

Integration of Inland Waterway Transport in the Intermodal Supply Chain: a Taxonomy of Research Challenges

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HIGHLIGHTS

- Research challenges related to geographical and territorial evolutions are proposed.
- Research is needed to increase the operational efficiency of inland waterway transport.
- Intermodal transport decisions need to be integrated with supply chain decisions.
- A fourth group of research challenges concerns external cost calculations.
- All outlined research tracks call for detailed freight data.

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ABSTRACT

This paper identifies research opportunities which will enable the further integration of inland waterway transport in the intermodal supply chain. Intermodal transport may be interpreted as a chain of actors who supply a transport service. Inland navigation can play a crucial role in increasing supply chain service performance. A first group of research challenges lies in the evolving relationship between transport geography and logistics activities. The next set of research challenges has the objective to encourage efficient operations in IWT: development of a system wide model for IWT, integration of operational planning systems and analysis of bundling networks. A third group of research efforts is directed towards shippers and consignees who use the intermodal transport chain to send or receive their goods: further development of models that integrate intermodal transport decisions with supply chain decisions and creation of green supply chains. A fourth cluster of research challenges concerns the problem domain of external cost calculations. Finally detailed time series data on freight transport should be collected to support these future research tracks.

KEYWORDS

Intermodal transport, inland navigation, research challenges, integration, supply chain

1 INTRODUCTION

Policy makers at European as well as regional levels express the need to stimulate inland waterway transport (IWT) as part of the intermodal transport chain (European Commission, 2011). A growing market share for intermodal transport should mean a shift towards more environmental friendly transport modes, less congestion and a better accessibility and opening-up of the seaports. The promotion of IWT is a long-term priority to achieve a sustainable transport system in Europe. Currently, inland waterway transport plays an important role in the hinterland connectivity of major seaports in Western-Europe. However, recent years show a stagnating tendency in freight transport by inland waterways in Europe (see e.g. Figure 1). Further investments and research efforts are needed to enhance the modal share of inland waterway transport. This is for instance underlined by the NAIADES action programme (Navigation and Inland Waterway Action and Development in Europe), which was launched by the EU in 2006 (European Commission, 2006). The NAIADES II programme (European Commission, 2013) aims at further enhancing the quality of inland waterway transport. A high quality transport mode is according to their definition well-

governed, efficient, safe, integrated into the intermodal chain, with quality jobs occupied by a skilled workforce, and adhering to high environmental standards.

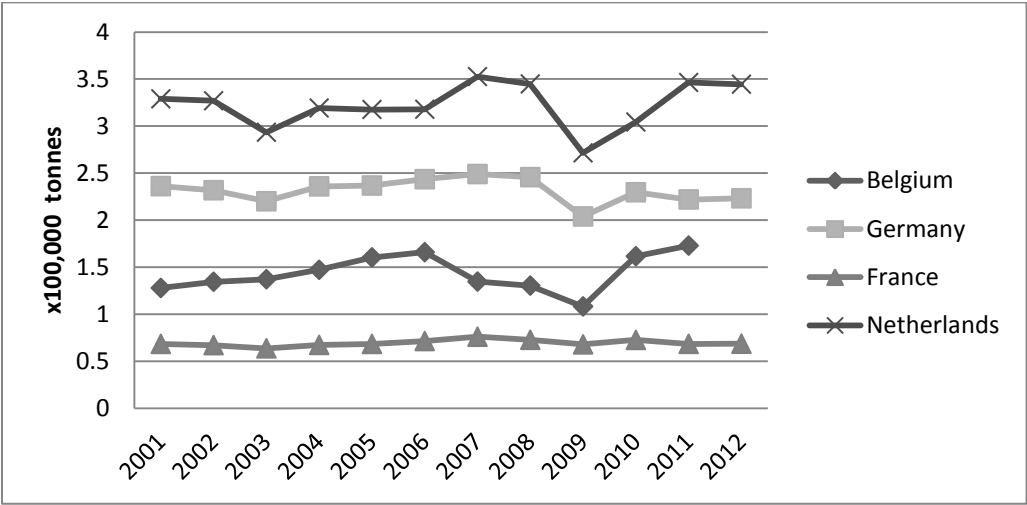


Figure 1: Goods transport by inland waterways in Europe (Figures for the four EU member states that have the highest amount of good transport in terms of thousands of tonnes) (Eurostat, 2013).

In this paper we identify research opportunities which will enable the further integration of inland waterway transport in the intermodal supply chain. As intermodal transport involves the transportation of goods in a single loading unit, meaning goods are not transferred between loading units during the intermodal journey, inland waterway transport of bulk goods is not considered in this paper. Furthermore, we focus on the characteristics of intermodal waterway transport in Europe. A comparison between North American and European gateway logistics is provided by Rodrigue and Notteboom (2010).

Intermodal transport may be interpreted as a chain of actors who supply a transport service. Inland navigation can play a crucial role in increasing supply chain service performance. Actors potentially involved in the transport chain are shippers, road hauliers, terminal operators, barge operators, waterway operators and consignees. The numerousness and variety of stakeholders demand for purposive actions to smoothen the intermodal supply chain. For the following seven topics, necessary future research efforts are proposed which may support the integration of inland navigation in the intermodal supply chain. These seven research topics are selected as follows.

First, the geographical and territorial context plays a significant role in the organisation and development of intermodal barge transport. Therefore, section 2 elaborates on the evolving relationship between transport geography and logistics activities. Changes in distribution networks are linked with supply chain decisions. Inland waterway terminals are taking up a

more active role in supply chains. Also the integration of IWT in urban freight transport networks is addressed.

The next three sections deal with research proposals to increase the operational efficiency of IWT. These research challenges aim to support barge operators, terminal operators, waterway operators and port authorities in their operations. Increasing the operational efficiency will remove practical barriers (such as time constraints) for shippers to make use of intermodal barge transport and will result in a smooth flow offering an attractive alternative for unimodal road transport. In order to improve the operational efficiency of IWT in the intermodal supply chain, the effect of operational measures need to be estimated for the network as a whole, instead of studying isolated parts (such as locks, inland terminals and port operations). Section 3 thus points out the need for a system wide model for IWT.. Such a model will allow analysing the network-wide impact of synchronization efforts, of congestion measures and of alternative priority rules and lock planning algorithms for IWT. As described in section 4, a large opportunity to increase the operational efficiency also lies in the integration of planning systems applied in IWT operations. An integration of operational planning methods may increase the efficiency of the overall IWT network and may lead to a higher service level due to possible time savings. For example lock planning and quay handling should be tuned to another so as to achieve a smooth flow of barges in the port area. A third research topic aimed at increasing the operational efficiency of intermodal barge transport is the analysis of bundling networks (section 5). Bundling freight of multiple shippers or inland terminals offers the opportunity to achieve economies of scale and thus boost the competitiveness of intermodal barge transport. Operational efficiency is also increased as inland vessels with bundled freight will arrive in the port area with larger call sizes per terminal and with a reduced number of stops.

A next group of research efforts is directed towards shippers and consignees who use the intermodal transport chain to send or receive their goods. Section 6 discusses integrated models developed for the analysis of supply chains involving inland waterways. Although research attention for intermodal transport has grown considerably in the last decades (see e.g. Caris et al., 2013), only few papers address the issue of integrating intermodal transport in the supply chain. SC efficiency may be supported through extensive coordination, whereby each stage of the chain minds the impact of actions on all others. An example of such coordination mechanisms are models aimed at integrating production and distribution decisions. A joint optimization of transport and supply chain decisions may convince shippers to use intermodal waterway transport. Section 6 further discusses intermodal waterway transport in light of green supply chain management. Green supply chain management integrates environmental thinking into supply chain management. Transportation is the most visible part of a supply chain in terms of environmental friendliness. However, an environmental friendly transport mode such as IWT will only be chosen by a shipper if it fits well in his supply chain.

Section 7 focuses on the calculation of external costs for IWT. A major argument often used at policy levels for promoting the integration of IWT in intermodal supply chains is the claim that it is a more environmentally friendly and in general a more sustainable transport mode than road transport. However, as technological innovations are incorporated faster in road

transport vehicles, this claim has come under considerable pressure in recent years. On the other hand, a broader view is required to assess the sustainability of a transport mode than merely looking at vehicle travel related external costs. Other transport components, related to vehicle fleet and transport infrastructure, should be taken into account as well. Future directions are therefore given for a correct assessment of the sustainability of IWT in comparison to other transport modes. Additionally, external costs related to transshipments on terminals should also be considered, as these are part of the intermodal supply chain process. Such a detailed assessment can help the IWT sector to determine main points of focus in order to retain the sustainable advantage of intermodal IWT compared to road transport. A better understanding of sustainability aspects and focused efforts in improving this potential will in turn help to promote further integration of IWT in supply chains. Furthermore, a sound external cost assessment should also be looked at from the perspective of a correct internalization of external costs.

Finally, the need for disaggregate time series data to support research in IWT is pointed out in section 8. The previous research topics call for high precision data on freight flows and modal choices. High quality data is also needed in light of the tendency to increase the behavioural realism of freight transport models. Insights in how logistic decisions are made are necessary to predict and influence future freight flows.

In each section an overview of past research is presented and research gaps are highlighted. Section 9 summarizes the major research directions to succeed in creating an integrated intermodal barge transport chain.

2 GEOGRAPHICAL PERSPECTIVE

In 2004, Hesse and Rodrigue already point out the clear link between transport geography and logistics and freight distribution. Instead of the classic idea that freight transport is a derived demand, the authors suggest an integrated demand between production and distribution activities. Flexibilization, globalization and changing production principles have led to smaller and more frequent freight flows over longer distances, favouring road and air transport modes. Stagnation of inland waterway volumes in Northwestern Europe is partly due to a shift of the economy away from industries that use bulk cargo, such as the steel industry. Containerization has enabled the transport of lower volume flows, while offering the opportunity to bundle goods and achieve economies of scale for IWT.

Changes have been observed in the structure of distribution networks. Hinterland access of ports has become a key element in their competitiveness. Notteboom and Rodrigue (2005) define a regionalization phase in port development. Ports constitute nodes in intermodal networks and competition takes place amongst transport chains instead of between ports. IWT plays a central role in Northwestern Europe in providing major transport axes towards hinterland shipper zones. Due to congestion and lack of space in port areas, inland hubs have been constructed along waterways, providing reliable connections. Around these inland terminals, logistic zones have emerged, offering additional services such as customs clearance,

empty depot for containers, value added logistics, and attracting regional or global distribution centers. Collaborative agreements and vertical integration are appearing in these hinterland transport chains, aiming at increasing the geographical scope or offering door-to-door transport services (Notteboom, 2007). Inland terminals are taking up a more active role in supply chains, leading to extended gates and extended distribution centers (Rodrigue and Notteboom, 2009). Rodrigue et al. (2010) identify the following four supply chain functions of inland terminals: consolidation, transloading, postponement and light transformations. According to Rodrigue (2012), locational decisions of logistics service providers are likely to be linked to decisions concerning outsourcing and supply chain management. A better insight in the decision making process in supply chain location decisions is highly relevant to understand and predict future evolutions in distribution networks.

As container volumes are still expected to grow, inland terminals are facing the challenge to increase throughput. Notteboom and Rodrigue (2009) identify challenges in light of the growth in containerization. The authors argue that inland distribution networks should adapt to the large volumes in maritime transport and extend the massification at sea as far inland as possible. Multiple gateways or inland corridors may compete to attract freight flows by offering different cost, time and reliability advantages. According to Notteboom (2010), the growing demand for routing flexibility stimulates competition for distant hinterlands. Therefore, providing reliable connections for continental distribution further along the transport chain, is becoming a crucial transport market for inland barge terminals. On the other hand, Notteboom and Rodrigue (2009) state that the acute trade imbalances are unlikely to persist and this may imply a more regional structure of production and distribution in the future. In light of these challenges, future research may support inland waterway terminals in their choice on which strategic collaborations to make and how to anticipate on these changing distribution structures.

The pre- and post-haulage distance defines the market area of an intermodal terminal as a circular shape which comprises the set of all points around the terminal for which intermodal transport is less expensive than road-only transport. Yet, Niérat (1997) shows that, in a homogeneous space, the shape of the terminal market area is part of the family of Descartes' ovals. This shape depends on the services 'direction provided by the terminal. Based on this result, Limbourg and Jourquin (2010) include the heterogeneity of space and determine the market area of several rail-road terminals. Bearing in mind this specific shape would certainly improve land-use planning issues around inland waterways terminals.

Climate change is also expected to have major impacts on inland waterway transport across Europe through disturbances in waterway hydrology: longer periods with strong water swells and drops. To allow fully loaded barges, the water level must be neither too high (limited air draught) nor too low (limited draught). Therefore, the water level impacts the load factor of barges and thus the transportation costs. Moreover, in winter, ice jams can paralyze inland waterway traffic on the river. According to the survey of Koetse and Rietveld (2009), the majority of the studies on the impact of climate focus on instantaneous or short-term impacts. The literature is almost silent on long-term effects. Jonkeren et al. (2011) studied the effect of climate change on modal split in the river Rhine area. They conclude that even if the effect on

the modal split is limited in this area, the predicted change in modal split is undesirable in the light of the policy goal of the European Commission to shift cargo from road to other transport modes. More research is needed to find out if this limited effect is similar in other river areas. Furthermore, an interdisciplinary approach should be applied to assess the potential impact of climate change on transportation (Jaroszweski et al., 2010).

Research on intermodal transport mainly focuses on large transport distances rather than on urban freight transport in order to attain economies of scale (Quak, 2008). Due to the pressure of space on logistics and freight transport in metropolitan areas, logistic activities need to be tuned to the physical environment. Dablanc (2007) points out that the provision of appropriate urban logistic services is slow despite the growing needs. There are initiatives integrating inland waterway transport within a metropolitan logistic perspective. Maes, Sys and Vanelslander (2012) identify two concepts in linking inland waterway transport with urban distribution. On the one hand, deliveries in cities where the last mile transport is performed with barges, such as for example the use of electric boats in the city centers of Utrecht and Amsterdam (Holland) to deliver high volume goods such as beverages, frozen products, perishable products, building materials, etc. to businesses in the city centre and to collect reverse waste flows on the way back. On the other hand, deliveries to or from cities where goods are transported to a terminal near or in the city centre, but where the first or last mile transport is performed by trucks, such as for example the transport of paper waste from Paris to Rouen (and recycled paper rolls back to Paris). In their review of city logistics solutions using inland navigation in Europe, Janjevic and Ndiaye (2014) identify several segments of urban freight transport for which inland navigation can be used, including transport of palletized goods, transport of containerized goods, deliveries to local shops and restaurants, deliveries of parcels, transport of waste and recycled materials, and service trips. Detailed research and analysis of the total costs and benefits linked to these concepts is however scarce, as well as an assessment of their potential for implementation in different settings. Raimbault et al. (2012) compare the spatial logics in terms of transport and territorial integration of three logistics locations in the Paris region. They conclude that some logistics facilities can help to implement more sustainable metropolitan logistics; others appear as a problem. They also bring to light that this logistics diversity is a challenge for spatial metropolitan planning, which entails to governance issues in terms of relationship between public management, urban planning, and infrastructure, and the decisions of private enterprises. Flämig and Schulte (2011) propose within the research project 'Binnen_Land' potential strategies for inland ports to function as logistic hubs in cities in Germany. The researchers indicate possible conflicts of interest between urban and port development. City ports are faced with growth restrictions and a lack of engagement in urban plans. Lendjel and Fischman (2013) study existing barge transport chains in France in the research project 'Ville Durable / Fluide'. As the last kilometers have to be performed by road, a synchronization between barge and truck rotations is necessary. Barges may serve as a floating warehouse as an answer to the scarcity of available storage space. However, the authors prove that transaction costs to set up urban river logistics are high and the site-specificity of river ports in cities constitutes an important barrier.

The use of IWT in urban areas is also desirable from an environmental perspective. Van Lier and Macharis (2011) calculated substantial benefits in terms of external transport costs saved by using the inland port of Brussels, where some 255000 truck trips going in or out the city are avoided on a yearly basis due to inland waterway transport, mostly in the bulk product categories minerals, building materials and petroleum products, but also in food products and containers. Dooms, Haezendonck and Valaert (2013) compared the environmental performance of inland ports by performing a dynamic green portfolio analysis of eight European inland ports, making the distinction between two inland port types: 'metropolitan supporting' types (MS) and 'industry supporting' types (IS). The two types of ports were found to differ on three dimensions: traffic structure (strong dominance of construction materials, oil products and consumer goods for regional distribution in MS ports), traffic imbalances between inbound and outbound inland waterway traffic (share of inbound traffic substantially larger than that of outbound traffic for MS ports), and land occupation (MS ports occupy less land than IS ports relative to the size of the urban region where they are located reflecting the potential tension between land uses in the metropolitan areas versus the industrial areas). According to Dooms et al., the main challenges for MS ports consist of preserving their existing land and seeking opportunities to expand within the urban regions along the inland waterway infrastructure they exploit, even though expansion opportunities are scarce and require a long-term approach.

3 SYSTEM WIDE MODEL FOR IWT

A first research challenge is modelling the waterway transportation system as a whole. Multiple research efforts have already been undertaken to model isolated parts of the transportation network, such as locks, inland terminals and port operations. These components of the transportation system interact with each other. Network models have been constructed on a more aggregated level for strategic decision making and policy support. For example, within Macharis et al. (2011), the LAMBIT model (Macharis, 2004) is combined with the NODUS model (Jourquin et al., 1999) and a discrete event simulation model for inland waterways, creating a decision support framework for intermodal transport policy analysis. However, a system wide model of the detailed operations in inland waterway transport is missing. Such a model is highly relevant for the following three reasons. First, a model covering all aspects of the inland navigation network may demonstrate benefits of synchronization and enable an analysis of the entire network. Synchronization may for example be realized between consecutive locks or between locks and nearby terminals. Lock openings and priority rules of multiple locks may be tuned to another so as to create a smooth flow through the network. A planning system in which shippers may fix a time window for lock passage in advance could also reduce waiting times and synchronize barge operations. Terminals may adapt their loading/unloading operations and departure schedules to the operations of nearby lock systems. Also hinterland and port operations could be better aligned. Second, a system wide model for IWT will further allow decision makers to explore the outcomes of alternative decision choices to reduce congestion, rather than providing a forecast of a predetermined future. Waterway administrators may for example want to compare

infrastructural investments on their ability to reduce congestion in the network. A third application area is the analysis of alternative priority rules and heuristics for lock planning to assess their effect when implemented across the network. All these options may be analyzed under varying scenarios of transport demand, as increases in volume and changes in type of vessels are expected in the inland waterway network in the near future.

Because of the increased complexity when studying the entire network and the required level of detail, discrete event simulation is often applied. Simulation models are appropriate to interpret the structure of a complex system. Two research papers describe simulation models that measure congestion levels in an inland waterway system with multiple interdependent locks. In these papers, Smith et al. (2009) and Bilbrey and Schonfeld (2009) study river navigation systems in North-America, which have significantly different characteristics from the European ones. In their study area barges are joined into tows for transport, which need to be transferred through locks with one or two chambers. These tows often may have to be split again into groups of barges when their size exceeds the chamber size. After lockage the groups of barges are joined again to continue their journey. Bilbrey and Schonfeld (2009) present an online simulation model for short-term analyses, which provides managers with real-time information on congestion in the network. Instead of focusing on traditional simulation modelling outputs (such as throughput and utilization), the emphasis of the model by Bilbrey and Schonfeld lies on the simulation of location and behaviour of entities within the system with a short-term horizon. Recently, Tierney et al. (2014) describe an integer programming model for analyzing traffic flows in an inter-terminal transportation network in sea ports, taking into account congestion. However, the model does not take lock operations into account and cannot handle multiple types of vehicles traveling on the same arcs. The scarcity of mathematical models or simulation models that measure congestion levels and take interdependence of locks into account demonstrates the complexity of this research opportunity in intermodal waterway transport.

4 INTEGRATION OF OPERATIONAL PLANNING SYSTEMS

A second challenge is the integration of various planning systems for the operational planning in inland waterway transport. For example, lock planning systems and quay handling systems could be adjusted to achieve an efficient handling of inland vessels in the port area. Both operational problems are currently planned separately. Consequently, inland barges are often first queuing to pass a lock and next queuing to load or unload freight at sea terminals. Time savings could be achieved by a joint planning of both queuing systems. Scientific research may assist in designing supporting planning tools and demonstrating potential time gains.

Also lock openings and priority rules of multiple locks may be tuned to another so as to create a smooth flow through the network. Consecutive lock systems may influence each other's arrival rate due to their relatively short in-between distance and thus the inability of vessels to spread again. Martinelli and Schonfeld (1995) add that the interdependence between locks increases with the utilization rate of a lock and the system size (i.e. number of consecutive locks). These interdependencies lead to misleading results when applying planning models for

single lock systems. If interdependencies exist, total delay in the waterway network system is different from the sum of isolated delays at the individual locks. Arrival rates at the second lock show great similarities with departure rates at the first lock. These arrival rates may not be assumed to be independent events when studying congestion in the inland navigation system. Mathematical models in literature (Nauss, 2008; Verstichel et al. 2011) calculate waiting times for single lock operations. Nauss (2008) categorizes the lock scheduling problem of a single lock with a single lock chamber as a single job shop that services two assembly lines (upstream and downstream vessels). He proposes linear and nonlinear integer programming formulations for determining an optimal sequence for locking vessels at a single lock that would either clear the existing queue in the shortest time interval or minimize the sum of total waiting times for vessels in the queue, or minimize a weighted sum of both objectives. A feasibility-based implicit enumeration approach is used to solve the nonlinear problem formulation. Verstichel et al. (2011) extend the existing knowledge on lock scheduling by studying locks with multiple parallel chambers. The authors decompose the lock scheduling problem into a bin packing sub problem and a scheduling sub problem. The bin packing sub problem groups vessels which may jointly pass through the lock. In the scheduling sub problem these groups of vessels are assigned to lock chambers in a certain order. The scheduling sub problem is identified as an identical parallel machine scheduling problem with unit processing times, release dates and sequence dependent setup times. The scheduling sub problem may be solved to optimality, but a heuristic approach is proposed to find a near-optimal assignment for the bin packing sub problem. The only researchers that take interdependence in lock systems into account, apply simulation models and derived meta-models to predict delays in such waterway systems (Martinelli et al., 1993; Dai and Schonfeld, 1998). Dai and Schonfeld (1998) model the waterway system as a series of G/G/1 queues, representing generally distributed arrivals and service times and single chambers at each lock. Next, formulas from queuing theory are estimated from previously obtained simulation results.

Another planning problem at the operational level is the combination of priority rules for allowing inland vessels to enter a lock and planning methods for placing these vessels inside the lock chambers. The most common priority rule in practice is taking the first vessel that arrives to the lock (first in first out or FIFO discipline). Alternatively, priority could be given to vessels that can be locked most quickly (shortest processing time first discipline). Ting and Schonfeld (2001) add a fairness principle to this priority rule, putting a limit on the number of vessels that may pass another vessel. Theunissen and Janssens (2005) propose a less-flexibility-first heuristic for supporting the decision where to place the vessel in the lock, aiming to place as many vessels as possible from the arrival queue. The authors assume a group-FIFO discipline, in which the first n vessels are allowed to sail into the lock. Their algorithm gives priority to placements with low flexibility either of the lock or of the vessels to be placed. Verstichel et al. (2014) develop a multi-order best fit heuristic for the ship placement problem, assuming a FIFO queuing discipline for lockage. However, current literature ignores the relationship between priority rules for lockage and lock placement models. Lock operations may be interpreted as a bi-objective planning problem. Waterway administrators aim to maximize system efficiency, resulting in fast overall lockage operations.

Shippers want to minimize their individual waiting time for lock passage. A measure of user satisfaction may be introduced, depending on how shippers perceive their own waiting time and how they experience the fairness of the lock operations.

An integration of the operational planning tools for inland navigation will create a smoother transport flow, making the intermodal barge transport chain competitive to unimodal road transport in terms of operational performance. However, developing and implementing these planning tools implies a considerable research effort in the near future.

5 ANALYSIS OF BUNDLING NETWORKS

A third research topic is the analysis of bundling networks for intermodal barge transport. Consolidation of freight flows may improve the efficiency of intermodal operations. Inland terminals may cooperate with the objective to create denser freight flows and achieve economies of scale. In this way, the attractiveness of intermodal barge transport could be improved (Caris et al., 2011; 2012). Caris et al. (2011, 2012) study bundling strategies for intermodal barge transport in the hinterland network of a major port in Western Europe. One potential network concept is the uncoupling of the hub-and-spoke services in the port area from the trunk haul services with direct connections to the hinterland. Four alternative hub-and-spoke scenarios for bundling in the port area are compared by means of discrete event simulation (Caris et al., 2011). The economic feasibility of a hub-and-spoke network for barge services in the port of Rotterdam is discussed by Konings et al. (2013). The authors conclude that a hub-and-spoke network has the potential to deliver a better cost performance than the current operations provided the handling costs of exchanging containers in the hub can be kept within limits. Caris et al. (2012) analyze the organization of intermodal barge transport in a corridor network. Inland terminals may bundle freight to and from the same sea terminals in the port area. A service network design formulation is proposed to identify interesting cooperation scenarios and selected cooperation scenarios are simulated and compared with their previous work on bundling in the port area. Braekers et al. (2013) present a decision support tool for service network design in intermodal barge transport. Barge operators, logistic service providers or shipping lines that want to offer regular roundtrip barge services between a number of ports located along the same waterway may use this model to determine vessel capacity and frequency of these roundtrips. For each service type (capacity and frequency) the model determines optimal shipping routes and number of containers to be transported in a corridor network. The decision maker may use this information, together with information on other factors like customer preferences, to evaluate all possible types of service and choose the best among them.

Bundling networks require cooperation between multiple partners in the intermodal transport chain. The actors in the network have to agree on how to set up and organize the bundling operations. Questions rise which type of bundling network is manageable in reality and how will benefits be allocated among the participants in the cooperation. Konings et al. (2013) put forward that the behaviour of the players in the container barge industry might be the most critical issue in setting up a hub-and-spoke network for intermodal barge transport, rather than

operational or technical considerations. Research into which business models are appropriate for this complex cooperation environment can support the integration of inland navigation in the intermodal supply chain.

6 SUPPLY CHAINS INVOLVING INLAND WATERWAYS: INTEGRATED MODELS

A supply chain (SC) can be defined as an integrated system in which raw materials and components are purchased, turned into finished products and delivered to the end customer. Expanded coordination, whereby each stage of the chain minds the effect of its actions on all others, improves SC efficiency and reduces environmental impact.

When, on the contrary, production and distribution activities are managed independently, inventories are used as buffers between the various operations, implying costs of carrying inventory. Therefore, coordinating production and distribution decisions reduces inventories and product cycle time. The optimization of the production-distribution system allows companies to achieve substantial cost savings, given the ever shrinking manufacturing resources and the pressure to meet customer expectations (Elhedhli and Goffin, 2005). Integrating production and distribution decision-making can be achieved at strategic, tactical and operational levels. Strategic production and distribution decisions include issues such as the size and location of distribution centres or the selection of a transportation mode; tactical decisions deal with questions such as productivity or fleet size, and operational decisions concern precise scheduling or dispatching issues. Fahimnia et al. (2013) point out that opting for multiple transport paths and shipment modes in developing production-distribution models opens up a new line of research towards tackling alternative shipment costs and achieving economies of scale.

Despite the growth in intermodal freight transport, scientific literature hardly mentions the issue of integrating intermodal transport in the SC. Robinson (2002) points out that the choice of ports is made in the context of the overall SC: cargo flows search for routes offering the lowest cost and for ports offering efficient hinterland accessibility. Groothedde et al. (2005) state that the use of a relatively slow mode of transportation, such as inland waterways transport, does not automatically imply an increasing lead time. Combining inland waterways and road transport has the advantage of achieving economies of scale and scope while ensuring responsiveness and flexibility. Multimodal networks aim at finding the best combination of modes. More recently, Bierwirth et al. (2012) introduce the intermodal rail-road transportation problem for the tactical planning of mode and service selection. Meisel et al. (2013) continue on this problem setting, but also combine production planning with distribution planning for intermodal rail transport. The authors present an optimization model that jointly decides on production setups, output volumes, inventory management, cargo consolidation at intermodal terminals, and capacity booking of road and rail transport means in a multi-period planning horizon. This could also be an interesting research perspective for intermodal barge transport.

Regarding the intermodal transport network, the most suitable one appears to be the hub network (Bookbinder and Fox, 1998). This is hard to solve, opening the way to heuristics (Ishfaq and Sox, 2011). In addition, actual short-haul operations account for a relatively large share of the overall costs (Caris and Janssens, 2013) with a lot of processes still waiting to be optimized. Moreover, the authors highlight the scarcity of research models for analyzing various policy measures relating to intermodal transport. As concerns Belgium, Macharis and Pekin (2009) present an assessment of policy options such as that of introducing new terminals and subsidies. Setting up and managing intermodal transport service networks are complex per se, given the multiplicity of objectives, constraints and parameters. In addition, taking into account external costs due to emissions could lead to developing non-linear optimization models (see e.g. Barth and Boriboonsomsin, 2008).

Intermodal services also play a role in SC performance. Indeed, value added services (packaging, breakage, labelling, returning empty returnable transport items, storage, clearing, repairing, tests, quality control etc.) can motivate the use of inland waterways transportation. Instead of taking place in warehouses, value added services are currently accomplished in some intermodal hubs (ports or terminals) by using the opportunities of modal transfer breaks of intermodal transport processes. Integrating the new role of ports and terminals in the SC is a topic of increasing relevance.

Finally, Verma et al. (2012) propose an intermodal routing problem for containerized hazardous materials. Their objective is to minimize transportation cost and the expected risk inherited by a specific mode of transportation. Inland waterway transport is considered as a safe and secure transport mode. Transportation of dangerous cargo by barge could enhance transport safety for enterprises as well as society.

A topical subject in scientific research are green supply chains. Srivastara (2007) gives one definition of green supply chain management (GSCM): he defines GSCM as “Integrating environment thinking into supply chain management, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to the consumers, and end-of-life management of the product after its useful life”. Some products are environmentally-friendlier than others. Dekker et al. (2012) consider three aspects: how products are produced, transported and stored (inventories), and recycled (reverse logistics). They also study packaging and returnable transport items.

Most research on green SC focuses on reverse logistics or closed-loop SC (Sasikumar and Kannan (2009) and Gupta and Lambert (2009)). As regards the environment, however, transportation is the most visible aspect of SC. Among the key transportation factors having an environmental impact, Meyer-Rühle (2011) and Banister (2008) identify modal split and energy efficiency. Achieving a modal shift can only be competitive with road transport if it can fit well into their SC. Many criteria are taken into account in freight modal choice decisions (e.g. Beuthe, 2003; Witlox, 2003; Grosso 2011) such as cost, speed and reliability of delivery, frequency, information exchange, flexibility, safety, security, flexibility, infrastructure availability and capacity, regulation and legislation, traceability and environmental considerations.

Meixell and Norbis (2008) review the overall literature on transportation choice. Their account reveals that several important themes are under-represented such as environmental and energy use concerns, SC integration, or the role of the internet and emerging information technologies. Later, Hoen et al. (2012) estimate the carbon emissions of different modes of transport and formulate a model which analyzes the trade-off between inventory and transport costs. They also investigate the effect of different types of regulations with respect to emissions relating to the selected transport mode and the corresponding emissions. Whereas studies relating to SC typically focus on costs as the optimization criterion, some recent ones also include environmental aspects. Mallidis et al. (2010), e.g., include a choice of port of entry in their SC design model. As shipping is environmentally-friendly, it pays off to choose the nearest port for a customer. Yet another example can be found in Geerlings and Van Duin (2011), who assess emissions due to transport distances in a container terminal, container handling processes and transshipment at terminals.

Future research should pay special attention to quantifying and formulating multiple objectives which may include traditionally objective functions (e.g. cost, time and service level) and current objective functions for greenness and sustainability. These multi-objective methods can help identify the synergies between cost and environmental objectives, such as Macharis et al. (2010) do concerning the strategic choices made for the Flemish transportation and logistics sector. Minimizing emissions, though, requires the use of appropriate models (Demir et al., 2011). It also represents a challenge because new mathematical models must be developed to assess the impact of incentives for energy reduction. This is the case of the Pollution-Routing Problem, an extension of the vehicle routing problem, defined by Bektas and Laporte (2011). Moreover, the information needed by the carrier to determine the various costs of transporting goods is often very hard to determine. This fuzzy information can also add to the complexity of greening SC models.

In addition to the above considerations, inland waterways transport offers a high potential for additional cargo volume in Europe. Characterized by the concentration of freight traffic between major hubs and by relatively long distances, green corridors (European Commission, 2007) deal with the provision of sustainable freight transport logistics services. Along these corridors, industry is incited to rely on co-modality to have capacity for rising traffic volumes while improving environmental sustainability and energy efficiency. EU highlights that green corridors could be used to experiment innovative transport units and advanced intelligent transport system applications. Equipment pooling should also be considered. Pan et al. (2013) describe a case where transportation equipment is pooled between several companies in order to increase load factors. They quantify the effect of this pooling on carbon emissions and stress that future research still needs to generalize the obtained results to overcome the greater cost of the more environmentally-friendly transportation means.

A waterway corridor is wider than the waterway: it is the area which impacts, or is impacted by a waterway. Many European cities are crossed by rivers and canals. These cities have to cope with limited city space and increased traffic to supply their inhabitants and to guarantee their attractiveness, economic power and quality of life. Therefore, sustainable freight transportation systems are critical to the development of cities in reducing emissions and

congestion. In several cities, consolidation activities take place at so-called city distribution or consolidation centres. These are intermediate transfer points where goods can be stored or transferred between barges and small environmentally-friendly city trucks, thus lowering the pressure on city roads and reducing greenhouse gas emissions. In particular (INE/EFIP, 2008), thousands of tons of paper reach Paris' newspaper and magazine printers by barge and the waste collected is shipped back by barge to Rouen for recycling; since 1990, the Belgian city of Liège has moved an increasing part of its household refuse by barge. Benjelloun et al. (2010) review some seventy city logistics projects, proposals, and actual systems, which altogether reveal a number of additional trends and challenges. As little literature related to the design, evaluation, planning, management and control of such systems exists, this implies challenging research perspectives.

7 EXTERNAL COSTS OF IWT

Whereas the previous section elaborated on the role which intermodal waterway transport can play in creating green supply chains, this section further focuses on the environmental costs of IWT. Very high on the research agenda is how to keep the positive sustainable image of IWT compared to other transport modes intact. IWT is indeed still scoring very well taking all categories of external costs into account, but looking more into detail, results are mixed. IWT is not performing so well in certain categories, and in some categories it is losing ground compared to other modes. In this section first a state of the art is given on the current state of affairs and subsequently the research challenges will be listed.

In order to compare the broader sustainability of different transport modes, it is useful to assess the level of external costs associated to them. "An external cost arises, when the social or economic activities of one group of persons have an impact on another group and when that impact is not fully accounted, or compensated for, by the first group." (Bickel and Friedrich, 2005). In the case of transport modes, the most important external cost categories are climate change, air pollution, noise, accidents, and congestion. Also external costs related to up- and downstream processes such as pre-combustion processes related to fuel consumption, are significant. Looking at the total external costs, IWT on average performs better than road transport. If infrastructural costs are additionally taken into account, IWT also clearly outperforms rail transport (Figure 2).

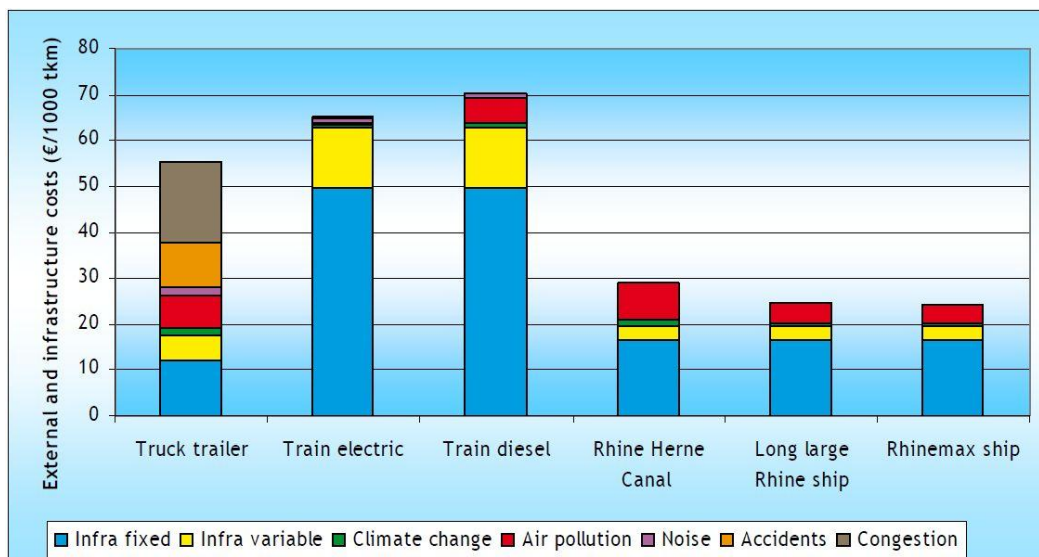


Figure 2: External and infrastructure costs of container transport in 2009 (€2009 per 1000 tkm). (NEA et al., 2011)

As indicated in the overview studies by Maibach et al. (2008) and more recently Gibson et al. (2014) on external transport costs in the EU, external noise and accident costs for IWT are indeed negligible, whereas for road transport these costs are significant. Also for rail, especially in urban areas and during the night, noise costs can be significant, even taking into account the so-called rail bonus, which implies that at the same A-weighted energy-equivalent noise level, railway noise is frequently preferred to road traffic noise, usually attributed to differences in spectrum, time structure, and meaning of sound (Fastl, Fruhmann and Ache, 2003). Regarding environmental costs, the environmental performance of a transportation mode is very much linked to its energy efficiency. The study of Planco (2007) with regards to some very relevant waterway trajectories shows that inland waterways score better than rail and much better than road transport in terms of energy efficiency and this holds for bulk cargo as well as for container transport (Figure 3).

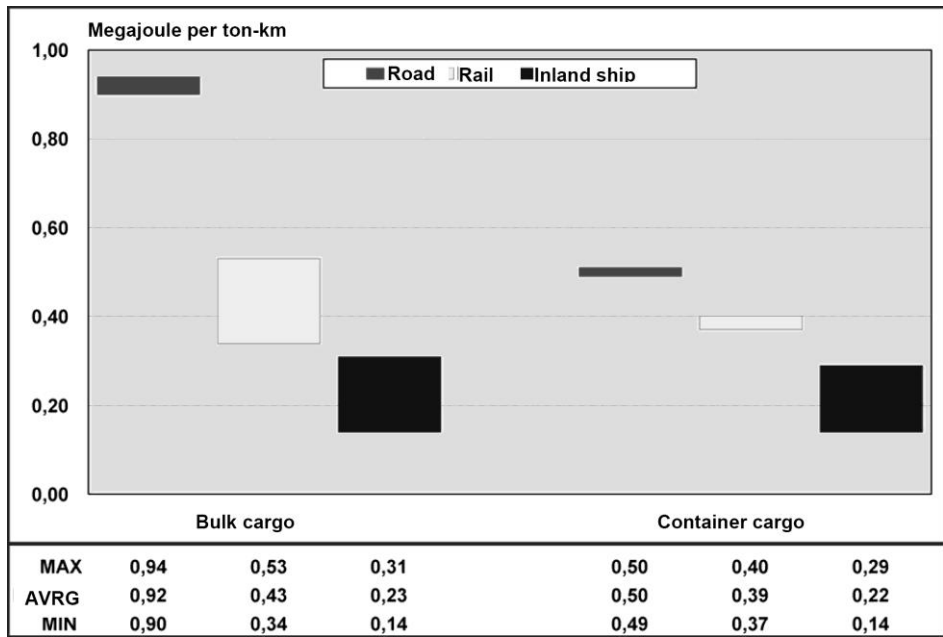


Figure 3: Spread and Averages of Primary Energy Consumption on Selected Transport Relations (in Megajoule per tonkilometer). (Planco, 2007)

For air pollution, the monetary valuation of each emission depends on the damage consequences they cause. Prominent in literature is the relatively high valuation of particulate matter (PM) as these dust particles have the biggest impact on public health (Maibach et al., 2008; De Nocker et al., 2010). However the estimated cost for society also depends on where those emissions are being emitted and how they are dispersed (Impact Pathway Approach developed in the Externe project series (Bickel and Friedrich, 2005)). With regards to total emissions, den Boer et al. (2011), demonstrated that IWT is scoring better for CO2 emissions than road transport, but worse for SO2, PM and NOx.

Evidence that the sustainable advantage of IWT over other transport modes is under pressure and expected to relatively decrease in the future is provided by NEA et al. (2011). Figure 4 shows the relative change in three external cost categories between 2009 and 2020.

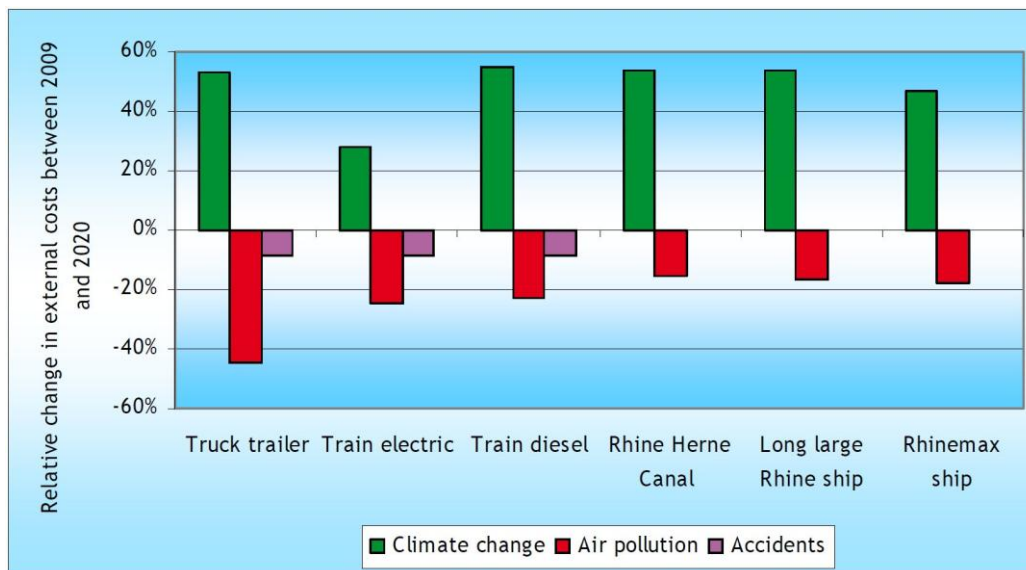


Figure 4: Relative changes in climate change, air pollution and accidents between 2009 and 2020 (container transport). (NEA et al., 2011)

Climate change costs are expected to increase for all modes between 2009 and 2020, because although the CO₂ emissions per tonne kilometre decrease for all modes, this is outweighed by the increase in the shadow price of CO₂. However, for air pollutant costs the decrease is clearly largest for road transport (44%) and more limited for rail and especially IWT transport (respectively 23%-25% and 15%-18%). A more limited decrease in air pollutant emissions per tonne kilometre for these modes is expected. For accident costs, the expected relative decrease is the same for road and rail transport (ca. 9%). Since IWT transport does not cause (significant) external accident costs, the other modes succeed to relatively decrease the gap in external accident costs.

Adding this all together, the total external costs per tonne kilometre decrease by ca. 8% for road transport, while for rail and IWT a smaller decrease of 1%-2% is estimated, especially caused by the smaller reduction in air pollutant costs of these latter modes compared to road transport (NEA et al., 2011).

Other studies however show that, if additional efforts are done, IWT should be able to keep its advantage. For SO₂, the stricter norms imposed for IWT on a European level already very much decreased emission levels (Delhaye et al., 2010). The problem of NO_x and PM are also high on the agenda of the EC. The CCR norms that apply to the IWT sector will come in a new phase in 2016. Although not yet fixed, the norms will be much more stringent and comparable to those of the Euronorm VI for trucks. Attaining these new norms is very challenging but the technologies to achieve this are available. The combination of a particulate filter and a selective catalytic reduction (NEA et al., 2011) and the use of new technologies such as dual fuelling, where a combination of LNG and diesel, or LNG with electricity is being used, would attain this norm. A list of possible technologies for barges and their impact is discussed in detail by Franckx, Vanhove and Schoukens (2011) and NEA et al.

(2011). Also the updated external cost calculator for Marco Polo freight transport project proposals takes into account different alternative fuel technologies in addition to using low sulphur fuel oil (diesel particulate filter, selective catalytic reduction, a combination of both, and LNG) (Brons and Christidis, 2013). Their results show the large range of possible marginal external emission (climate change and air pollution) costs for IWT, depending on the technology used, type of ship and freight capacity. Values range from €26.0 per 1000 tonne kilometre for an IWT tanker of 250-400 tonnes on low sulphur oil to €1.9 per 1000 tonne kilometre for an IWT tanker of 401-650 tonnes on LNG. This wide range of values underlines the risks of using averages when comparing transport modes and stresses the importance of looking at the right level of detail when analysing the sustainability of transport modes.

Taking into account the above issues, following research topics can be identified which are relevant for taking action in order to support the claim that IWT is a more environmentally sustainable transport mode than road transport. Such assessment is vital to provide a rationale to companies to promote the integration of IWT in intermodal supply chains from a corporate social responsibility viewpoint, as well as to convince policy levels of the need for external cost internalization.

The evolution and implementation of recently developed as well as still developing engine technologies for inland waterway vessels should be screened in detail and the assessment of their impacts on polluting levels should be updated regularly taking into account new scientific insights. Also the resulting change in vehicle fleet for IWT with reference to the renewal rate of vessels and/or motors using different technologies should be mapped in detail in order to assess the level and evolution of external air pollution costs of IWT more accurately. Also fuel consumption and the resulting external climate change costs should be recorded based on data in real conditions, in order to avoid using average figures. This data would also allow checking the validity of modelled external cost key figures. At the same time, the technological advances for other transport modes, in particular road and railway transport, should be mapped as well, so that both energy consumption and air polluting emissions are known in detail for the different transport modes. Special attention in this regard is needed on increasing the knowledge on the level of electricity production for rail traction, since differences in the electricity mix used can lead to very different external emission costs.

Looking at an even higher scale, it is also important to assess the sustainability of different transport services (water, road, and rail) from a Life Cycle Assessment perspective. Frischknecht (1998) defines Life Cycle Assessment (LCA) as a method for the analysis and assessment of potential environmental impacts along the life cycle of a good or a service. In Figure 2 infrastructure costs were taken into account, but these are the internal infrastructure costs that are the result of public and private investment. However, also the externalities related to construction, maintenance, operation and disposal of both infrastructure and vehicle fleet should be analysed in detail. This would allow to map the sustainability with regard to air polluting and greenhouse gas emissions of the total transport service, and not solely of the vehicle travel related externalities, which are usually considered. Only a few LCA studies

with a focus on freight transport have been performed so far (Eriksson, Blinge and Lövgren, 1996; Spielmann and Scholz, 2005; Facanca and Horvath, 2007; van Lier and Macharis, 2013), and a detailed analysis on a European level to compare the different transport modes is lacking to date. Such an analysis can be based on the ecoinvent database, which was created by the Swiss Centre for Life Cycle Inventories and is a reference work for life cycle inventory data covering the areas of energy, building materials, metals, chemicals, paper and cardboard, forestry, agriculture, detergents, transport services and waste treatment (Frischknecht et al., 2005). Applying this methodology however requires collecting detailed data regarding construction, maintenance, operation and disposal of both vehicle fleet and infrastructure, and the relevant processes involved (van Lier and Macharis, 2013). Using specific data related to materials, transport and energy used in these processes would allow to apply the emission factors of relevant ecoinvent subprocesses. To compare the different transport services, LCA's of the different transport services should be carried out.

Regarding the assessment of external air pollution costs, a crucial determinant is the receptor density, namely the amount and characteristics of people being exposed to the pollution. The key figures published in literature however are not always differentiating in a satisfactory way for differences in receptor densities for the different transport modes, which is particularly relevant for emissions that are active on a local scale (such as PM). It would therefore be relevant to assess in what way transport on the existing infrastructure is differing with regards to receptor densities on the major transport corridors (e.g. between the ports of Rotterdam/Antwerp and the Ruhr area in Germany). This could be done using detailed GIS data for the relevant dispersion distances surrounding the transport infrastructure.

Additionally, external environmental costs related to transshipments on terminals should also be considered, as these are part of the intermodal supply chain process. Differences in external effects between intermodal barge and rail terminals should be examined.

All these research efforts would allow a much more profound, detailed and differentiated comparative analysis of the sustainability of different transport modes, but would also allow to identify focus points in order to improve the environmental performance of IWT and aid its integration in a green intermodal supply chain.

8 IMPROVEMENTS IN DATA COLLECTION

A final research topic is the collection of disaggregate time series data concerning inland waterways. High precision data is needed for the analysis of intermodal transport chains in general, and inland waterway transport in particular, as is evidenced by various research avenues highlighted in the other sections of this paper. Moreover, the need of high quality data is underlined by the general tendency of increasing the behavioural realism in models predicting travel demand generated by persons (see e.g. Cools et al., 2010) and freight (see e.g. Roorda et al., 2010). With regard to this evolution in transport modelling, de Jong et al. (2013) highlighted that the integration of logistic services should be noted as one of the most

important improvements. Furthermore, the importance of focussing on the logistic chain is stressed by the authors of this paper in Section 7.

Next to the improved modelling of freight demand, in the light of the development of policy measures aimed at stimulating intermodal transport, more reliable information is needed to elevate the efficacy of these policy measures. In particular, data is needed with respect to the impact of ICT innovations on intermodal transport (Perego et al., 2011). Especially, information on the interactions and coordination between different actors in the intermodal chain is missing (Caris et al., 2013). In this context, data stemming from RIS (River Information Services) have the potential to provide key information for improving the planning and management of the different processes in the intermodal chain (Schilk and Seemann, 2012).

With respect to existing data sources for freight planning, it should be noted that they do not accurately reflect the nature of supply chains and increasingly complex logistics practices in freight-dependent industries, and that it is more difficult to document detailed freight activity through information gained from traditional shipper surveys as the growing role of third-party transportation providers makes freight less visible to many shippers and receivers (Chase et al., 2013a). Some concrete steps are highlighted by Chase et al. (2013b) and include: (i) data sets developed through collaboration with the private sector to create a knowledge base on intermodal transfers, (ii) protocols to collect data on a regular basis, (iii) industry-level forecasts that are sensitive to the unique factors of different industries, (iv) data at a disaggregated level (local) that can be aggregated for larger geographic analyses, (v) an accessible data bank for freight modeling developed with the cooperation of GPS device providers, ITS infrastructure owners, and other data providers, and (vi) development of a universal multimodal, open-source data bank.

9 CONCLUSIONS

Inland navigation has received a great deal of attention to achieve a sustainable transport system in Europe. This paper identifies necessary research efforts to integrate inland waterway transport in the intermodal supply chain.

A first group of research challenges lies in the evolving relationship between transport geography and logistics activities. Changes in distribution networks are linked with supply chain decisions. Inland waterway terminals are part of a hinterland network which constantly changes. Research may support inland waterway terminals in their choice on which strategic collaborations to make and how to anticipate on spatial evolutions. More research is also needed on the impact of climate changes on IWT. Finally, research may support the further integration of IWT in urban distribution networks.

A second group of research challenges has the objective to encourage efficient operations in IWT. These research challenges aim to support barge operators, terminal operators, waterway operators and port authorities. A first challenge is to synchronize operations in the inland

waterway network. This can be done by integrating related operational planning systems, e.g. for lock planning of consecutive locks and quay handling, both in the hinterland network and in the port area. Second, the network-wide impact of synchronization may be measured by a system wide model of the detailed operations in IWT. Such a model can assist waterway administrators to assess the effect of infrastructural and operational measures, such as the introduction of alternative priority rules for lockage processes, under alternative scenarios of transport demand. A third challenge is to define appropriate business models to manage bundling networks in IWT. Bundling freight leads to economies of scale, but the benefits have to be allocated in a way that all members have an incentive to stay in the cooperation network.

A third group of research efforts is directed towards shippers and consignees who use the intermodal transport chain to send or receive their goods. First, the further development of models that integrate intermodal transport decisions with supply chain decisions needs research attention. A joint optimization of transport and supply chain issues may convince shippers to use intermodal barge transport. Second, IWT can play a vital role in creating green supply chains. Multi-objective methods are required to add environmental objectives to current decision support models for supply chain management.

In order to remain a sustainable transport mode, the external costs of inland navigation should be safeguarded. A fourth group of research challenges concerns the problem domain of external cost calculations. The evolution of new engine technologies and resulting changes in vehicle fleet for IWT may bring new perspectives for the external costs of IWT. Furthermore, the sustainability of alternative transport modes may be compared in detail by means of Life Cycle Assessment.

Finally, all these research tracks call for detailed freight data. Information should be gathered not only on the freight flows but also on the underlying logistic decisions taken.

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