount to 2.01 cent per ton-kilometer and thus are substantially higher than the external costs of railway transport (0.80 cent per ton-kilometer) and inland waterways (0.27 cent per ton-kilometer).

In view of these statistics and recent developments, it becomes evident that measures have to be taken to counteract the negative environmental performance of freight transport. For quite a long time, governments all over Europe have recognized the environmental harm of the transport sector and have committed themselves towards sustainable development as a policy goal. This has resulted in a vast number of national and international strategies, environmental conventions as well as regional development programs (Howes *et al.*, 2017). On the global level, the Paris Agreement (UNFCCC, 2016) was a key milestone for world-wide climate policy. The Paris Agreement was adopted by the United Nations Framework Convention on Climate Change (UNFCCC) at the Paris climate conference (COP21) in December 2015. It is the first binding agreement that sets a specific

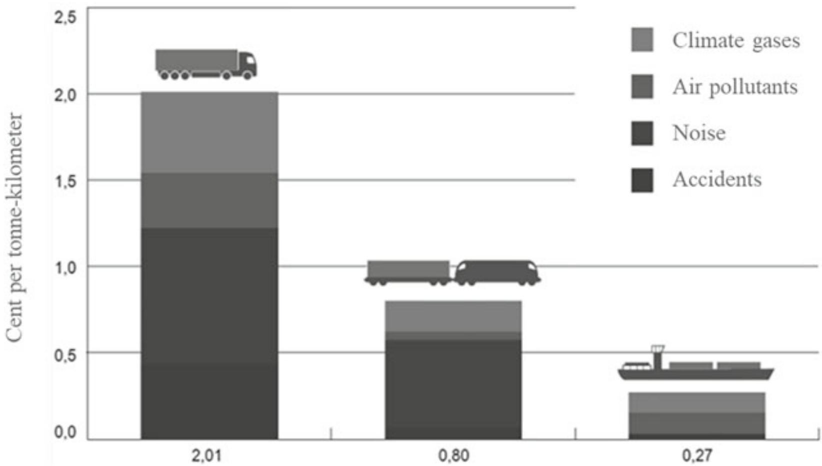

Figure 1.2 Sum of external costs for different transport modes. (average values for selected transports of bulk goods, via donau, 2019)

limit for global warming. The aim is to combat climate change by keeping global warming to well below 2 °C (UNFCCC, 2016). Compared to the preceding Kyoto Protocol, the Paris Agreement is an important step forward as it involves the commitment of 195 contractual parties. The Kyoto Protocol only targeted industrial countries (and only those which ratified the convention).

In accordance with the Paris Agreement, each party has to set measures to comply with the climate targets. Europe has taken a leading role as it aims to become the first climate-neutral continent. For that purpose, the European Green Deal was released, which provides an ambitious action plan to ensure that there are no net emissions of greenhouse gases by 2050. The action plan includes measures to facilitate the efficient use of resources by advancing towards a circular economy. Biodiversity should be restored and emissions should be cut. It is intended to convert the political commitment into a legally binding obligation to ensure that the Green Deal does not turn into empty promises. A proposal for a European Climate Law (COM(2020) 80 final) has been developed, which aims to write into law the goal to become the first climate-neutral continent. The law involves measures to keep track of progress and enables the adjustment of actions to reach the targets. In accordance with the global stock take exercise set out in the Paris Agreement, progress should be analyzed every five years.

To realize the goals of the European Green Deal, transport emissions will need to be reduced dramatically. This is a challenging task since global transport demand is predicted to triple by the year of 2050, which would result in twice as many carbon emissions (International Transport Forum, 2019). An ambitious roadmap published by the European Technology Platform ALICE suggests a framework to reduce all logistics-related emissions to zero by 2050 (Punte *et al.*, 2019). Efficiency gains should be leveraged to better use transport capacities and increase the productivity of the whole freight system. The deployment of sustainable vehicle technologies should additionally support the decarbonization of freight transport (Punte *et al.*, 2019). The ALICE roadmap towards zero emission logistics is indisputably an important step towards green and sustainable future logistics. However, it remains unclear whether the measures suggested in this roadmap will be accepted and enforced by the relevant stakeholders.

1.2 Research Gap and Objectives

Despite the intense political endeavors described above, the environmental performance of the transport system has not improved so far (Islam *et al.*, 2016; European Commission, 2019). It seems that existing measures are not sufficient to motivate transport users to implement sustainable freight transport strategies. To set measures which efficiently encourage the introduction of sustainable freight transport, the demand for and acceptance of sustainable freight transport must be understood. Without transport users' demand for environmental transport practices, sustainable freight transport will fail (Lindholm and Blinge, 2014). It is therefore important that policy measures address the needs of transport users and promote their demand for sustainable freight transport.

Many different alternatives exist to realize sustainable freight transport, but studies on the demand for these alternatives are scarce. In the course of this thesis, three sustainable freight transport strategies will be discussed in detail. These three strategies are horizontal collaboration in a Physical Internet (PI) network, multimodal freight transport and Liquefied Natural Gas (LNG) as alternative fuel. Each of these three strategies contributes in a different way to the goal of reducing greenhouse gas emissions from freight transport. Horizontal collaboration aims to avoid transport by enabling the bundling of transport streams and by increasing the utilization of transport capacities. Multimodal transport aims to shift freight to sustainable transport modes. And finally, LNG is a technological solution which aims to improve the environmental impact of road transport.

Considerable research has already been conducted on each of these three sustainable freight transport strategies. However, the majority of publications focus on the *supply* of these three sustainable strategies. The following Table 1.1 gives an overview of supply-related literature on the three strategies.

Table 1.1 Studies on the supply of sustainable transport strategies

Sustainable transport strategy	Supply-related topics covered in the literature	References
Horizontal collaboration & transport bundling in a PI network	Design and use of containers in the PI network: standardization, modularization, handling cost, intelligent containers,…	Hofman *et al.* (2016), Sallez *et al.* (2015), Landschützer *et al.* (2015), Lin *et al.* (2014)
	Inventory problems in the PI network: optimized inventory levels, warehousing services, reduced inventory costs, maximized utilization,…	Ji *et al.* (2019), Yang *et al.* (2017), Darvish *et al.* (2016), Pan *et al.* (2015)
	Distribution and transport in the PI network: network optimization, optimized routing, loading patterns, truck scheduling,…	Chargui *et al.* (2020), Ji *et al.* (2019), Gontara *et al.* (2018), Fazili *et al.* (2017), Tran-Dang *et al.* (2017), Venkatadri *et al.* (2016), Walha *et al.* (2016)
	Dynamic pricing and auction trading in the PI network	Qiao *et al.* (2019), Qiao *et al.* (2018), van Riessen *et al.* (2017), Kong *et al.* (2016)
Multimodal freight transport	Multimodal transport terminals: Hub location, hub design,..	Osorio-Mora *et al.* (2020), Li and Wang (2018),Kumar and Anbanandam (2019), Karimi and Bashiri (2018)
	Multimodal transport scheduling: optimum routing, transshipment, time constraints,…	Abbassi *et al.* (2019), Wolfinger *et al.* (2019), Layeb *et al.* (2018), Ghaderi *et al.* (2016), Le Li *et al.* (2015)
	Multimodal pricing: cost allocation and pricing schemes,….	Zheng *et al.* (2016), Kordnejad (2014), Shi and Li (2010)
LNG as an alternative fuel	Vehicle technology: pressure of LNG vehicles, vehicle design,…	Yonggang *et al.* (2013), Shangbing (2009), Wiens *et al.* (2001)

(continued)

Table 1.1 (continued)

Sustainable transport strategy	Supply-related topics covered in the literature	References
	Fueling systems: tank technology, refueling station design,…	Deng *et al.* (2019), Zhou (2011), Xiaodong and Wang Shunhua (2009), Xie *et al.* (2007), Chen *et al.* (2004)
	Safety in LNG operations: safety at storage facilities,..	Aneziris *et al.* (2020), Li (2019), Zhu (2011), Chun (2010)
	Lifecycle analyses of LNG applications	Langshaw *et al.* (2020), Xunmin (2019), Song *et al.* (2017), Arteconi *et al.* (2010)

As can be seen in Table 1.1, a multitude of topics associated with the supply of sustainable freight transport is covered by the literature. The literature on PI indicates how to design and use containers in the PI, how to solve inventory problems in the PI, how to optimize distribution and transport and how to price PI services. All of these topics are important for the supply of PI services. Similarly, the multimodal literature supports multimodal terminal design, multimodal transport scheduling and multimodal pricing. Again, these questions are related to the supply of multimodal services. And finally, the LNG literature specifies the LNG vehicle technology, fueling systems, safety in LNG operations and it provides lifecycle analyses—all of which is relevant to supply LNG.

All of the topics listed in Table 1.1 are undoubtedly important for the provision and implementation of sustainable freight transport. However, these topics mostly neglect the transport users' perspective and needs. As explained above, sustainable freight transport will not be implemented without transport users' demand to do so. As a matter of fact, studies on transport users' demand of the aforementioned three sustainable freight transport strategies are scarce. Kim *et al.* (2017) was critical about the fact that few studies consider the relationship between demand-side characteristics and the choice of transport services. Perboli *et al.* (2017) deal with horizontal logistics collaboration (synchromodality, a preliminary stage of PI) and find that existing literature is very much focused on the technical, ICT and optimization issues. This finding was confirmed by Pfoser *et al.* (in press), where a comprehensive literature review of 85 publications on synchromodality was conducted. Out of these 85 publications, hardly any study focuses on demand-side questions of horizontal logistics collaboration. Literature reviews on multimodal freight transport come to the same conclusion. SteadieSeifi *et al.* (2014) and Agamez-Arias and Moyano-Fuentes (2017) clearly show that multimodal literature predominantly deals with multimodal freight transportation planning, i.e. the optimization of multimodal service supply. Finally, the same can be said for LNG as an alternative fuel. Osorio-Tejada *et al.* (2017, p. 790) write that "the main difficulties for the deployment of LNG-fueled trucks are market related". Further research is therefore needed to evaluate the requirements of the market and the demand conditions for LNG.

The excessive focus on technological and supply-related questions of sustainable freight transport bears the risk of designing services and concepts which are not matching with the industrial needs (Perboli *et al.*, 2017). As illustrated above, there is a clear lack of market-related research on the demand for sustainable freight transport. This thesis contributes to the larger body of literature by providing insights into the demand for sustainable freight transport. The acceptance of an innovation is an important precondition and first step of the demand for this innovation (Dillon and Morris, 1996). Since many strategies for sustainable freight transport are in an early development stage, acceptance of these strategies must emerge before they can find widespread application and demand (McKinnon, 2018). The thesis therefore aims to analyze the determinants of sustainable freight transport acceptance. The intention is to understand acceptance in order to be able to propose measures to influence acceptance (and finally demand) for sustainable freight transport. Knowing the determinants of acceptance allows the design of measures which attract transport users to implement sustainable freight transport and help decarbonize logistics.

Based on the research gap described above, two main objectives can be derived for this thesis (Figure 1.3). The first objective is to analyze the determinants of transport users' sustainable freight transport acceptance. The second objective is to develop user-centric policy measures which promote the implementation of sustainable freight transport.

Both objectives of this thesis aim to advance the diffusion of sustainable freight transport. The objectives refer to different steps in the innovation diffusion process described by Reusswig *et al.* (2004) (see Figure 1.3): the first objective is related to the acceptance step which involves users' demand for sustainable freight transport. While many authors claim to have measured acceptance (see list of acceptance studies later in Section 5.1.3), they barely deliver a profound understanding of what actually influences acceptance and what leads to increased acceptance (Adell *et al.*, 2018). It is therefore an important contribution of this thesis to deliver an understanding of users' profound needs and requirements towards the introduction of sustainable freight transport. The second objective is related to the implementation step since the developed policy measures target

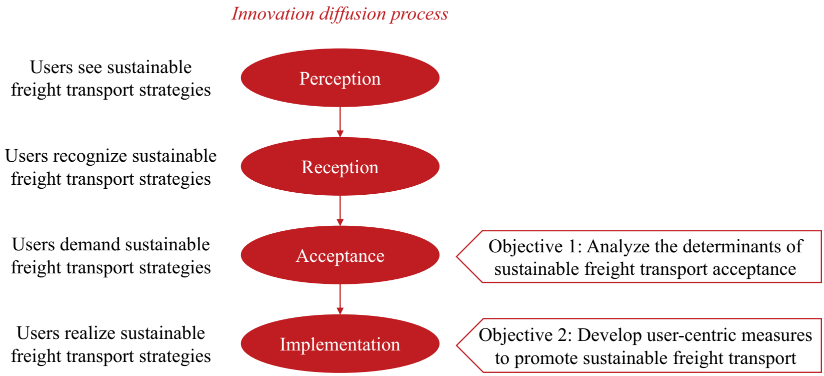

Figure 1.3 Innovation diffusion process and related objectives of the thesis. (own illustration based on Reusswig *et al.*, 2004)

the implementation of sustainable freight transport. The development of policy measures is based on the previously defined determinants of sustainable freight transport acceptance. According to Mattauch *et al.* (2016), demand-side regulations have been recommended to be effective by transport research for a long time. Therefore, the acceptance for sustainable freight transport will be analyzed in this thesis to develop measures which precisely address the requirements of the demand side. To summarize, the overall motivation of this thesis is to encourage the diffusion of sustainable freight transport by gaining an understanding for the acceptance of sustainable freight transport and suggesting suitable policy measures.

1.3 Structure and Research Questions

In this thesis, three different strategies for sustainable freight transport are under investigation, namely (1) horizontal collaboration in a PI network (2) multimodal freight transport and (3) LNG as an alternative fuel. Each of the three strategies falls within another pillar of the common ASI (avoid-shift-improve) framework. The ASI framework is widely used to structure strategies for sustainable transport. The fact that this thesis covers all three ASI pillars allows the comparison of the similarities and differences that exist between the different types of strategies.

As stated above, the objective of the thesis is first to study the acceptance of three specific sustainable freight transport strategies, and then develop policy measures which promote sustainable freight transport. The cases of the three sustainable freight transport strategies (PI collaboration, multimodality, LNG) were studied in detail within different research projects where the author of this thesis was involved in recent years. The findings of the three cases reveal the determinants of acceptance and policy measures to promote the three strategies for sustainable freight transport. These findings are summarized in various publications, which form the basis of this cumulative thesis (Figure 1.4). The aim of the present manuscript is to juxtapose the results of the individual publications and evaluate the patterns among the three strategies. This results in a list of overarching determinants which influence the acceptance of sustainable freight transport in general as well as overarching policy measures which are suitable to promote sustainable freight transport in general.

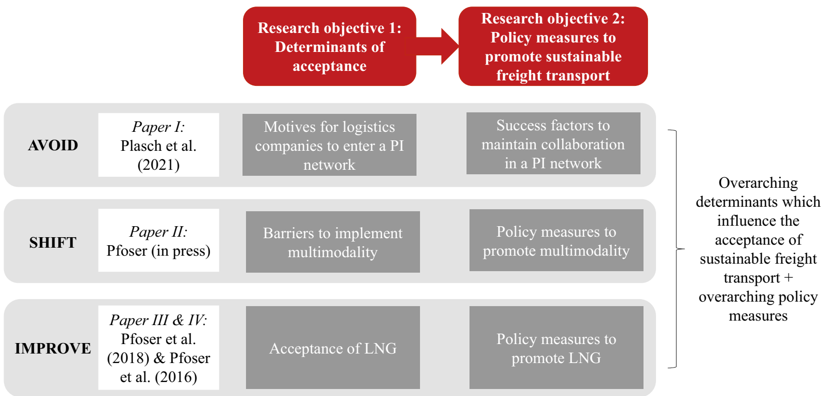

Figure 1.4 Structure of the thesis

The four papers contribute to answer the research questions underlying this thesis. The first research question aims to explain why PI collaboration, multimodality and LNG have been chosen as sustainability strategies under investigation in this thesis:

RQ 1: Which sustainable freight transport strategies exist to reduce the negative environmental impact of freight transport?

RQ 1 will be answered in Chapter 4 "Strategies for sustainable freight transport". Here, an introduction of the ASI-framework will be given to present a classification of sustainable freight transport strategies. Afterwards, three particular strategies (each representing a different ASI pillar) will be introduced in detail. As mentioned above, these three strategies are horizontal collaboration in a PI (avoid pillar), multimodality (shift pillar) and LNG as an alternative fuel (improve pillar).

The subsequent second research question refers to the acceptance of the three sustainable freight transport strategies under investigation in this thesis and contains three sub research questions:

RQ 2: Which determinants influence the acceptance of sustainable freight transport strategies?

RQ 2.1: Which motives support the acceptance of horizontal collaboration in a PI network?

RQ 2.2: Which barriers prevent the acceptance of multimodal freight transport?

RQ 2.3: Which determinants influence the acceptance of LNG as an alternative fuel?

The three sub research questions are answered in the four papers which constitute this thesis. Plasch *et al.* (2021) [Paper I] analyze the motives to enter horizontal collaboration in a PI network. These motives are defined as the reasons which encourage logistics companies to become part of the PI network. The motives determine the demand for PI collaboration, and as such they represent the determinants of PI acceptance (RQ 2.1). Pfoser (in press) [Paper II] evaluates the barriers to multimodal freight transport. Detailed insights into logistics companies' considerations of multimodality are given. From these insights, conclusions can be drawn about the determinants of multimodal freight transport acceptance to answer RQ 2.2. Pfoser *et al.* (2018d) [Paper III] show the determinants of LNG acceptance, which answers RQ 2.3. Additional insights about the acceptance of LNG are included from another paper, namely Pfoser *et al.* (2016a) [PAPER IV]. In Subchapter 3.3 "Determinants of sustainable freight transport acceptance", the results of the sub research questions 2.1 – 2.3 are merged to answer the overarching RQ 2 and summarize the determinants of sustainable freight transport acceptance.

Assuming rational behavior of decision makers, sustainable freight transport strategies should be used much more than it is currently the case since they increase the efficiency (as they decrease the emissions) of the whole logistics system (McKinnon *et al.*, 2015). The hesitant use of sustainable strategies suggests that market failures exist which distort the acceptance of sustainable strategies at present (Engel and Saleska, 2005; Sinnandavar *et al.*, 2018). The third research question will therefore examine:

RQ 3: Which market failures currently distort the acceptance of sustainable freight transport?

RQ 3 will be answered in Subchapter 4.3 “Market failures in sustainable freight transport”. A number of market failures will be presented which result from the empirical investigation in this thesis. These market failures represent a relevant basis for the development of policy measures since policy measures should target the elimination of the market failures (Pindyck and Rubinfeld, 2013).

The fourth and final research question comes along with three sub research questions to develop policy measures for sustainable freight transport:

RQ 4: Which policy measures promote the implementation of sustainable freight transport strategies?

RQ 4.1: Which success factors promote the implementation of PI networks?

RQ 4.2: Which policy measures promote the implementation of multimodal transport?

RQ 4.3: Which policy measures promote the implementation of LNG as an alternative fuel?

Again, the three sub research questions are answered in the three papers which constitute this thesis. Plasch *et al.* (2021) [Paper I] elaborate success factors for horizontal collaboration in a PI network. Success factors represent requirements needed to collaborate continuously in the PI network. If the success factors are not present, the partners will leave (or not even join) the PI network. Therefore, measures can be derived on how to establish the required success factors (RQ

3.1). Pfoser (in press) [Paper II] develops policy measures to facilitate multimodal freight transport (RQ 3.2). Pfoser *et al.* (2018d) [Paper III] present policy measures to promote LNG as an alternative fuel (RQ 3.3). In the present manuscript, the results of the sub research questions 3.1 – 3.3 are merged to answer the overarching RQ 3 and summarize the policy measures for sustainable freight transport acceptance.

1.4 Outline

The remainder of this thesis is organized as follows: Chapter 2 gives the conceptual background for this thesis. It will be defined what acceptance means in the context of sustainable freight transport. Furthermore, the prevalent typology to classify policy measures for sustainable freight transport is presented. Chapter 3 describes the research design of this thesis. Chapter 4 introduces the ASI (avoid-shift-improve) framework and gives an overview of existing strategies for sustainable freight transport. In particular, the three strategies chosen as subject of this thesis (PI, multimodality, LNG) will be presented and differentiated from similar concepts. It will be justified why these three particular strategies have been chosen as subject of this thesis.

Chapter 5 discusses the acceptance of sustainable freight transport strategies. First, the theoretical foundation of sustainable freight transport acceptance will be given. Finally, the acceptance of horizontal collaboration in a PI network, the acceptance of multimodal freight transport, and the acceptance of LNG as an alternative fuel are compared and the overarching determinants for the acceptance of sustainable freight transport are derived.

Chapter 6 presents policy measures to promote sustainable freight transport. First, a theoretical framework is developed to support the development of policy measures. This is followed by an overview of market failures in the sustainable freight transport market to point out which problems have to be addressed by the policy measures. Finally, policy measures for horizontal collaboration in a PI network, multimodal freight transport, and for LNG as an alternative fuel are compared and overarching policy measures to promote the acceptance of sustainable freight transport are suggested.

The concluding Chapter 7 closes this thesis with a synthesis of results, responses to the research questions, a presentation of the contributions to the domain of sustainable freight transport and a short outlook with some suggestions for future research.