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Back to the future: A system approach for the uptake of Inland Water Transport of freight in Northwestern Europe

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Back to the future: A system approach for the uptake of Inland Water Transport of freight in Northwestern Europe

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Abstract

Inland water transport (IWT) was once a dominant freight mode in Northwestern Europe but declined with the rise of rail and road transport. Today, IWT is reconsidered within decarbonization strategies to reduce emissions, congestion, and land-use pressures. Technological advances have improved operational efficiency, yet behavioural, organizational and contextual barriers persist. This study examines how interactions among business models, technologies, behaviours, and contextual conditions shape the transition towards IWT using a qualitative system dynamics approach. Nineteen semi-structured interviews with shippers, logistics operators, public authorities, and researchers from Sweden, Belgium, France, Germany, and the Netherlands informed the development of a causal loop diagram describing the freight transport system. Feedback analysis identified five reinforcing and two balancing loops governing IWT uptake and revealed three leverage points: organizational capabilities, maturity of IWT usage, and acceptability. These leverage points explain how transport demand, service reliability, infrastructure development, and stakeholder involvement and coordination reinforce or constrain the expansion of IWT. Their influence varies across bulk, container, and RoRo transport, highlighting that effective interventions must reflect the operational characteristics of different commodity flows rather than relying on generic policy measures. By integrating organizational, technological, behavioural, and contextual processes within a single systems framework, this study advances understanding of freight transport transitions and provides a basis for designing interventions that enable the shift toward IWT as a modern adaptation of a historically proven concept.

Keywords: Inland Water Transport, modal shift, freight transport, system dynamics.

1. Introduction

Inland water transport (IWT) was historically a backbone of freight transport in Northwestern Europe, but its role declined with the expansion of road and rail systems during the twentieth century. Between 1970 and 2004, IWT lost around 12% of its share in tonne-kilometres (European Commission, 2004), and by 2023 it accounted for only 1.7% of total EU freight transport (Eurostat, 2026a). Despite its historical importance and technical potential, IWT remains a marginal component of European freight transport.

As Europe pursues the transition towards a carbon-neutral transport system, IWT is receiving renewed attention within freight decarbonisation strategies. Compared with road transport, IWT offers lower greenhouse gas emissions per ton-kilometre, higher energy efficiency, and reduced congestion and land-use pressures (McKinnon et al., 2015; Konings and Wiegmans, 2017). The EU NAIADES III program sets targets to increase IWT volumes by 25% by 2030 and 50% by 2050 relative to 2015 levels. However, observed trends diverge from these ambitions. By 2024, overall IWT performance had declined by approximately 16% compared with 2015 (Eurostat, 2026b), indicating that persisting structural barriers limit uptake despite policy support.

Northwestern Europe concentrates most of Europe's inland waterway freight activity and includes countries with different levels of IWT maturity. Belgium, France, Germany, and the Netherlands have long-established IWT networks and together account for nearly 80% of EU inland waterway freight flows, supported by major waterways such as the Rhine and Seine (Eurostat, 2026b). In contrast, Sweden has a small share of IWT activity but has opportunities to increase its use through waterways that connect Lakes Mälaren and Vänern with seaports and major consumption centres. These countries provide a suitable empirical setting because they represent both mature and emerging IWT systems and allow the study of freight transport transitions at different stages of system development.

Improving infrastructure and vessel technology alone is insufficient to accelerate freight transport transitions (Ben-Akiva et al., 2026). Although advances in digitalisation, automation and alternative propulsion have improved operational performance in IWT (Notteboom et al., 2021), transport decisions remain shaped by organisational routines, contractual arrangements and coordination across supply chains (Roso et al., 2020). Shippers continue to favour road transport because of established procurement practices, short planning horizons and perceived flexibility (Calderón-Rivera et al., 2024). Fragmented decision-making, power asymmetries and uncertainty in freight volumes further limit long-term investment in IWT services (Williamsson et al., 2020; Rogerson et al., 2020). These observations suggest that technological capability is a necessary but insufficient condition for freight transport transitions through IWT, as these transitions depend on how organisational, market and institutional actors coordinate transport demand and supply.

Moreover, conditions that shape freight transport transitions through IWT vary across commodity types and contextual maturity of IWT operations. For instance, factors enabling freight transport transitions in mature IWT systems may not apply in low-maturity contexts (Rogerson et al., 2020), and requirements for bulk flows differ from those for containerized transport or RoRo. Freight transport transitions through IWT need to consider nuances influenced by operational characteristics rather than adopting a generic approach. A systems perspective is required to understand how these interactions generate reinforcing and balancing dynamics across different operational setups.

System dynamics (SD) has been widely applied to analyse freight transport decarbonization and modal shift, including freight transport transitions through IWT. Existing SD studies have examined policy interventions, infrastructure investment and emission trajectories through feedback effects, delays and long-term dynamics at national or regional scales (e.g. Ghisolfi et al., 2022; Nassar et al., 2023). However, these models typically represent behavioural and organisational processes in an aggregated manner. Business models, contractual relationships, organisational capabilities and stakeholder coordination are usually treated as exogenous assumptions rather than endogenous components of the transport system (Ghisolfi et al., 2022; Pirouzrahi et al., 2025). Current SD research provides limited insights into how organisational, technological and contextual changes jointly influence freight transport transitions through IWT.

This study addresses this need by applying a qualitative SD approach to analyse freight transport transitions through IWT based on experiences in Northwestern Europe, i.e., Sweden, Belgium, France, Germany and the Netherlands. The empirical material draws on nineteen semi-structured interviews with shippers, logistics operators, public authorities and researchers involved in established IWT operations, pilot initiatives and emerging IWT concepts. Interviews focused on actors actively implementing or testing IWT services, providing an enriched empirical base despite context differences. The study identifies key variables across the freight transport system and maps their interactions through a causal loop diagram to examine leverage-points that may generate

system-wide effects for the adoption and scale of IWT operations. The central research question guiding the study is: *How do interactions among business models, technologies, behaviours, and contextual conditions give rise to leverage points that shape freight transport transitions through inland water transport?*

By identifying reinforcing and balancing feedback loops and their associated leverage points, this paper contributes to freight transport research in three ways. First, it develops an empirically grounded systems representation of freight transport transitions through IWT by integrating business models, technologies, behaviours, and contextual conditions within a single causal structure. Second, it explains how interactions among these dimensions generate reinforcing and balancing feedback mechanisms that converge into three leverage points governing the evolution of IWT uptake. Third, it demonstrates that although these leverage points are common across IWT applications, their operational expression varies across commodity types, providing a systems-based foundation for designing targeted interventions rather than one-size-fits-all policies.

2. Conceptual framework

This paper conceptualizes the uptake of IWT as emerging from the interaction of four complementary dimensions: business models, technologies, behaviours, and contextual conditions. These dimensions shape how transport services are organised, delivered, perceived, and embedded within freight systems.

2.1. Business models, technologies, behaviour and contextual conditions

Business models define how organisations create, deliver and capture value through the configuration of activities, resources and relationships. In freight transport, they determine how transport demand is organised, how risks and costs are distributed among actors, and how transport services are procured and coordinated. In the context of IWT, business models differ from those supporting road transport because they rely on economies of scale, longer planning horizons, and a higher degree of coordination across production, storage, and transport functions (Konings, 2009; Williamson et al., 2021). Successful transition towards IWT depends on business models capable of aggregating freight demand, reducing uncertainty, and aligning incentives among shippers, logistics providers, ports, and other stakeholders (Williamson et al., 2020). Rather than simply responding to existing transport demand, these business models contribute to creating new markets by overcoming organisational barriers associated with modal change and fostering collaboration around shared environmental and operational objectives (Konings, 2009; Williamson et al., 2020; Sallnäs et al., 2022).

Technologies determine the operational capabilities, efficiency and environmental performance of transport systems. They influence transport costs, service quality and the operational constraints under which freight services are delivered. Recent technological developments have expanded the operational potential of IWT through innovations in vessel design, automation, digitalisation and alternative propulsion systems (Calderón-Rivera et al., 2024). Shallow-draft vessels, modular barges and electric or hybrid propulsion have increased the range of waterways suitable for freight transport, while digital technologies improve planning, scheduling and information sharing across supply chains. Automation and remote operation further enhance operational efficiency and address labour constraints (Williamson et al., 2020). Nevertheless, technological improvements alone are insufficient to accelerate the uptake of IWT because their benefits depend on complementary organisational and contextual changes that enable

their implementation and effective use (Williamson et al., 2020; Koralova, 2017; Zhu et al., 2021; Calderón-Rivera et al., 2024).

Behaviour refers to the routines, perceptions and decision-making processes that influence the willingness of organisations to adopt and use transport alternatives (Ben-Akiva et al., 2026). Modal choice is shaped not only by objective measures such as costs or environmental performance, but also by organisational culture, risk perception and accumulated experience (Sallnäs et al., 2022). Previous research consistently identifies behavioural factors as one of the main barriers to IWT adoption. Road transport benefits from strong organisational inertia resulting from its familiarity, flexibility and perceived reliability, whereas IWT is frequently regarded as more complex, less flexible and associated with greater operational risks (Rogerson et al., 2020). Transitions towards IWT depend on actors capable of reducing uncertainty and building confidence through demonstration projects, pilot operations and long-term collaboration. Entrepreneurial initiatives and learning processes play an important role in establishing the legitimacy and credibility required for broader adoption (Rogerson et al., 2020; Williamson et al., 2020; Sallnäs et al., 2022).

Contextual conditions encompass the physical, institutional and regulatory frameworks within which freight transport systems operate. It includes infrastructure availability, governance arrangements, investment frameworks and environmental conditions that enable or constrain transport operations. In the case of IWT, contextual conditions determine the practical feasibility of services through factors such as quay infrastructure, waterway characteristics, intermodal connections, and access to energy infrastructure. Seasonal variations in water levels, bridge clearances, lock dimensions and ice conditions may constrain vessel operations, while fragmented governance and long investment cycles frequently delay infrastructure improvements. Because these contextual conditions evolve over extended time horizons and require coordination among multiple public and private actors, they often become important sources of inertia that influence the pace of freight transport transitions towards IWT (Rogerson et al., 2020; Nassar et al., 2024).

Although these four dimensions have received considerable attention individually, their effects on the uptake of IWT are inherently interdependent. Business models influence investment in technologies and the organisation of transport services; technological developments reshape operational capabilities and service performance; behavioural responses determine whether these innovations are adopted; and contextual conditions enable or constrain the effectiveness of the other three dimensions. Understanding freight transport transitions towards IWT therefore requires a framework capable of representing where these interactions occur and how these interactions influence IWT uptake. This motivates the adoption of a transport system perspective. This integrated perspective provides the conceptual foundation for the system approach adopted in this study, which examines how interactions among these dimensions generate feedback mechanisms that shape the uptake of IWT.

2.2. A system perspective on IWT uptake

To analyse the interactions among business models, technologies, behaviour and contextual conditions, this study adopts a transport system perspective. Rather than treating these dimensions as isolated determinants of modal choice, the transport system perspective specifies where they operate, how they interact, and how changes in one part of the system influence others. This provides the structural basis for identifying feedback mechanisms through system dynamics.

Following Wandel et al. (1994), the freight transport system is represented as a set of interconnected layers through which freight demand, transport services and infrastructure interact.

The framework distinguishes three operational layers, i.e., the supply chain, transport and infrastructure, and two interfaces that mediate their interactions, i.e., the transport services market and traffic. This representation does not describe business models, technologies, behaviour or context dimensions themselves; instead, it identifies where these dimensions influence decisions and operations within the freight transport system.

The supply chain layer comprises freight generators and receivers, thereafter shippers. It represents the organisation of production, distribution and logistics decisions that generate demand for transport services. The transport layer refers to the provision of IWT transport services by freight companies, including service design and operation. The infrastructure layer comprises the physical assets that enable IWT, such as waterways, quays and intermodal connections. The transport services market mediates interactions between supply chain actors and freight companies through procurement, contracts and pricing, while traffic captures the interaction between transport operations and infrastructure use.

This layered representation provides a structured basis for system dynamics modelling. It supports the identification of feedback mechanisms across system components and helps define model boundaries and causal relationships. In the context of IWT, this perspective is particularly relevant because barriers and drivers often emerge from misalignments between system components rather than from deficiencies within a single layer (Browne et al., 2022).

The four dimensions introduced in Section 2.1 provide the analytical lens through which variables are identified, whereas the transport system framework provides the structural organisation of those variables within the causal loop diagram. Together, they define the conceptual basis for the qualitative system dynamics model developed in this study.

3. Research design

This study applies a qualitative system dynamics (SD) approach to analyse the uptake of IWT in freight transport systems. SD is well suited to the analysis of complex socio-technical systems (Sterman, 2000), where feedback loops, delays, and non-linear interactions connect system variables (Shepherd, 2014). Previous qualitative transport studies have used SD to examine system-level transformations associated with policy interventions and changes in business practices (Raoofi et al., 2024). In this study, SD is not used to predict modal shares but to identify relevant system variables, their interactions and feedback mechanisms, and the leverage points that influence the transition towards IWT.

The empirical analysis covered five Northwestern European countries: Sweden, Belgium, France, Germany and the Netherlands. Northwestern Europe provides an informative setting because it combines mature inland waterway systems (Belgium, Netherlands, Germany, France) with emerging systems (Sweden), allowing observation of IWT transitions across different stages of development. The sample included stakeholders positioned at different tiers of the supply chain, i.e., shippers (5), transport providers (7), forwarders (1), ports (1), as well as research centres (2), and policy makers (3).

Data were collected through nineteen semi-structured interviews and complemented with research and business reports. Participants were selected through purposive sampling to capture complementary perspectives across the freight transport system. Data were analysed through qualitative coding along four thematic dimensions: business models, green technologies, behaviours, and context.

The causal loop diagram (CLD) developed from the coded data captures interdependencies between variables across five components of the Wandel 1994's transport system. The objective

of the CLD is explanatory rather than predictive. Triangulation between coded data, actors' validation and model structure ensured empirical consistency and conceptual validity.

The causal loop diagram was developed in five steps. First, variables were extracted from the coded material. Second, causal links and polarity were assigned based on interview evidence and discussions among the paper's coauthors. Third, feedback loops were identified and grouped into reinforcing and balancing mechanisms used in the comparative analysis across commodity types. Fourth, leverage-points were identified to focus the recommendation of interventions on variables with potential system-wide effects.

Validation took place through a survey to participants and follow-up interviews, during which actors assessed the plausibility of relationships and the identified leverage-points.

4. Results

Thematic coding of interviews led to the identification of variables relevant to the potential uptake of IWT (listed in Table 1) across the thematic codes of business models, technologies, behaviours, and context by each transport system component (Wandel et al., 1994), i.e., supply chain layer, transport services market, transport layer, traffic interface, and infrastructure layer.

Table 1. List of variables by system component

Supply chain layer	***Transport layer***	***Infrastructure layer***
• Organizational capabilities [BM] • Stakeholders' complexity [BM] • Uncertainty in decision making [BH] • Engagement/communication [BH] • Production & storage capacity planning [BM] • Road transport inertia [BH]	• Shifted volume [Response variable] • IWT cost [BM] • Ton-km efficiency [BM] • Service level [BM] • Energy consumption [T] • Vessel innovation [T] • Availability of handling equipment [T] • Handling cost [T] • Diversification in IWT services [BM] • Service specialization based on cargo type [BM]	• Maturity level of IWT usage [C] • Availability of infrastructure for modes integration [C] • Investment in IWT infrastructure [C] • Complexity in IWT infrastructure management [C]

Transport services market	***Traffic interface***
• Contract length [BM] • Transport cost of other modes [BM] • IWT volumes uncertainty [BM] • Cargo imbalance [BM] • Incentives [BM] • Negotiation power [BH] • Flexibility in functional requirements [BH] • Administration work [BM] • Regulatory flexibility [C]	• Acceptability of IWT [BH] • Quays and navigation channels compatibility with vessels [C] • Green energy access [T] • Number of actors providing IWT services [BM] • Conflicts in infrastructure access with other modes [C] • Safety risks due to IWT [BH] • Externalities reduction [BM]

BM: Business models; T: Technologies; BH: Behaviours; C: Contextual.

The supply chain layer includes variables featuring business model aspects and behaviours that influence modal choice decisions of shippers, e.g., producers, retailers, and their supply chain facilitators, e.g., freight forwarders. This layer includes variables such as the number and complexity of stakeholders in the supply chain with a role in modal choice decisions, uncertainty

in how transport procurement decisions are made, and the level of engagement and communication within and across organizations. It also reflects shippers' capabilities to coordinate production and storage capacity needed to match IWT services and the inertia of established road transport choices.

The transport layer considers business model and technology aspects of IWT service having carriers as the main stakeholder. Central variables at this layer are the shifted volume and total transport cost, fed by variables such as ton-kilometre efficiency, handling cost and service level. Energy consumption, vessel innovation and handling equipment availability reflect technological features of IWT services. Diversification in IWT services and cargo-specific specialization capture the introduction of additional transport and infrastructure providers that offer varied routes, frequencies, and tailored operations to different IWT requirements.

The infrastructure layer consists of the physical environment that enables IWT operations and integration with other modes particular for each context. It includes the maturity of IWT usage, the availability of infrastructure for multimodal connections, and the level of investment in waterways, quays and terminals. It also considers variables related to the complexity of managing shared infrastructure across actors and uses.

The interplay between the supply chain and transport layer is mediated by the transport services market which includes variables related to the transactions between shippers and carriers via contracts and features of the negotiation process in the procurement of IWT services. This interface includes cost competitiveness with respect to other modes, uncertainty in IWT volumes, and cargo imbalance, impacting contractual aspects such as length, transparency, and flexibility. It also covers negotiation power, from the carrier perspective, modal shift incentives, trials, and regulatory flexibility, as well as operational variables like administrative work, and visibility of transport services.

Seemingly, the traffic interface links the transport and infrastructure layers and reflects the acceptability of IWT within its physical and social context. This interface includes variables such as quays and navigation channels compatibility with vessels, access to green energy, and the number of service providers operating on the waterways and port infrastructures for IWT. It also considers conflicts with other modes in the use of transport infrastructure, safety risks, and variables like training availability, crew fatigue, and externalities reduction (congestion, emissions, accidentality, among others).

The directionality and polarity of interactions among the listed variables within and between system components informed the causal loop diagrams presented in the following section. A causal relationship was included only when supported by empirical evidence from interviews and considered theoretically plausible by the research team.

4.1. Causal loop diagram describing the shift toward IWT

Figure 1 presents the causal loop diagram (CLD), showing the identified variables organised according to the system component to which they belong. The causal links are coloured green for same-direction influence and red for opposite-direction influence. The blue box highlights the main response variable, representing the shift in freight volumes towards IWT, while the orange boxes indicate the leverage points identified in the analysis, which are discussed in Section 4.2.

The CLD includes five reinforcing loops and two balancing loops. For clarity, the explanation focuses on these loops rather than individual links. The validation of feedback loops through a survey and interviews resulted in modifications to the CLD, already incorporated in the

descriptions below. Changes in the relationships between variables, depending on the type of the transported goods are discussed in Section 4.3 as part of the analysis across commodity types.

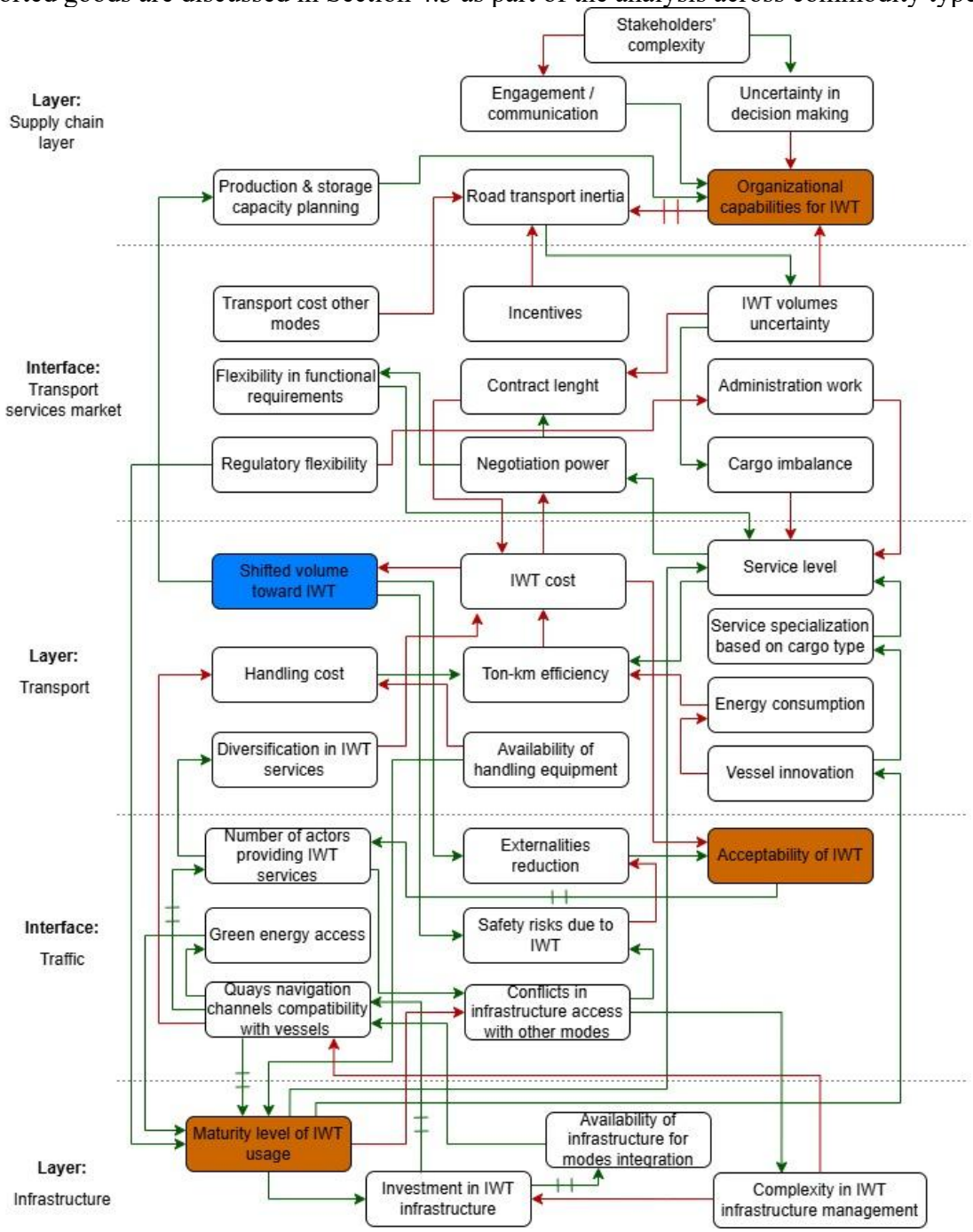
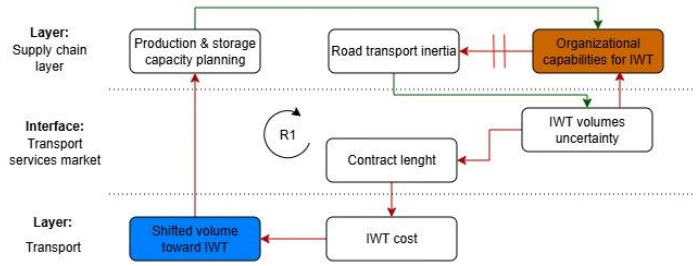


Figure 1. Causal loop diagram describing the shift towards IWT.

R1: IWT procurement

Figure 2 illustrates the reinforcing loop labelled as IWT procurement together with interviewees' quotes that exemplify the displayed relationships. Interdepartmental coordination and communication enable early planning and the use of large vessels over trucks, fostering long-term adoption of IWT. Long-term commitments on IWT volumes reduce flow uncertainty and

allow competitive contracts, which incentivise IWT use. As shifted volumes increase, companies adapt production and storage practices to align with IWT operations, closing the loop.



"Complex structure of stakeholders who would need to have their opinions expressed and taken into account." (Carrier, Sweden)

"Very difficult to make companies use a new logistics mode when others have existed for so long." (Living Lab, Belgium)

"If you don't have the expertise and specialized procurers, trucks will be much easier (to purchase)." (Shipper, Sweden)

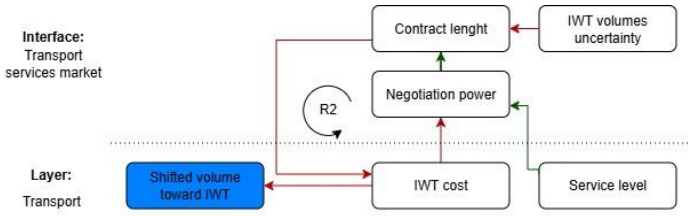
"Lengthy process for developing first services in IWT. Once offered, it gets momentum." (Carrier, France)

Figure 2. IWT procurement loop

This reinforcing loop captures one of the main drivers of inland water transport (IWT): transport demand. Realising the benefits of IWT requires planning practices that differ from those used in road transport. The larger capacity of vessels, fixed service locations, and longer lead times require early coordination of production, inventory, and transport planning to achieve the economies of scale inherent to IWT. Meeting customer demand efficiently and sustainably therefore depends on effective coordination within shipper organisations and with freight forwarders and carriers. Such coordination requires communication across managerial and operational levels, supported by procurement tools that integrate demand forecasts with storage capacity and transport planning. Over time, these organisational capabilities strengthen business models centred on IWT and reduce the behavioural inertia associated with established reliance on road transport. This transition is represented through delayed link between organizational capabilities and road transport inertia in Figure 2.

R2: IWT contracts negotiation

Service providers, e.g., carriers, may get negotiation power. Negotiation power strengthens as IWT service levels improve through greater reliability, frequency, and shorter lead times. Service level improvements depend on business models and technology factors such as vessel innovation, service specialization based on cargo type, reduced administrative burden, balanced cargo flows, as well as contextual factors related to IWT infrastructure maturity. Increased negotiation power through feasible and attractive value propositions to shippers enables transport operators to influence contract length and flexibility in service requirements. Longer and clearer agreements reduce uncertainty and get volumes commitment from shippers, which in turn stabilises demand and supports further service enhancements, closing the reinforcing loop (Figure 3). Moreover, investment risks in new IWT technologies (digitalisation, vessels and handling equipment innovations) decrease as contract length increases with benefits for both carriers, operating more cost-efficiently, and shippers, experiencing improved service levels of transport services.



"Decisions regarding new innovative inland or short-sea shipping solutions need longer contract periods, e.g. 5 years, because the transport provider needs to make investments." (Carrier, Sweden)

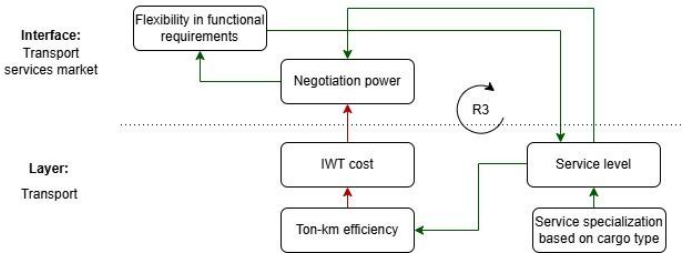
"The environmental aspect is not decisive for long-term contracts, (…) it is difficult to find a customer willing to pay for more green maritime transport solutions. Efficiency and value offer need to be at the core of IWT service proposition." (Shipper, Sweden)

"(…) there is a preference [from carriers] for contract length over price." (Carrier, Sweden)

Figure 3. IWT contract negotiation loop

R3: IWT efficiency

Efficiency also acts as a reinforcing mechanism driven by the interplay of business model and behavioural variables. Although it depends on the type of IWT operation (further elaborated in Section 4.3), as higher efficiency is more likely in transport services for long distances and big volumes. It is also achieved by coordinating goods flows in opposite directions to avoid empty trips, which requires flexibility in functional requirements and specialised equipment to handle different goods without risking products integrity and quality.



"And because the barges are quite large – about 50 meters long and 7 meters wide– it makes sense to transport bulky goods: wooden beams, construction materials, waste from building sites, or bulk paper and wood waste. Using the onboard crane, the boats can adapt to different types of cargo." (Carrier, France)

"The main challenge is cost. (…) But as adoption grows, it will become more affordable." (Carrier, France)

"In reverse logistics, we also transport waste and recyclable goods. Currently, we transport beverages for distribution, as well as construction materials for building sites." (Carrier, France)

Figure 4. IWT efficiency loop

Service level attributes, i.e., reliability, frequency and lead times, have a direct impact on ton-kilometre efficiency and therefore on IWT cost (Figure 4). This loop connects with R2 given that the effect of reduced IWT cost impact negotiation power of transport providers, influencing back service levels and efficiency variables.

R4: IWT infrastructure development

Infrastructure development constitutes another reinforcing loop, driven primarily by contextual factors that can either enable or constrain the uptake of IWT. Figure 5 illustrates the

variables and interviewee quotes emphasizing the importance of vessel compatibility with navigation channels and quays. This compatibility is influenced by the availability of infrastructure that integrates IWT with other transport modes –needed for first and last mile operations–, the development of handling equipment suitable for urban and port environments, and the necessary investments from private and public sectors. Improving quay infrastructure, navigation channels, and multimodal integration, reduce conflicts over transport infrastructure access and contribute to the maturity of IWT usage. However, these effects are not immediate. As represented by the delayed links in Figure 5, infrastructure planning, administrative procedures, and construction require considerable time before improvements translate into greater IWT uptake.

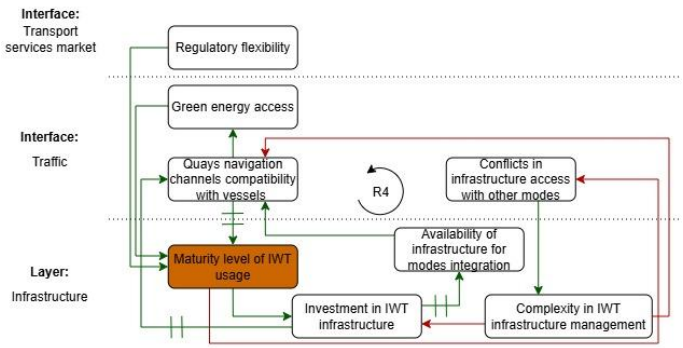


Figure 5. IWT infrastructure development loop

"For the large volumes, it is the boat that applies (...). Land legs at both ends. From quarry to port and from unloading to customer." (Shipper Sweden)

"The canal is a big risk. If a channel is closed or has low water levels, schedules must change. Therefore, it is an advantage for trucks." (Shipper Sweden)

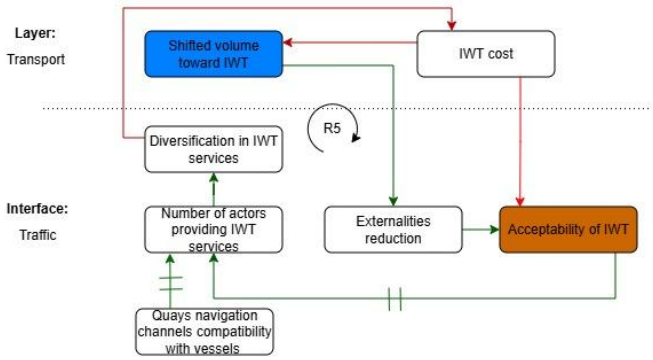
"The real challenge is fuelling infrastructure. For electric or hydrogen vessels, the necessary facilities are not yet fully developed." (Carrier, France)

Complexity in IWT infrastructure management introduces an opposite-direction influence within this loop. Unclear responsibilities for investment and maintenance may leave IWT infrastructure in legal limbo, resulting in deteriorating quays and non-navigable channels. These conditions obstruct the uptake of IWT and undermine efforts to achieve system maturity. Furthermore, regulatory frameworks may enable higher maturity levels of IWT usage as they not only ensure operational feasibility but also incentivize the use of IWT due to environmental benefits. Access to refuelling or charging stations along waterways needs to be considered too, as environmental benefits of IWT can only be realized when vessels operate using clean energy sources.

R5: Environmental impact and service offer

The final reinforcing loop reflects the impact of volumes shifted to IWT on environmental conditions and the availability of transport services. IWT is recognized as a sustainable freight alternative due to its lower emissions, reduced noise, and contribution to alleviating road congestion. These positive externalities encourage policies that promote IWT over road transport and position it as a viable solution for companies seeking to meet sustainability targets. Reduced environmental impacts combined with cost-efficient operations enhance the acceptability of IWT among businesses and the wider community.

Greater acceptability attracts additional service providers, diversifying offerings and driving down costs, which in turn reinforces the loop by further increasing the volume shifted to IWT as shown in Figure 6. However, the entry of new actors into the market can occur at a slow pace –delay symbol in the diagram– and remains conditioned on contextual factors highlighted in R4, particularly quays infrastructure and navigation channels.



"The main benefit is lower environmental impact. One barge can replace up to 40 trucks, reducing noise, congestion, and pollution. This is especially relevant since large cities are introducing low-emission zones. Using barges helps meet these requirements." (Carrier, France)

"Road congestion and scalability are two big drivers for the shift from road to waterway transportation." (Carrier, Sweden)

"During these 20–25 years, services have also been developed on other waterways, in northern France and beyond." (Carrier, France)

"In these two years, we have come to the conclusion that it is not a consolidation towards a port that is needed for the uptake of IWT, we need the diversification [more than one port]." (Public authority, Sweden)

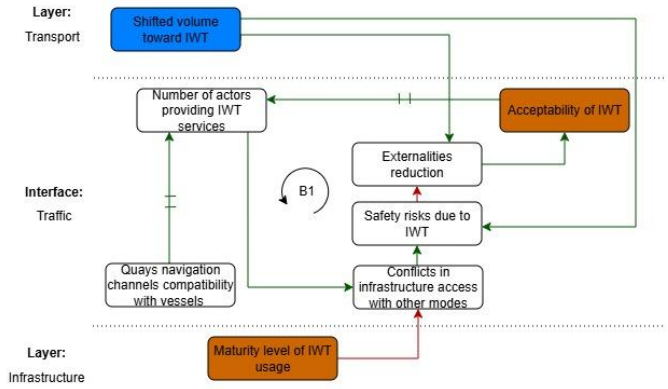
Figure 6. Environmental impact and service offer loop

B1: Saturation of transport infrastructure

The saturation of transport infrastructure due to increased IWT represents one of the system's balancing loops shown in Figure 7. Increasing the number of actors providing IWT services can strain infrastructure access, creating conflicts among IWT users and other modes as well. Rising conflicts elevate safety risks, undermining the potential of IWT to mitigate externalities. Safety concerns are further influenced by crew fatigue due to the intensity of operations and the limited availability of personnel with the necessary skills (e.g., pilots, crew), highlighting the need for education programs including IWT operations. Although these concerns apply to other transport modes, they are critical for IWT in context such as Sweden (the big Swedish lakes).

Infrastructure access conflicts also stem from inadequate quays and navigation channels, exacerbated by complex governance structures, unclear investment responsibilities (as mentioned in R4), and the overall lack of maturity in IWT usage. This immaturity is reflected in the limited familiarity of companies, authorities, and the wider community with IWT operations in urban and regional contexts. Therefore, improvements in the acceptability of IWT do not immediately translate into an increased number of service providers. Even when IWT becomes more attractive from an environmental or economic perspective, the entry of new operators is delayed by the time required to build market confidence, secure investments, acquire vessels, and develop the capabilities needed to provide services. As a result, the positive effect of acceptability on market participation occurs gradually, introducing a delay that moderates the expansion of IWT services and the subsequent pressure on transport infrastructure.

This balancing loop suggests the existence of tipping points in the development of IWT. As transport volumes increase, the benefits associated with modal shift may gradually diminish if investments in infrastructure, governance, and human resources do not keep pace with demand. Beyond a certain level of utilisation, access conflicts, safety risks, and operational complexity can increase more rapidly than system capacity, slowing or even reversing further uptake.



"Operating logistics in Paris requires us to work in short time slots - half an hour, one hour, sometimes two. Once we finish unloading, we must leave the quay clean so pedestrians and cyclists can use it again." (Carrier, France)

"*A challenge is to integrate the greenery and waterways with the urban environment to improve the quality of nature in the city*." (Municipality, Sweden)

"Quays should not be usage specific to maximize the utilization of space in the urban environment." (Municipality, Belgium)

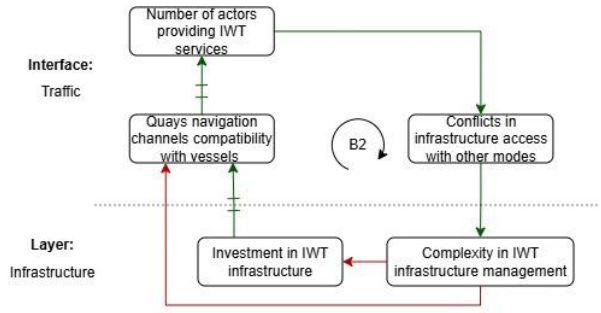
"*Many quays in the city are being rebuilt into promenades to host businesses such as restaurants, which makes finding quays for loading and unloading more challenging than it already is.*" (Municipality, Sweden)

"Takes a long time to build knowledge and networks among customers and actors." (Shipper, Sweden)

Figure 7. Saturation of transport infrastructure loop

B2: Investment in IWT infrastructure

The second balancing loop concerns investment complexity. The involvement of multiple stakeholders in IWT infrastructure, such as national and local governments, ports, and private owners, complicates governance and slows investment processes. This delay reduces the usability of existing infrastructure and limits the compatibility of quays and navigation channels with vessel and operational requirements. While this issue is less pronounced in port facilities, it becomes a significant barrier in urban areas, where incompatible conditions hinder the entry of new service providers and constrain integration with other transport modes. These limitations further exacerbate conflicts over infrastructure access, as shown in Figure 8.



"The quay ownership problem where one stakeholder could own the quay, a second stakeholder could manage operations on the quay, a third could own the real estate on the quay and a fourth could use the quay." (Carrier, Sweden)

"Different restrictions and regulations need to be implemented for how long boat owners can stay in one place, similar to parking spaces." (Municipality, Belgium)

"Does not matter if the municipalities invest in quays, if the goods owners do not invest... Everyone has to do their part." (Municipality, Sweden)

Figure 8. Investment in IWT infrastructure loop

This loop also highlights potential infrastructure and governance tipping points. As the utilisation of quays and navigation channels increases, additional traffic may lead to disproportionate increases in waiting times and conflicts with other transport modes. At the same time, a growing number of actors and fragmented governance responsibilities can exceed the capacity of existing coordination mechanisms, slowing investment processes and delaying decisions on infrastructure development and access.

The interplay of reinforcing and balancing loops exhibits the system dynamics of the IWT uptake driven by variables that relate to business models, technologies, behaviours and context. Reinforcing loops with a same-direction influence toward shifted volume amplify IWT uptake through developed organizational capabilities for IWT, improved service levels, infrastructure, and acceptability, while balancing loops highlight constraints related to infrastructure conflicts and investment complexity. This system perspective provides the basis for the identification of leverage-points that generate system-wide effects towards IWT uptake, further described in the following section.

4.2. Leverage-points with potential for system-wide effects

Three leverage points emerged across the feedback loops as potential drivers for transformations in the shift towards IWT: organisational capabilities, maturity of IWT usage, and acceptability. These leverage points were identified based on their centrality in mediating interactions among the different components of the transport system. They also act as mechanisms to delay or shift the tipping points identified in the balancing loops, allowing the reinforcing loops to remain dominant over a broader range of transport demand. Their relevance was further confirmed during the stakeholder validation workshop, where participants recognised their potential to build momentum for the modal shift towards IWT. These leverage points capture the effect of variables related to business models, technology, behaviour, and contextual conditions, making them strategic entry points for interventions that support the uptake of IWT.

Organizational capabilities comprise variables related to business models and behaviours that determine how shippers plan, negotiate, procure and coordinate transport services. This leverage-point articulates variables featuring the supply chain layer and the transport market interface, addressing a necessary condition for IWT uptake: transport demand. Actions targeting this leverage-point influence freight volume certainty by involving stakeholders in decisions on transport procurement, and production / storage planning that meet the economies of scale inherent to IWT. Improved organizational capabilities for IWT lead to long-term contractual agreements with transport providers, which in turn benefit service levels and reduce total IWT costs.

Maturity of IWT usage encompasses variables associated with context and technologies within the transport, traffic and infrastructure components of the transport system. It reflects the degree to which IWT constitutes an established mode for goods movement, conditioned to vessel-infrastructure compatibility, technological advancements in handling equipment, access to renewable energy sources, and regulatory frameworks that facilitate IWT operations. Actions at this leverage-point affect service levels, development of IWT infrastructure, improved access to available infrastructure in coordination with other transport modes, thereby influencing the central response variable, i.e., shifted volume toward IWT.

Acceptability reflects the perception of IWT services within business networks and the general community. It includes variables on behaviour at the transport and traffic components of the transport system. Acceptability is shaped by impacts of IWT operation on the environment, and features related to efficiency of transport services, service levels and overall IWT cost. Actions

aimed at improving acceptability stimulate diversification in service provision and foster market competition, which contribute to cost reductions. Furthermore, this leverage-point incorporates balancing mechanisms that address safety concerns and mitigate conflicts over infrastructure access, reinforcing the legitimacy and attractiveness of IWT as a sustainable transport alternative.

These leverage-points interact through variables related to business models (service level, contract length, diversification of IWT services), technologies (vessel innovation, digitalization, green energy access), behaviours (decision-making structures, coordination, road transport inertia, and public perception), and context (quays infrastructure, navigation channels, regulations and investment), converging to the key response variable of the system model: shifted volume. The identified leverage-points serve as reference elements for designing interventions that create system-wide effects as discussed in section 5.

4.3. Findings across commodity types

The functioning of feedback loops and leverage-points experience nuances across commodity types – bulk, container, and RoRo. This section describes features of commodity types and summarizes differences in feedback loops for each case in Table 2.

Bulk transport is characterized by operations that rely on large volumes, specialized handling, and coordination between multiple actors. Although differences exist among type of goods transported, e.g., agriculture, construction, waste, mining, among others, overall, the use of inland waterways in this segment is often constrained by fragmented quay ownership, limited storage capacity at sources and quay sides, and uncertainty in demand. Planning is affected by variability in production, warehousing, and seasonal flows, which complicates the alignment between transport supply and demand. Operational challenges, such as delays and handling constraints, further reduce reliability. In addition, imbalances in flows frequently lead to empty trips, affecting cost efficiency. While bulk transport can benefit from economies of scale, it requires substantial space at ports and may create operational dispersion of goods and traffic. These features contribute to its relatively low priority in port space allocation.

Container transport presents a more standardized and scalable system. The use of containers allows consolidation of flows and facilitates handling, storage, and transfer between modes. This standardization supports efficient use of port space through stacking, which increases its attractiveness in port operations. However, strong competition from road and rail transport limits incentives for modal shift. The interviews indicate that commercial arrangements, such as trial periods and flexible agreements, are important to demonstrate the feasibility of IWT. Operationally, container transport depends on coordination across actors and the availability of digital tools for tracking and tracing. Despite these advantages, issues such as empty container movements and the allocation of responsibilities for repositioning remain relevant challenges, not only for IWT, but also to other transport modes.

RoRo transport is characterized by regular, scheduled operations and a strong focus on time performance. The system is designed to ensure continuous flows between origin and destination, often aligned with fixed timetables. This makes it particularly sensitive to delays and disruptions, especially at port interfaces. Compared to bulk and container transport, RoRo operations require significant port space and efficient terminal handling. The interviews also indicate that communication between actors plays a central role in maintaining service reliability and supporting long-term engagement. While RoRo offers lower emissions compared to road transport, its uptake is influenced by behavioural factors, including resistance to change and the need for alignment across supply chain actors.

Table 2. Nuances of feedback loops across commodity types

Loop	Bulk	Container	RoRo
R1 - Procurement	Structured planning in sectors with stable demand (e.g. construction); high dependence on coordination for handling and port access; limited flexibility due to variability in flows	Consolidation enables volume aggregation; higher volumes support increased frequency and regular services; more flexibility in planning compared to bulk	Procurement aligned with fixed schedules; strong coordination between shippers and carriers; limited flexibility due to timetable constraints
R2- Contract negotiation	Contracts based on full loads; limited consolidation; affected by seasonality and demand variability	Higher volumes increase negotiation power; consolidation supports longer-term and more flexible contracts	Stable demand supports long-term agreements; contracts aligned with scheduled services and operational regularity
R3 - Efficiency	Requires specialized equipment; limited flexibility; coordination challenges lead to empty trips; port handling may increase costs	Standardization supports efficiency; digital tracking improves coordination; empty container repositioning remains an issue	High sensitivity to delays; efficiency depends on synchronization with first/last mile; tight operational time windows
R4 - Infrastructure development	Flexible use of quay infrastructure - limited quay requirements; dependent on specialized loading equipment; unclear investment responsibilities	Requires advanced infrastructure (e.g. cranes, sufficient draft); higher investment needs; strong dependence on port infrastructure	High dependence on port space and terminal capacity; constrained by availability of dedicated infrastructure and integration with other modes
R5- Environmental impact & service offer	Lower emissions but potential local impacts (e.g. material loss); acceptability varies by cargo type	Strong alignment with sustainability goals; benefits from modern vessels and efficient operations; supports service diversification	Lower emissions than road; sustainability supports uptake but depends on operational reliability and service quality
B1- Infrastructure saturation	Large space requirements at quay side areas; low priority in port access; dispersed operations increase congestion	Efficient space use through stacking; higher priority in port allocation; still affected by congestion	High demand for port space; strong competition for terminal capacity; sensitive to access constraints
B2 - Investment in infrastructure	Unclear responsibilities for quay and equipment investment; slow development	High upfront investment (e.g. cranes); once installed, reinforces priority in port access	Investment constrained by market uncertainty and capacity limitations in vessels and terminals

5. Discussion

This study aimed at examining variables, their interactions, and leverage-points influencing IWT uptake using a system dynamics approach. The findings reinforce previous research showing that business models, technologies, behaviour and contextual conditions all influence the uptake IWT, but they also provide a more integrated explanation of how these dimensions jointly shape freight transport transitions. Rather than acting as independent determinants of modal choice, the results demonstrate that their effects emerge through reinforcing and balancing feedback mechanisms operating across the freight transport system. This perspective extends existing literature, which has predominantly examined these dimensions separately, by explaining how interactions among organisational, technological and institutional processes impact system behaviour (Williamson et al., 2020, 2021; Sallnäs et al., 2022; Calderón-Rivera et al., 2024; Ghisolfi et al., 2022).

The first contribution concerns the role of business models in enabling freight transport transitions. Previous studies have emphasised that business models supporting IWT require longer planning horizons, demand aggregation and stronger coordination among supply chain actors than those supporting road transport (Konings, 2009; Williamson et al., 2020; Sallnäs et al., 2022). The present findings extend this understanding by showing that business models are not merely organisational arrangements facilitating IWT operations, but mechanisms through which reinforcing feedback develops. Organisational capabilities, contractual stability, production planning and service diversification interact to reduce uncertainty and increase volume commitment, thereby strengthening the competitiveness of IWT. Business models influence modal shift not only through immediate operational improvements but also by creating the conditions under which subsequent technological investments and service development become economically viable. This interpretation highlights the dynamic nature of business models within freight transport systems, shifting attention from static organisational configurations towards adaptive processes that continuously reshape transport demand and service provision.

The second contribution concerns the role of technological development. Existing literature frequently presents innovations such as vessel modernisation, automation, digitalisation and alternative propulsion as key enablers of IWT competitiveness (Williamson et al., 2020; Koralova, 2017; Zhu et al., 2021; Calderón-Rivera et al., 2024). While the present study confirms their importance, it also places technological innovation as a necessary condition rather than a sufficient one to initiate freight transport transitions. Technologies act as enabling conditions whose effects depend on complementary organisational capabilities and contextual maturity. Improvements in digital planning, vessel performance or handling equipment contribute to modal shift only when transport demand is sufficiently coordinated, contractual arrangements reduce investment uncertainty, and infrastructure supports reliable operations. This finding helps explain why similar technological innovations often produce different outcomes across operational contexts and supports recent calls for more systemic approaches to freight transport decarbonisation that account for organisational and institutional processes alongside technological change (Ghisolfi et al., 2022; Pirouzrahi et al., 2025).

The findings also refine current understanding of behavioural and contextual influences on IWT adoption. Previous studies have consistently identified organisational routines, risk perceptions and infrastructure limitations as major barriers to modal shift (Rogerson et al., 2020; Williamson et al., 2021; Nassar et al., 2024). The causal loop analysis suggests that these factors should not be interpreted as static constraints but as endogenous properties of the freight transport system. Organisational inertia towards road transport decreases as firms accumulate operational experience and strengthen coordination capabilities, while acceptability evolves through improvements in service quality, environmental performance and stakeholder involvement. Similarly, infrastructure maturity reflects cumulative investments, governance arrangements and operational learning rather than a fixed physical condition. This interpretation is relevant because it highlights the temporal dimension of freight transport transitions, where behavioural responses and contextual conditions continuously co-evolve with technological and organisational developments instead of remaining external constraints.

These findings contribute to a more systemic understanding of freight transport transitions by demonstrating that business models, technologies, behaviour and contextual conditions become influential through their interactions rather than through their individual effects. The reinforcing loops identified in this study illustrate how organisational learning, service improvements and market confidence can progressively strengthen the competitiveness of IWT, whereas the

balancing loops reveal that infrastructure constraints, governance complexity and safety concerns may eventually limit further expansion if system capacity does not evolve accordingly. This dynamic perspective complements previous system dynamics research, which has primarily examined freight decarbonisation through aggregated representations of infrastructure investment, modal shares and policy interventions (Ghisolfi et al., 2022; Nassar et al., 2023; Pirouzrahi et al., 2025). By explicitly incorporating organisational capabilities, contractual arrangements and behavioural processes as endogenous elements of the transport system, the proposed framework provides a complementary explanation of why similar policy or technological interventions may lead to different transition pathways depending on the maturity and organisation of the freight transport system.

These findings suggest that freight transport transitions are governed less by individual technological or organizational improvements than by the interactions among them. The three leverage points identified in this study provide a systems-level explanation of how business models, technologies, behaviours, and contextual conditions jointly shape the evolution of IWT. Rather than identifying new barriers or drivers, this perspective explains how established determinants reinforce or constrain one another, thereby influencing the pace and direction of modal shift. This conceptual understanding also provides a basis for identifying interventions capable of influencing system behaviour.

5.1. Translating leverage points into system interventions

Building on this system perspective, the leverage points provide a practical framework for designing interventions that influence the dynamics of freight transport transitions rather than addressing isolated barriers. Because reinforcing and balancing feedback mechanisms operate simultaneously, isolated actions are unlikely to produce sustained system change. Instead, effective interventions should strengthen reinforcing processes while delaying or mitigating the balancing mechanisms that constrain system growth. Although the three leverage points are common across IWT applications, their operational expression differs according to the characteristics of bulk, container, and RoRo transport. This section illustrate how these differences translate into targeted interventions for each leverage point.

Organizational capabilities

Organizational capabilities emerged as the leverage point most directly associated with the generation of transport demand. The reinforcing procurement and contract negotiation loops indicate that improvements in planning, coordination and procurement practices reduce uncertainty in freight volumes, facilitate longer contractual commitments and create the conditions for sustained investment in IWT services. These findings suggest that interventions should focus on increasing coordination among supply-chain actors rather than solely improving transport operations.

However, the operational expression of these interventions differs across commodity types (Table 3). In bulk transport, interventions emphasize securing stable freight volumes through longer-term contractual arrangements, coordinated planning, and investments in organizational capabilities that reinforce economies of scale. For container transport, the priority shifts towards collaborative procurement, information sharing, and demand consolidation to improve service frequency and reduce operational uncertainty. In contrast, RoRo transport benefits from interventions that strengthen coordination between shippers and operators that support synchronized scheduled services and more efficient utilization of existing capacity.

Table 3. Illustrative interventions targeting organizational capabilities across commodity types

Intervention	Bulk	Container	RoRo
Promoting longer-term contracts *(Business model domain)*	Promote longer-term contractual arrangements where freight volumes can be secured. Their applicability depends on the characteristics of the commodity; they are common in project-based sectors such as construction and in agricultural supply chains with stable production volumes	Balance long- and short-term contractual arrangements according to flexibility requirements. Longer-term contracts provide investment security, whereas shorter-term agreements enable operators to respond to fluctuations in demand	Longer-term contractual arrangements are a core element of the business model, providing the stability required to sustain regular scheduled services and long-term investment
Supply-demand matching under efficiency conditions *(Business model domain)*	Identify return loads along transport corridors to reduce empty trips and improve vessel utilization	Balance inbound and outbound container flows by coordinating services across ports and logistics operators, thereby reducing empty repositioning	Optimize route utilization by balancing freight flows across scheduled services and making use of available transport capacity
Collaborative procurement *(Business model domain)*	Promote collaboration among shippers with similar cargo-handling requirements. Consolidation is generally less critical because individual shippers often generate sufficiently large transport volumes. Collaboration should therefore focus on coordinating procurement rather than consolidating freight	Facilitate collaborative procurement through the consolidation of freight volumes and transport orders across multiple shippers, improving service viability and frequency	Promote shared transport capacity where appropriate. Although consolidation requirements are generally lower than in container transport, capacity sharing can improve asset utilization and operational efficiency
Digitalization and data-sharing standards *(Technology domain)*	Improve visibility of vessel location and operations through shared digital platforms to support planning and coordination	Enhance intermodal coordination through real-time tracking of vessels and containers, providing greater schedule reliability and operational transparency	Intermodal coordination requires certainty in schedules eased by digitalization
Align sustainability goals with transport procurement *(Behaviour domain)*	Integrate Scope 3 emissions into procurement strategies, particularly in hard-to-abate sectors such as construction. Strengthen shippers' capacity to influence cleaner transport operations while balancing cargo value against the additional cost of sustainable transport.	Encourage procurement practices that prioritize low-emission transport services, subject to the availability of sustainable shipping solutions and supporting infrastructure such as on-shore power supply	Respond to increasing end-consumer sustainability expectations by integrating environmental criteria into procurement decisions and expanding access to on-shore power infrastructure where regulations require it

Maturity of IWT usage

The analysis also indicates that increasing the maturity of IWT extends the range over which reinforcing loops remain dominant before balancing mechanisms associated with infrastructure saturation become limiting. Maturity therefore represents more than infrastructure availability; it reflects the combined development of physical assets, technological capabilities and governance arrangements that support reliable transport services.

The interventions identified in Table 4 illustrate that increasing IWT maturity requires coordinated investments in infrastructure, digitalization, regulation, and governance. Their implementation, however, varies across commodity types. In bulk transport, priorities include

flexible quay configurations, onboard handling capabilities, and governance arrangements that accommodate heterogeneous cargoes and established freight flows. Container transport relies more heavily on standardized handling infrastructure, interoperable digital platforms, and coordination among a larger number of actors to manage complex intermodal operations. For RoRo services, interventions focus on efficient terminal interfaces, regular service operations, and governance mechanisms that support multimodal integration

Table 4. Illustrative interventions targeting maturity of IWT usage across commodity types

Practical implications	Bulk	Container	RoRo
Innovation pilots for autonomous vessels (*Technology domain)*	Pilot autonomous vessel operations in specific canals or urban waterways where routes are fixed and traffic density is low. The heterogeneity of vessel designs limits broader implementation, although autonomous mooring systems represent a promising application	Pilot autonomous cargo-handling equipment where coordination among multiple stakeholders and complex terminal operations can be effectively managed. The operational complexity of container logistics makes full vessel autonomy more challenging	Fixed schedules and regular service patterns provide favourable conditions for piloting autonomous vessel operations
Interoperable digital platforms (*Technology domain)*	Improve visibility between terminals and vessels to support transport planning and operational coordination. Digital integration should also facilitate information exchange between transport operators and bridge or canal gate managers	Improve visibility between terminals and vessels while integrating intermodal operators into digital platforms. Information exchange with bridge and canal gate managers further supports planning and coordination across transport modes	Improve visibility between terminals and vessels while enabling real-time coordination with bridge and canal gate managers. Digital integration with intermodal operators is particularly important for supporting tight operational schedules, where just-in-time operations remain challenging
Regulations facilitating IWT (*Context domain)*	Tailor permitting requirements to the type of goods transported, reflecting commodity-specific environmental risks such as dust and noise. Streamline permits for cargo-handling equipment and adapt pilotage requirements to river navigation and urban inland waterways	Environmental permitting, particularly with respect to noise, while ensuring efficient cargo-handling operations	Environmental permitting, particularly regarding noise, while maintaining operational efficiency and service reliability
Governance structures coordinating multiple stakeholders (*Context domain)*	Establish governance structures that coordinate infrastructure managers across locks, rivers, fairways, and quays/terminals. Governance is facilitated by fewer actors, relatively mature freight flows (e.g., the Swedish case), and	Strengthen governance structures coordinating infrastructure managers across locks, rivers, fairways, and quays/terminals. Compared with bulk transport, coordination is more complex due to the involvement of additional	RoRo operations are less common on inland waterways than in short-sea shipping, increasing the need for coordination among multiple actors

	vessel designs adapted to navigating narrow waterways. Educational initiatives on procedures and permitting can further support coordination	actors, particularly shippers, and the lower maturity of inland waterway systems	
Co-investment schemes (*Context domain)*	Strengthen coordination across levels of government to support co-investment in infrastructure and vessel innovation, enabling the use of existing quays and waterways	Promote shared investment models, including the leasing of handling equipment, through coordinated collaboration between terminals and ports.	
Standardization of quay design and handling equipment (*Context domain)*	Vessels equipped with onboard cranes, reducing the need for quay-side lifting equipment. While crane investments are comparatively lower from a port perspective, adequate quay bearing capacity remains essential	Investment in standardized quay cranes and cargo-handling systems to support efficient container operations	Investment in dedicated ramps to enable efficient loading and unloading of RoRo vessels

Acceptability

Acceptability constitutes the third leverage point through which environmental performance, operational reliability and stakeholder confidence reinforce the expansion of IWT services. Unlike organizational capabilities and maturity, which primarily influence operational performance, acceptability determines the willingness of both market actors and society to support the continued development of IWT. Improvements in environmental performance, reductions in congestion and greater service reliability increase confidence in the mode, encouraging market entry and diversification of transport services.

The analysis further suggests that acceptability is shaped by the interaction between operational performance and stakeholder perceptions, making it inherently context dependent. As shown in Table 5, interventions extend beyond improving environmental performance to include targeted awareness campaigns, engagement with local communities, investment in zero-emission technologies, and incentives that demonstrate the value of IWT. Their relative importance varies across commodity types. In bulk transport, interventions address local environmental impacts, the coexistence of freight operations with urban activities, and confidence in new corridors. Container transport places emphasis on demonstrating operational performance while improving compatibility with intermodal logistics systems. In RoRo transport, interventions focus on strengthening confidence across the supply chain through reliable scheduled services and coordinated operations, while maintaining public support through effective community engagement.

Table 5. Illustrative interventions targeting acceptability across commodity types

Practical implications	**Bulk**	**Container**	**RoRo**
Performance-based incentives (*Business model domain)*	Design incentives that capitalize on economies of scale, increasing the operational attractiveness and	Design incentives that address the operational complexities of first- and last-mile	Design incentives that enhance the efficiency of transport modes connected to IWT, for

	acceptability of IWT for bulk transport	connections, reducing barriers to the acceptability of IWT	example by avoiding congested routes. Economies of scale can further strengthen the acceptability of IWT
Urban logistics zones (*Context domain)*	Manage high-value urban space through shared-use arrangements, such as time windows, to accommodate freight operations while maintaining urban attractiveness. Increasing user familiarity with scheduled operations can improve acceptance. Key considerations include space requirements, visual impacts, and the safe sharing of waterways with other users through appropriate traffic management	Design urban logistics zones to facilitate efficient freight flows while ensuring the safe sharing of waterways with other users through appropriate traffic management	
Investment in zero-emission vessels and infrastructure (*Technology and context domain)*	Invest in vessels equipped with onboard facilities (e.g., waste management systems) to reduce the need for land-based infrastructure. Coordinated investment in both vessels and infrastructure is required, although modifications to bridges and other historically valuable assets may affect public perception. High investment costs also influence the acceptability of IWT	Investment in zero-emission vessels and infrastructure is generally well accepted by the public, although the associated capital costs remain a major challenge for implementation. Higher acceptance within the general public but investment challenges implementation	
Awareness campaigns *(Context domain)*	Awareness of IWT is generally high where freight flows are well established. Awareness campaigns become particularly important when introducing new operations or opening new transport corridors	Greater awareness efforts are needed due to the lower maturity of IWT operations. Demonstration projects and media campaigns can increase awareness and stimulate interest among potential users	Greater awareness efforts are needed due to the lower maturity of IWT operations. Demonstration projects and media campaigns can increase awareness, with a stronger emphasis on supply chain actors than on the general public
Engagement with local communities *(Context domain)*	Noise level tests for (un)loading compared to other modes. Engagement of surrounded communities. Addressing the concerns related to noise from the engines and smell. Clear and communicated plans to manage these aspects. Safety to other waterway users	Engagement of surrounded communities. Addressing the concerns related to noise from the engines and smell. Clear and communicated plans to manage these aspects. Attention to visibility impacts due to vessel dimensions. Safety to other waterway users	

These interventions demonstrate that leverage points provide strategic directions for influencing system behaviour rather than prescribing universal interventions. While the underlying mechanisms remain consistent across the IWT system, their implementation must account for the operational characteristics of different commodity flows and the maturity of local IWT systems.

Successful freight transport transitions towards IWT require combinations of interventions that simultaneously strengthen organizational capabilities, increase the maturity of IWT usage and improve the acceptability of the mode, thereby reinforcing the positive feedback processes identified in this study while delaying the emergence of balancing mechanisms.

6. Conclusions

This study developed a qualitative system dynamics model to explain how freight transport transitions towards inland water transport emerge from interactions among business models, technologies, behaviours, and contextual conditions. Rather than viewing these dimensions as independent drivers of modal shift, the findings show that their effects arise through reinforcing and balancing feedback mechanisms operating across the freight IWT system. This systems perspective reveals that the transition towards IWT depends not only on improving operational performance but also on strengthening the interactions that enable transport demand, reliable service provision, and long-term stakeholder commitment.

Three leverage points, i.e., organizational capabilities, maturity of IWT usage, and acceptability, provide a framework for understanding how these interactions influence system behaviour. Organizational capabilities influence the ability of shippers and intermediaries to plan, procure and commit volumes to IWT services, reducing uncertainty and enabling contractual stability. Maturity of IWT usage reflects the alignment of infrastructure, technology and governance arrangements required for reliable and cost-efficient operations. Acceptability captures how IWT is perceived by businesses and communities and mediates the role of environmental benefits in adoption decisions. Together, they demonstrate that accelerating IWT uptake requires coordinated interventions addressing organizational, technological, institutional, and societal dimensions simultaneously. The comparison across bulk, container, and RoRo transport further shows that while these leverage points are common across IWT operations, their implementation must reflect the operational characteristics of different freight segments rather than relying on generic interventions.

Beyond IWT, the proposed framework offers a systems-based perspective for analysing freight transport transitions more broadly. By linking leverage points to feedback mechanisms, it provides a basis for designing interventions that strengthen reinforcing processes while delaying the balancing mechanisms that constrain system growth. This perspective complements approaches centred on individual barriers or technologies by emphasising the dynamic interactions through which sustainable freight systems evolve. The findings contribute to understanding the transition toward renewed IWT use as a “back to the future” movement, i.e., a return to a proven concept adapted to contemporary system dynamics.

Future research should quantify the identified feedback mechanisms, evaluate the effectiveness of different intervention portfolios under varying operational contexts, and examine how the proposed leverage points apply to other freight transport transitions. Such work would support the development of adaptive policies capable of accelerating decarbonisation while improving the resilience and competitiveness of freight transport systems.

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