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Cargo consolidation in port-hinterland container transport: A spatial economic assessment for inland waterways

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ABSTRACT

Inland waterway transport (IWT) stands out as one of the most sustainable modes of freight transport for port-hinterland connections. However, the full potential of IWT remains underutilized in Europe due to logistical inefficiencies. Specifically, the low loading factors of vessels and containers result in the need for more services to transport the same level of cargo, leading to increased costs and travel time, thereby diminishing market competitiveness. The aim of this paper is to develop a spatial-economic assessment of a cargo consolidation strategy for IWT, leveraging a discrete event simulation model that accounts for network characteristics, modal competition with road and rail services, travel time, and costs. It employs an evaluation framework that focuses on cost savings per TEU of different implementation scenarios. A case study on container flows in the Rhine-Alpine Corridor was conducted, evaluating three strategic locations for deploying a container freight station. Compared to the baseline scenario, only one implementation location resulted in positive cost savings, contingent on the annual proportion of less-than-container-load units eligible for consolidation. The study offers insights for infrastructure planning decision-making by identifying a convenient location for the container freight station and determining the necessary conditions of container flows that would enable the policy to be beneficial.

1. Introduction

Inland waterway transport (IWT) offers sustainable advantages on major European freight corridors, utilizing only 17 % of the energy required by trucks per ton transported on often-congested roads (European Parliament, 2022). These advantages are also reflected in transport safety (Tao, Wu, & Zhu, 2017) and are achieved mainly due to economies of scale, which are more pronounced over longer port-hinterland connections (Shobayo & van Hassel, 2019). Specifically, a barge can transport a ton of cargo four times further than a truck can on the same amount of energy while incurring roughly half of the external costs per kilometer (European Commission, 2019). Consequently, policymakers in Europe have set objectives to increase the participation of IWT in freight transport markets. The 2020 Sustainable and Smart Mobility Strategy set a regional goal to increase the use of IWT and short-sea shipping by 25 % by 2030 and 50 % by 2050 (ECA, 2023).

However, the sustainable advantages of IWT are currently not fully exploited due to inefficiencies in the logistics system. These inefficiencies include vessels spending considerable time waiting at seaports (van der Horst, Kort, Kuipers, & Geerlings, 2019), compounded by sub-optimal river navigation and prolonged waiting times at bridges and locks (ECA, 2015). Additionally, low load factors of containers and vessels contribute to the logistics system's inefficiency, resulting in unnecessarily high numbers of containers transported and trips completed (Novimove, 2023). As a result, IWT is losing competitiveness compared to other modes. Between 2007 and 2021, the modal share of IWT decreased by around 14 %, reaching market participation of 5.6 %, while road transport overcame 75 % (Eurostat, 2023).

The effectiveness of modal shift policies can be constrained if the logistics system of sustainable transport modes is not competitive and reliable. This has been evidenced by the negative trend in IWT after low water levels disrupted navigability in the Rhine River during 2018, leading to a reduction in the loading factors of containers as the only possibility to maintain operations in port-hinterland connections along the corridor (CCNR, 2021). To make IWT more competitive and resilient, solutions to reduce inefficiencies include optimizing times at locks

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to reduce travel time, decreasing the vulnerability to critical water levels, and increasing the loading factors of containers to optimize transport capacity (EIP, 2020).

One potential solution to optimize the loading factor of a container is to consolidate cargo (CC) in a container freight station (CFS). A CFS is a warehouse or facility used to prepare Less than Container Load (LCL) shipments for the next segment of their journey by grouping cargo (i.e., consolidating) or ungrouping (i.e., deconsolidating) as needed (Freightos, 2023). In this sense, LCL shipments can be combined with other LCL shipments to fill a container without exceeding weight requirements. When this occurs, the container's loading factor is optimized, making it equivalent to a Full Container Load (FCL) shipment.

Evidence from road and combined transport indicates that CC can significantly reduce costs and emissions in port-hinterland logistics (Fan, Behdani, Bloemhof-Ruwaard, & Zuidwijk, 2019). However, there exists a gap in the literature regarding the economic feasibility of a CC strategy aiming at maximizing loading factors of container IWT in a port-hinterland network where this mode is competitive with road and rail transport. Such feasibility depends on three essential aspects: the transport demand that can be captured by the strategy, the supply of transport infrastructure, and the optimal location for conducting the consolidation process. Regarding the former, the potential benefits would depend on the proportion of container flows that can be consolidated. Should this proportion be too low, the costs incurred by the strategy may surpass the benefits (Long & Grasman, 2012). Concerning the latter, the location of the CFS can be crucial in reducing transport and external costs for existing inland networks with sufficient transport infrastructure and cargo flows. To maximize the potential benefits of the CC strategy, the CFS is typically situated close to transportation hubs such as seaports or inland terminals (Freightos, 2023), as greater benefits are anticipated for longer travel distances.

Considering the criteria outlined by Long and Grasman (2012) and Liang, Verhoeven, Brunelli, and Rezaei (2024) for location selection of inland hubs, including the degree of freight flows, availability of existing infrastructure, labor market and community readiness, there are three strategic options for situating the CFS for a CC policy or similar. The first option is directly at the seaport, allowing cargo to be consolidated immediately after the maritime segment and then dispatched to the hinterland (Long & Grasman, 2012). However, this option has drawbacks, including the need for sufficient spare capacity and the additional costs incurred from extra container handling at the seaport. The second option is to locate the CFS at inland terminals, allowing cargo to be consolidated toward the final destination in the hinterland and also on its way back to the seaports. In this case, market proximity and intermodal market profitability could increase, but multiple CFSs would be then required along the network (Liang et al., 2024). The third option is to position a single CFS at one inland terminal relatively close to the seaports where container flows converge on their way to the hinterland. Although this option could reduce costs and capture larger container volumes, it would necessitate a location that fulfills such specific conditions (Liang et al., 2024).

This research considers these scenarios and introduces a CC strategy in a transport network with multiple seaports and inland terminals, providing an economic assessment based on its cost implications. Consequently, the research question of this study is: What are the locations and cargo flow conditions for implementing an economically feasible CC strategy in a transport corridor where IWT competes with road and rail transport?

The question is addressed by conducting an assessment that integrates the CC process into a discrete event simulation model. The methodology accounts for input parameters such as network characteristics, available transport services, the container Origin-Destination (OD) matrix, travel time, transport cost, and modal share across different OD pairs. By integrating CC within the simulation, containers are initially assigned to IWT at the seaport. Then, the eligibility criteria for consolidation are applied to select containers heading toward the CFS. Subsequently, container loading factors are optimized by transferring shipments to other containers destined for the same destination. The main novelty of this research is a spatial economic assessment framework based on cost savings per TEU and comparing the net benefits obtained from implementing the strategy at different locations. Specifically, the economic impacts of the CC process on container IWT are calculated through comparative scenarios relative to a calibrated baseline setting.

A case study is conducted for the Rhine-Alpine Corridor (RALP), the busiest inland transport corridor in Europe, connecting over forty terminals from Belgium, France, Germany, the Netherlands, and Switzerland to the seaports of Amsterdam, Antwerp, and Rotterdam (European Commission, 2017). The RALP is part of the Trans-European Transport Network (TEN-T) and is recognized as one of the priority transportation routes to lead Europe toward a sustainable transition of freight transport by 2030 (European Commission, 2020). The RALP was also selected as a case study due to its potential for extended impact on connected waterways, including the Moselle, the Main (with its connection to the Danube via the Rhine-Main-Danube Canal), and the Neckar, as well as the Flemish and West German canal networks. Furthermore, given the RALP's significance within the European context, assessing a CC strategy here could serve as a valuable reference for major inland waterways in other regions, such as the Yangtze and Mississippi Rivers.

This paper contributes to the literature in three ways. First, it develops an assessment framework of the CC strategy that considers implementing the CFS at three feasible locations: the seaport, inland terminals, and a single strategic hinterland location. Second, it informs decision-making on resource allocation for improving IWT, indicating potential economic benefits derived from the CC strategy at each of these implementation locations. Third, it serves as the foundation for further operational assessment of the CC strategy performance for IWT in a context that involves multiple countries and regions.

The structure of the paper is as follows: Section 2 reviews the literature on the CC strategy. Section 3 outlines the methodology for integrating the CC strategy into a port-hinterland logistics network, with a specific application to the RALP. Section 4 presents the results. Finally, section 5 discusses the findings and concludes the paper, highlighting potential directions for future research.

2. Literature review

The implementation of CC has been studied across different transport modes. For instance, Zhao, Zhao, Hu, Li, and Stoeter (2018) analyzed over 25 cities in China using network science to implement consolidation centers for rail transport, optimizing loading factors and profit margins. Zhu, Wu, Smith, and Luo (2023) assessed a CC strategy for air transport, considering bundling regional cargo at a transport hub and aiming to minimize total expected costs. Urban consolidation centers have also been studied in specific contexts, such as Bukoye and Gadiraju (2022) who analyzed urban freight transport scenarios in a higher education setting in the UK to minimize costs, distance traveled, and CO_2 emissions. Tiwari, Wee, Zhou, and Tjoeng (2021) examined the impact of policy on emissions by assessing the effect of a carbon tax regulation on a CC strategy applied to maritime transport, reporting improvements in transport costs and emissions compared to the baseline case.

Concerning containerized cargo, the CC strategy was introduced by Qin, Zhang, Qi, and Lim (2014) to deal with the bundling and loading of diverse shipments at a warehouse for efficient distribution. The authors proposed a linear programming formulation and a memetic algorithm to minimize total container transport and parcel delivery costs. Since then, research has increasingly focused on the advantages of CC strategies in various markets and policy contexts. For instance, Fan et al. (2019) used analytical models to compare consolidation scenarios for perishable and dry cargo, developing different CC strategies to assess emission and cost reduction improvements. They reported that shipment distance and cargo type significantly affect CC performance.

Chen, Dong, and Chen (2017) also explored consolidation strategies in a perishable product supply chain where timing is critical. They proposed an analytical model to optimize the long-term benefits of the strategy, considering sensitivity to time, operational, and market parameters. Additionally, Satır, Erenay, and Bookbinder (2018) analyzed CC strategies for regular versus expedited orders, proposing solutions for large-scale problems and demonstrating the benefits of CC based on quantity thresholds rather than temporal parameters. Hanbazazah, Abril, Erkoc, and Shaikh (2019) developed a CC strategy for a third-party logistics provider, creating an integer programming model to account for cost functions that capture economies of scale from the strategy and testing sensitivity to various parameters, including market dynamics, delivery time windows, and costs.

Recent studies suggest the feasibility of implementing CC strategies in multimodal planning, contrasting with previous literature that primarily focused on single-mode strategies. Lv, Yang, Zhu, and Li (2019) studied a CC strategy in such multimodal setting, accounting for multiple origin-destination flows and quantifying the efficiency of transit consolidation. Furthermore, Oguntola, Ülkü, Saif, and Engau (2023) analyzed CC implementation in a multimodal logistics network for a multi-echelon supply chain, highlighting significant cost savings, especially for longer distances. Notably, the application of CC strategies in transport corridors where IWT competes with road and rail for transporting containerized cargo remains understudied. The most related study by Wang, Tan, and Chen (2023) showed the potential resiliency advantages during emergencies in the Yangtze River during the COVID-19 pandemic, concluding that flexible CC could significantly reduce port congestion time and total transport costs across regions with varying infection levels.

There are three literature gaps that remain within this stream of studies. First, previous research evaluating the potential impact of strategies like the CC in an IWT system has often been limited in using methodologies that capture both cost and time components in the mode choice process, as well as cargo assignment based on available transport capacity. One such methodology is discrete event simulation (DES), which has been employed to model changes in transport systems different than IWT, such as passage transportation in urban contexts. For example, Soza-Parra, Tiznado-Aitken, and Muñoz (2023) utilized DES to assess travel demand management strategies in Santiago de Chile during the disruptive scenario caused by the COVID-19 pandemic. The results help to identify specific locations and time periods in which waiting times and crowding conditions were likely to surpass defined thresholds. In the context of freight transport, Neagoe, Hvolby, Taskhiri, and Turner (2021) used DES to conduct a scenario analysis of congestion management initiatives at a port terminal in Australia, finding significant improvements in truck turnaround times, reliability, and emissions. The assessment framework in the research hereby presented intends to leverage the advantages of DES to model the economic feasibility of a CC strategy, capturing the mode choice of IWT as an alternative to rail and road transport.

Second, there is little research that assess the economic feasibility of inland freight hub locations for a CC or similar strategy. The study by Long and Grasman (2012) contributed by developing a decision making framework collecting interview data on the perspective of public and private multimodal stakeholders in the USA to understand the crucial criteria for inland hub locations. The results indicated that both qualitative and quantitative measures matter for the optimal final location selection, including freight flows, labor supply, existing infrastructure, community readiness and livability. From the perspective of the shipping lines, Liang et al. (2024) developed a consensus model for a group Best-Worst Method (BWM) which allows aggregating the evaluations of the various stakeholders. Applying this method to a case study of the Maersk shipping line, the authors concluded that the market volume potential is identified as one of the most important criteria. The results also indicate that a varying influx of the container volume has no impact on the most desirable location. While these studies capture the perspective of stakeholders, a methodology to assess the economic feasibility of the strategy still remains to be developed.

Moreover, these studies also indicate that each factor should be considered according to the specific transport context in which the inland hub will be placed. This relates to the third gap in the literature: there is limited evidence for the European IWT context, where long port-hinterland connections provide a favorable setting for CC strategies aimed at optimizing container loading factors and reducing transport costs. The cross-country nature of IWT in Europe further distinguishes its complexity compared to other regions, offering multiple potential locations for implementing consolidation centers. Consequently, this study aims to contribute by assessing the economic feasibility of a CC strategy in the international European context of the RALP. It proposes a DES model to account for cost and time components in the mode choice process, complementing existing literature on stakeholder considerations for the selection of inland hub locations. The following section presents the assessment DES methodology and the indicators used to measure the potential gains of this strategy, comparing the implementation of consolidation centers across three distinct locations in the RALP.

3. Methods and data

A multimodal corridor network is considered where containers arrive from seaports and are transported toward the hinterland by IWT, road, or rail transport. The performance of container IWT will be assessed after implementing the CC strategy compared to the baseline scenario. Fig. 1 illustrates the analysis framework followed in the study: First, a DES model is introduced to generate the baseline scenario. Second, the performance indicators are defined, and the baseline scenario is calibrated. Based on these, an impact evaluation is conducted after simulating the CC strategy in the RALP. Finally, the discussion is conducted by performing a sensitivity analysis of the results to critical input parameters.

3.1. Discrete event simulation

The main components of the simulation in the baseline case (i.e., without CC) are depicted in Fig. 2 and described below. The simulation requires various inputs, including network characteristics, available transport services, and the OD matrix of container freight. Once the simulation is initiated, a daily transport demand is generated from the input OD matrix, and three sub-models are activated consecutively.

As a starting point, the first sub-model computes the cost and time required for transporting a container for each OD pair q and transport mode m. The general specifications are depicted in the system of Eqs. 1a-1d, and Table 1 summarizes the notations. A symmetrical approach is developed for road and rail transport and the detailed specifications for these modes are presented in Appendix A.

The generalized cost is modeled with three cost components: transport, time, and reliability costs (Eq. 1a). In the first component, transport costs include operating and fixed costs, which are specified according to Hekkenberg (2013) (Eq. 1b). The second component (i.e., time costs) accounts for the Value of Time (VoT) to represent the costs of total operational time in monetary terms. Total operational time (Eq. 1c) is estimated as the sum of transport time (Eq. 1d) and time spent waiting and handling cargo. Finally, the third component (i.e., reliability costs) represents the respective calculation over the additional time spent waiting and handling cargo, considering the Value of Reliability (VoR). The generalized cost is obtained relative to the modal utilized capacity, which is calculated as the load capacity of each mode accounting for the utilization rate (i.e., $Cap^m * u^m$).

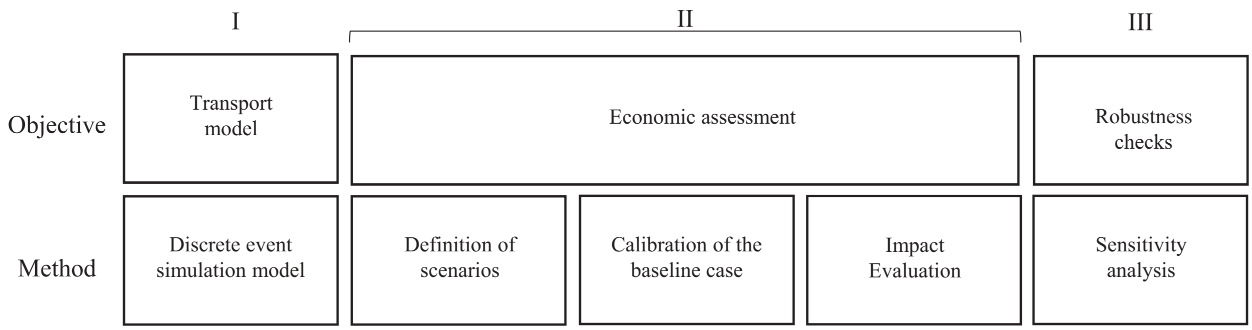

Fig. 1. Analysis framework.

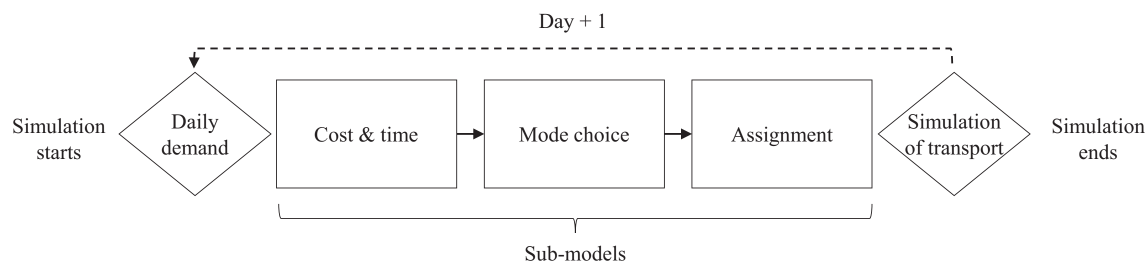

Fig. 2. Simulation components.

Table 1
Notations of the cost and time sub-model.

Notation	Definition	Unit
C^m	Generalized cost	€
C^m_{trans}	Transport cost	€
C^m_{fixed}	Fixed cost	€
C^m_{oper}	Operative cost	€
T^m_{oper}	Operative time	hr
T^m_{trans}	Transport time	hr
T^m_{wait}	Waiting time	hr
T^m_{hand}	Handling time	hr
Cap^m	Load capacity	–
D	Distance	km
S^m	Speed	km/h
u^m	Utilization rate of mode m	%
VOR	Value of Reliability	€
VOT	Value of Time	€

$$C^m = \left[C^m_{\text{trans}} + \left(T^m_{\text{oper}} * VOT^m\right) + \left(T^m_{\text{wait}} + T^m_{\text{hand}}\right) * VOR^m\right] \Big/ \left(Cap^m * u^m\right) \tag{1a}$$

$$C^m_{trans} = C^m_{fixed} + C^m_{oper} \tag{1b}$$

$$T^m_{oper} = T^m_{trans} + T^m_{hand} + T^m_{wait} \tag{1c}$$

$$T^m_{trans} = D / S^m \tag{1d}$$

The resulting values are then passed to the weighted logit model, which has been estimated following the method proposed by Nicolet, Negenborn, and Atasoy (2022), where the utility functions (U) and the corresponding choice probabilities are computed for all OD pairs in the simulation. These functions contain a systematic component (V) and an error term (ϵ) that follows an Extreme Value Distribution (Bierlaire, Bolduc, & McFadden, 2008). The formulation of the utility function for each mode (m) and cargo transported per OD pair (q) is expressed in Eq. (2).

Where the component V^m_q is modeled by accounting for the modal constant (α_m) and a set of I modal attributes $\left(X^m_{i,q}\right)$, including the generalized cost and transport accessibility of each mode. To conduct such estimation, one modal constant has to be normalized as the reference case.

$$U^m_q = V^m_q + \epsilon^m_q \tag{2a}$$

$$V^m_q = \alpha^m + \sum_{i \in I} \beta^m_i X^m_{i,q} + \varepsilon^m_q \tag{2b}$$

Based the considerations of Nicolet et al. (2022), the specific utility functions in the simulation include the generalized cost for each mode m on the specific pair $q\left(C_{m,q}\right)$ and transport accessibility. For intermodal transport (IWT and rail) this frequency is included as weekly transport services for each mode m for a specific pair q $\left(F_{m,q}\right)$. In contrast, the frequency of road transport is considered as demand-driven, with the number of services determined by population density. Hence, we incorporate the average population density of the origin and destination regions, expressed in thousands of inhabitants per square kilometer, to proxy the accessibility of road service ($PD_{road,q}$). The systematic component of the utility function for each mode (V_m) is detailed in Eq. 3.

$$V_{IWT,q} = \alpha_{IWT} + \beta_{c,IWT} C_{IWT,q} + \beta_f F_{IWT,q} + \varepsilon_{IWT} \tag{3a}$$

$$V_{rail,q} = \alpha_{rail} + \beta_{c,rail} C_{rail,q} + \beta_f F_{rail,q} + \varepsilon_{rail} \tag{3b}$$

$$V_{road,q} = \alpha_{road} + \beta_{c,road} C_{road,q} + \beta_{pd} PD_{road,q} + \varepsilon_{road} \quad \forall q \tag{3c}$$

Where α and β are the coefficients to be estimated, and α_m represents the specific constant for mode m. Since our analysis focuses on IWT, we designate the constant for this mode as the reference case. The coefficient $\beta_{c,m}$ reflects the significance of costs in the utility of mode m. Similarly, β_f and β_{pd} are the coefficients that indicate the importance of accessibility for intermodal and road transport, respectively.

Consequently, the probability of choosing mode m among the set of available modes M (i.e., IWT, road or rail transport) on a pair q is estimated following the logit model represented in Eq. 4. We compute the coefficients (α^m and β^m_i) that maximize the likelihood of obtaining the probabilities by retaining the model with the highest explanatory power. Each observation is weighted by the container flow for mode m on the corresponding pair q so those with most traffic have a greater impact on the coefficients' estimation. The log-likelihood function LL is expressed as Eq. 5, where Q is the set of all OD pairs considered, $P_q(m)$ represents the mode share or, alternatively, the probability of selecting mode m on pair q, and $w_{m,q}$ is the container flow for mode m and pair q.

$$P_q(m) = \frac{e^{V_{m,q}}}{\sum_{m \in \{M\}} e^{V_{m,q}}} \tag{4}$$

$$LL = \sum_{q \in Q} \sum_{m \in M} ln\left(P_q(m)\right)^* w_q^m \tag{5}$$

Once the mode choice has been performed, the assignment sub-model (Fig. 2) considers the available capacity to assign the containers to one of the three transport modes. This sub-model keeps track of the remaining capacity of each mode and indicates the service departure so that the simulation can execute it. Distinct assignment procedures are used for each of the three modes due to the required level of detail, higher for IWT than for road and rail transport. For road transport, it is assumed that trucks are always available to serve the demand. For rail transport, the commonly used rule of First-Come, First-Served is applied.

For IWT, a cost-minimization procedure is conducted and summarized in Eq. 6. Where S is the set of available IWT vessel services to be deployed on a certain route and C^{IWT} is the generalized cost. $\Delta T_{wait}^{IWT,s}$ captures the additional waiting time at port incurred during service s compared to the previous service in the set S, both expressed in hours. The cost component is obtained from Eq. 1a, and the waiting times at the port of origin and destination are retrieved from the last component of Eq. 1c. Consequently, a given container will then be assigned to the vessel service that minimizes the sum of costs.

$$\min_{s \in S} C^{IWT} + \left(VOT^* \Delta T_{wait}^{IWT,s}\right) \tag{6}$$

If a container cannot be assigned to the cheapest service because its capacity has been reached, the second cheapest option is selected. The capacity of a given service is determined per barge type by a dynamic capacity model that computes the maximum available payload given the vessel's dimensions, the amount cargo to be transported, and the water levels. Finally, the simulation clock advances to the following day, generating a new daily transport demand (Fig. 2). The loop continues until the yearly time horizon (i.e., 365 days) is simulated. The main outputs are reported when the simulation terminates, including transport volumes, modal shares, and costs.

3.2. Economic assessment

To assess the economic feasibility of the CC strategy, we estimate the net benefit for the inland network after discounting incurred costs (NB). The benefits come from transporting the same amount of cargo using a lower number of containers, and the costs arise from the consolidation procedure. Thus, the NB is the resulting difference between these new two values. We compare the baseline scenario against the implementation of the CC strategy. To illustrate such comparison, a differentiation is made between segments of the trip (i.e., before and after consolidation). The two compared scenarios are presented in Fig. 3. In the baseline case, the CC is not considered and the generalized cost of IWT is calculated for the LCL and FCL containers. In the CC scenario, vessels stop at terminal T of location N and reach the final destination only carrying fully loaded containers. Incurred costs involve the handling costs of LCL containers between terminal T to the CFS, the costs of reconstructing LCL into FCL containers, and the handling costs of emptied containers to the depot. Considering all pairs q in the network, the consolidation cost (C_c) is described by Eq. 7.

Notably, investment costs are not included as the CC strategy is developed utilizing the existing inland network infrastructure. Therefore, the simulation considers that terminal T is already operational in location N and possesses the required facilities. In the event that establishing an additional warehouse as a CFS at the terminal is neces-

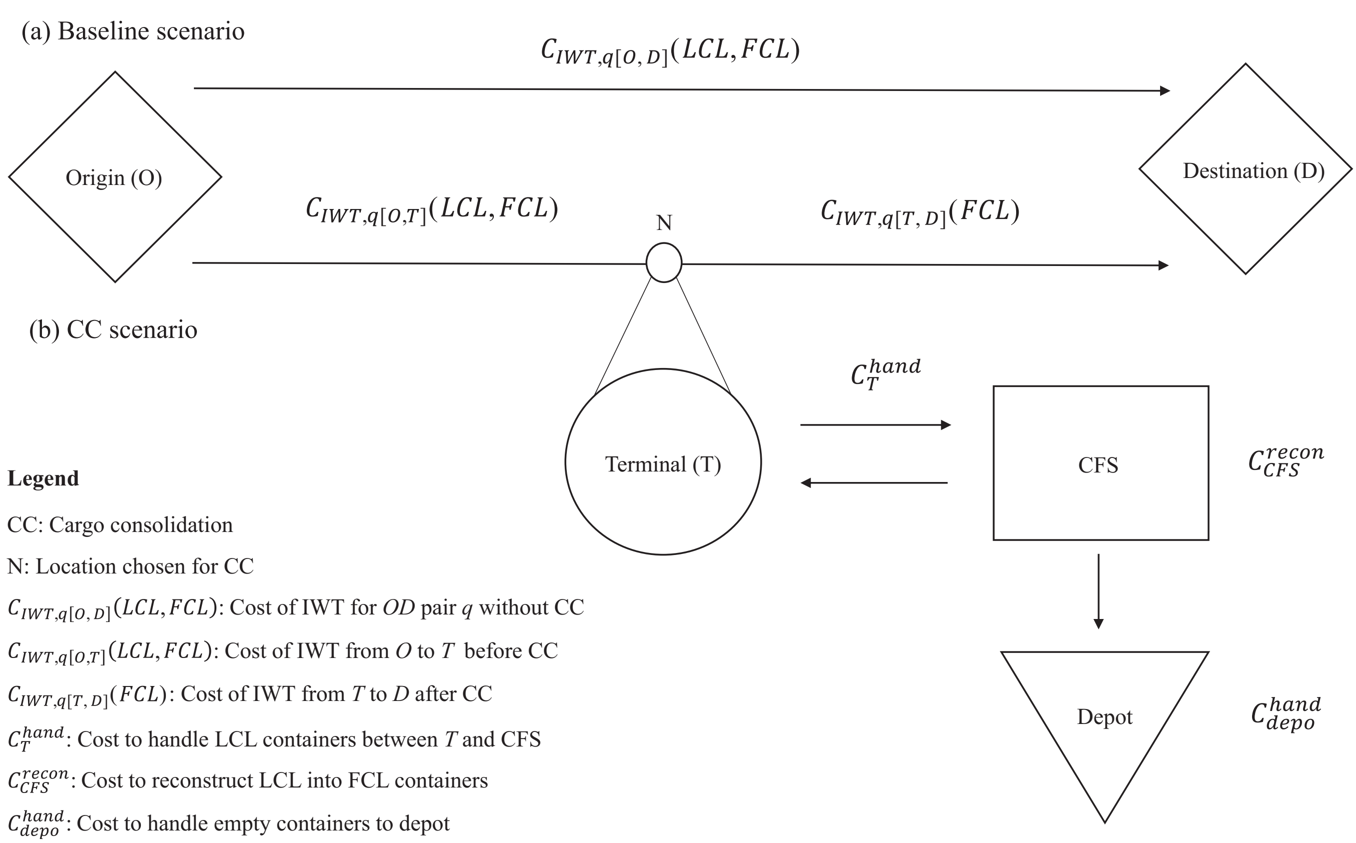

Fig. 3. Assessment scenarios.

sary, the associated costs are anticipated to be negligible and reflected only on the first day of the simulation. When considering the cost per container consolidated, such initial cost tends to diminish to virtually zero over time. Consequently, these costs do not impact the net benefit calculation for a one-year simulation period.

$$C_C = f\left(C_T^{hand}, C_{CFS}^{recon}, C_{depo}^{hand}\right) = \sum_{q=1}^{Q}\left[LCL_{q[OT]}\left(2C_T^{hand} + C_{CFS}^{recon}\right) + \left(LCL_{q[OD]} - FLC_{q[TD]}\right)C_{depo}^{hand}\right] \quad (7)$$

$$C_{IWT}^{*} = \sum_{q=1}^{Q}\left[C_{IWT,q(OT)}(LCLFCL) + C_{IWT,q(TD)}(FCL)\right] + C_C \quad (8)$$

In the baseline scenario (Fig. 3a), the generalized costs for each q is obtained as in the cost-time sub-model (Eq. 1a) and is aggregated considering all pairs in the network. In the CC scenario (Fig. 3b), the cost for each q is different between the first segment of the trip, from the origin to the terminal (*O, T*), and the second segment, from the terminal to the destination (*T, D*). Consequently, the generalized cost of IWT in the CC scenario accounts for the costs in each segment plus the costs of consolidation (Eq. 8). The net benefit is then calculated as the difference of costs between the two scenarios, and this difference will depend on the second segment of the trip (Eq. 9). Specifically, the strategy would report positive benefits if the costs of transporting only FCL containers in the second segment plus the incurred costs of consolidation are lower than the costs of transporting both LCL and FCL containers in that segment (i.e., baseline scenario).

$$NB = \sum_{q=1}^{Q} C_{IWT,q(O,D)}(LCL, FCL) - C_{IWT}^{*} \quad (9a)$$

$$NB > 0 \text{ if } \sum_{q=1}^{Q} C_{IWT,q(T,D)}(FCL) + C_C < \sum_{q=1}^{Q} C_{IWT,q(T,D)}(LCL, FCL) \quad (9b)$$

3.3. Case study

We collected annual container throughput data in TEUs and tonnes from Eurostat (2024a) for the years 2007 to 2021. The dataset contains information on loaded and unloaded container cargo flows between European regions, using the Nomenclature of Territorial Units for Statistics at the second level (NUTS-2), which is also the standard classification for regional policy development (Eurostat, 2024b).

This dataset provides the most systematic and disaggregated publicly available information on cargo flows within the RALP. Although it does not specify terminal-level origins and destinations, the NUTS-2 level disaggregation enables assessment at a regional scale. The selected regions are interconnected by a port network along the main waterways of the RALP, as illustrated in Fig. 4. This navigable network links over 20 regions, stretching from Antwerp (Belgium), Rotterdam, and Amsterdam (Netherlands) on the North Sea to Duisburg, Mannheim, Weil am Rhein (Germany), Alsace (France), and Basel (Switzerland).

The study period of 2007–2022 captures important trends and fluctuations in container TKM across these regions, marked by critical

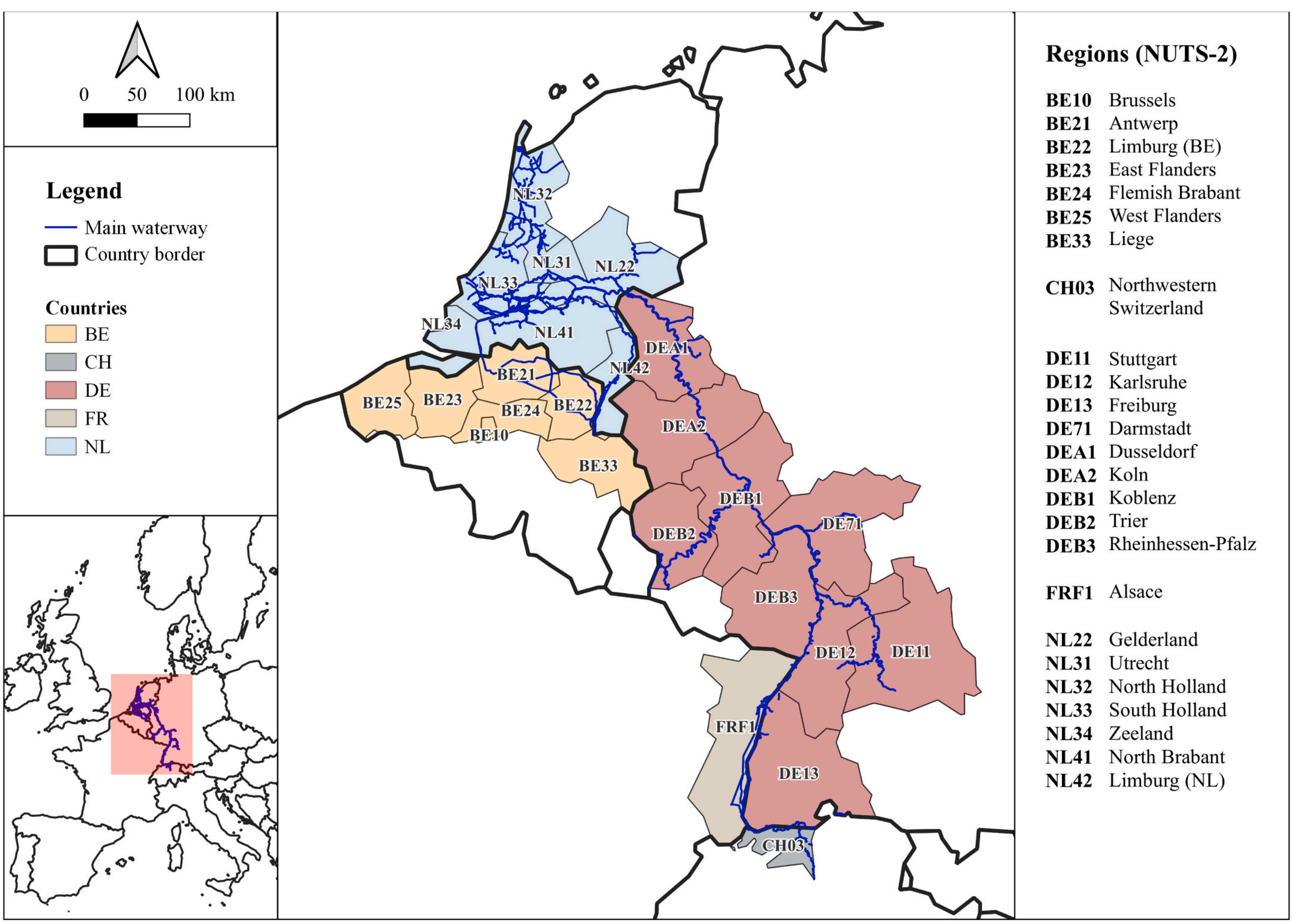

Fig. 4. Regions in the study.
Source: Adaptation from Bedoya-Maya, Beckers and van Hassel (2023).

disruptions in the transportation network. The 2008 financial crisis triggered a global economic downturn, reducing the demand for goods transported via inland waterways, including raw materials, chemicals, and finished products (Van Meir et al., 2022). Another key event was the Waldhof incident in January 2011, when a tanker barge carrying sulfuric acid collided with another vessel on the central segment of the Rhine River. Additionally, extreme water level variations in 2015, 2018, and 2022 impacted navigability, creating substantial challenges for freight transport (CCNR, 2023). Furthermore, this timeframe also includes fluctuations in container IWT during the 2020 pandemic and how the transport network adapted to such uncertain conditions.

Considering the findings of Long and Grasman (2012) and Liang et al. (2024), various locations are considered for deploying the CFS as part of the CC strategy. Given that higher cost savings are achievable over longer travel distances, there are three strategic options for testing the policy. The first is directly at the seaports of Antwerp and Rotterdam, where the consolidation process can occur after the maritime segment, yielding benefits for the entire port-hinterland connection. Fig. 5 (a) provides an overview of CC at the seaport. In this scenario, partly loaded containers are transferred from a seaport terminal to the CFS, where the cargo is consolidated. The fully loaded containers are then moved back to the terminal to proceed with their port-hinterland journey, while empty containers are transported to the depots.

The second option involves inland terminals serving the hinterlands, where cost savings could be realized in the final segment of the trip, as well as for flows coming from the hinterlands toward the seaports of Antwerp and Rotterdam; this scenario is illustrated in Fig. 5 (b). In this case, partly loaded containers are transported to a CFS at the inland terminals, from where the fully loaded containers are moved to their final destination in the hinterland. The empty containers can then be moved to the inland depots.

The final option considered is to implement the CC at a strategic hinterland location (SHL) that meets the criteria described in Section 1, i.e., the location closest to the seaports where container flows converge on their way to the hinterland. In the case of the RALP, the inland terminal of Nijmegen in the Netherlands is the location where container flows originating from Antwerp and Rotterdam intersect on their routes to hinterlands in Germany, France, Luxembourg, and Switzerland, as illustrated in Fig. 5 (c). Here, LCL containers are processed in Nijmegen, and eligible cargo passing through this SHL is consolidated. As a result of the CC strategy, fewer containers are transported from Nijmegen to their final destinations, and the empty containers are sent to the depots.

Next, the costs and benefits of the CC are calculated. We base the cost parameters for IWT transport and handling on Wrobel (2021), while the costs of container movement are derived from Ramos et al. (2021). The VoT and VoR are adopted from de Jong et al. (2014), which are the closest values published for this particular transport corridor (Table 2). To calibrate the baseline scenario (i.e., without CC), the matrix detailing the frequency of intermodal services (F_m) is sourced from Panteia, a research and consulting organization that collected the data through direct contact with the industry. The remaining input parameters for the cost and time sub-models are obtained from the European project Novimove (2023). The uncertain nature of these parameter is acknowledged, especially on VoT and VoR, so sensitivity of the cost sub-model will be conducted and presented in the results.

Subsequently, we approximate the loading factors of container flows

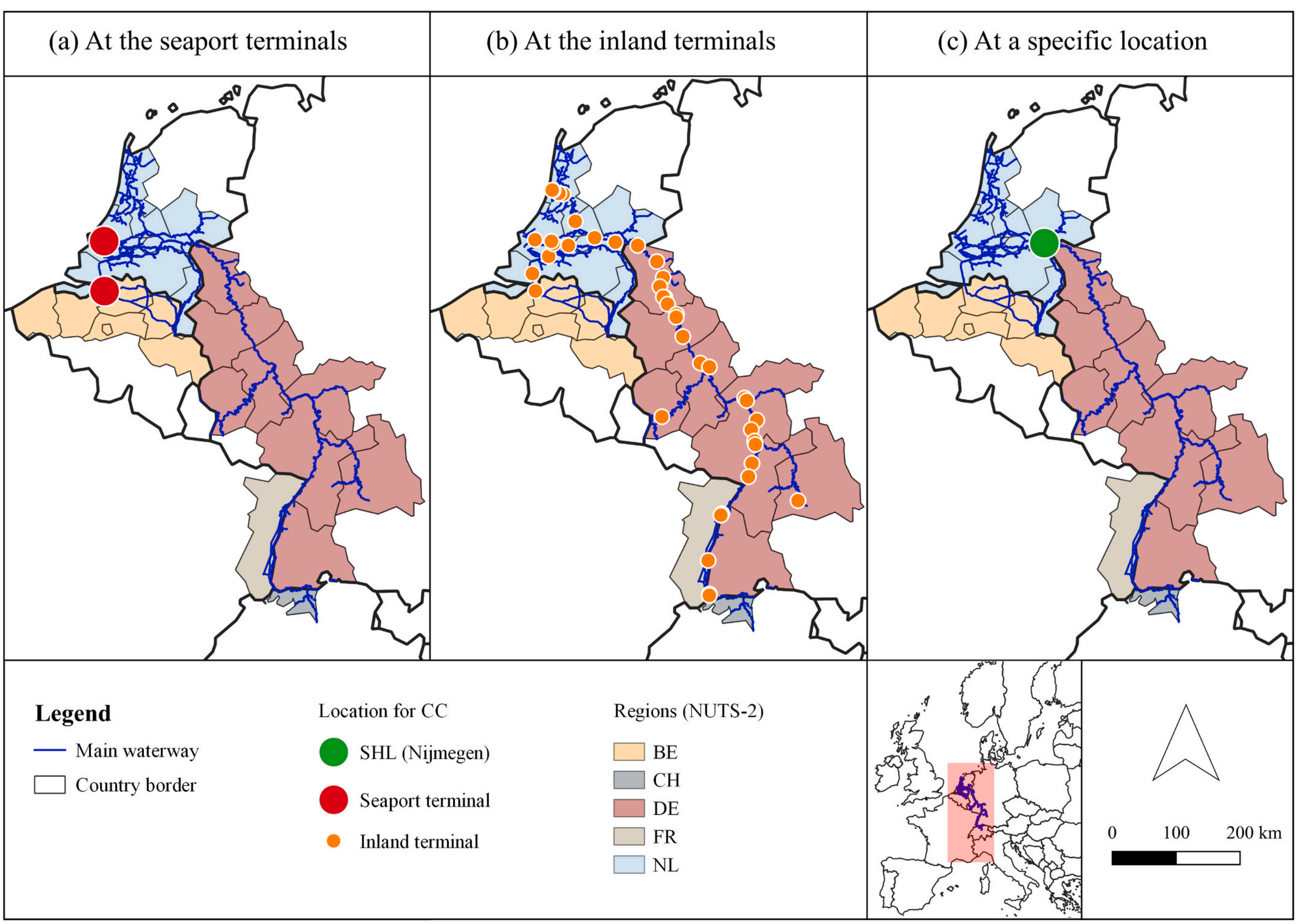

Fig. 5. Locations considered for implementing the CC strategy.

Table 2
Input data for CC.

Input	Unit	Parameter
Costs		
Personnel	€/TEU	35
Equipment	€/TEU	0.5
Overhead	€/TEU	0.5
Fixed	€/TEU	1.0
Handling deepsea terminal	€/TEU	35
Handling freight station	€/TEU	10
Handling empty depot	€/TEU	10
Handling inland terminal	€/TEU	10
Container movement per barge (in port)	€/TEU-Km	0.5
Worker hour	€/Hour	10
Time and distance		
Time needed to empty a container	Hours	3.5
Distance terminal to the freight station	Km	10
Distance freight station to empty depot	Km	5.0
VoT and VoR		
VoT of a ship waiting for a quay	€	98
VoT of a ship waiting for a lock/bridge	€	340
VoR of a ship waiting for a quay	€	18
VoR of a ship waiting for a lock/bridge	€	27

Source: Ramos et al. (2021), Wrobel (2021), de Jong et al. (2014), and Novimove (2023).

eligible for consolidation to estimate each scenario's potential benefits. First, non-fully loaded containers transported between each OD pair are separated from intentionally empty containers as these are returning toward the seaport or inland depots before exiting the inland corridor. Eq. 10a represents this procedure by considering all throughput loaded in terminals i of the origin region and unloaded in terminals j of the destination region. Second, we estimate the proportion of eligible containers as the fraction of partially loaded from the total containers transported per connection in the network (Eq. 10b).

Third, loading factors are calculated by considering the total tonnes transported per OD pair (Eq. 10c). The payload, excluding the empty weight of the container, is initially considered to be 20 t per TEU (XChange, 2023) and sensitivity of the results to this parameter will be presented in the results. Consequently, the loading factors for each OD pair are derived as the aggregated proportion of tonnes transported between terminals of origin and destination relative to the payload of eligible containers on the same link. From there, the LCL containers to be consolidated are estimated as the proportion of eligible containers with suboptimal loading factors (Eq. 10d).

The system of Eqs. 10a-10d summarizes this procedure, where TEU_{ij} represents the total TEUs loaded at inland terminal i and unloaded at inland terminal j. TEU_{ij}^{ue} denotes the empty containers returning from i to an empty depot. Conversely, TEU_q^e signifies the partially loaded containers at terminals i in the origin region and unloaded at terminals j in the destination region. $Eligibility_q$ represents the proportion of eligible containers from the total transport in the OD pair q, and $Load\ factor_q$ is the proportion of tonnes transported relative to the payload of eligible containers in the pair. For this calculation, $tonnes_{ij}$ is the total loaded at i and unloaded at j; and PL represents the payload, excluding the empty weight of the container. Ultimately, this information is utilized to calculate the LCL containers as the proportion of eligible containers with suboptimal loading factors for each pair.

We collected the required input data available at the regional NUTS-2 level from Eurostat (2024a) and compiled a dataset with the eligibility and loading factors for each OD pair. To facilitate comparison between the three assessed locations of the CFS, only flows passing through the SHL (Nijmegen) are considered. Table 3 presents the historical average flow from regions containing the seaports (i.e., Antwerp and Rotterdam) passing through the SHL toward the final destination region. We then applied the standard goods classification for transport statistics to distinguish among and segregate loaded containers from empty containers, swap bodies, pallets, and packaging. Lastly, we calculated the average loading factor and LCL containers for each OD pair between 2007 and 2021.

Table 3
Yearly average of container flows passing through the SHL (Nijmegen).

Origin	Destination	TEUs	Tons	LCL (%)
Antwerp (BE21)	Northwestern Switzerland (CH03)	9,437	70,467	54
	Stuttgart (DE11)	3,974	11,875	42
	Karlsruhe (DE12)	29,040	173,400	24
	Freiburg (DE13)	4,676	13,467	34
	Darmstadt (DE71)	19,948	81,000	43
	Dusseldorf (DEA1)	84,172	645,000	27
	Koln (DEA2)	23,455	152,667	31
	Koblenz (DEB1)	17,462	146,733	10
	Trier (DEB2)	1,146	1,200	30
	Rheinhessen-Pfalz (DEB3)	103,604	468,067	53
	Alsace (FRF1)	8,010	55,200	28
	Limburg (NL42)	15,708	178,800	19
South Holland (NL33)	Northwestern Switzerland (CH03)	32,974	244,667	39
	Stuttgart (DE11)	2,502	9,700	47
	Karlsruhe (DE12)	22,032	109,267	32
	Freiburg (DE13)	18,545	125,733	24
	Darmstadt (DE71)	28,594	141,733	51
	Dusseldorf (DEA1)	280,508	2,190,000	42
	Koln (DEA2)	37,852	238,533	37
	Koblenz (DEB1)	12,132	74,733	27
	Trier (DEB2)	546	143	55
	Rheinhessen-Pfalz (DEB3)	102,619	510,400	46
	Alsace (FRF1)	24,476	141,000	33
	Limburg (NL42)	107,140	784,733	51

Note: Values in yearly average 2007–2021.
Source: Own elaboration with data from Eurostat.

$$TEU_q^e = \sum_{i=1}^{I}\sum_{j=1}^{J} TEU_{ij} - TEU_{ij}^{ue} \tag{10a}$$

$$Eligibility_q = \frac{TEU_q^e}{\sum_{i=1}^{I}\sum_{j=1}^{J} TEU_{ij}} \tag{10b}$$

$$Load\ factor_q = \sum_{i=1}^{I}\sum_{j=1}^{J} \frac{tonnes_{ij}}{PL^{*}TEU_{ij}^e} \tag{10c}$$

$$LCL\ containers_q = \left(1 - Loadfactor_q\right)^{*}TEU_q^e \tag{10d}$$

4. Results

The estimated α and β coefficients, along with their standard deviations and p-values, are presented in Table 4. First, all cost coefficients (β_c) exhibit a negative sign, indicating that the utility of a given mode

Table 4
Estimation results of mode choice sub-model.

Parameter	Coefficient	Standard Error	p-value
α_{Rail}	−0.29	0.90	0.74
α_{Road}	1.46	0.47	0.00
$\beta_{c,IWT}$	−7.78	2.03	0.00
$\beta_{c,Rail}$	−4.16	0.88	0.00
$\beta_{c,Road}$	−3.70	0.57	0.00
β_d	−1.13	0.41	0.01
β_f	0.02	0.01	0.16

Note: LL is −1.335428e+08 vs. -2.050373e+08 of the model with one intercept.

will decrease if the corresponding generalized cost increases. These cost coefficients are statistically significant at the 1 % level. Second, the coefficient related to population density (β_d) is also significant at this level. Its negative sign indicates that the attractiveness of the road alternative decreases with an increase in population density. The underlying interpretation is that road networks will be more crowded in densely populated regions, thus causing some congestion and decreasing road efficiency and accessibility, while other modes become more attractive.

Third, the frequency coefficient (β_f) is positive but not significant, indicating that additional services per week will not necessarily increase the utility of intermodal transport. Finally, the values of the alternative-specific constants (α) reveal that, without considering cost and service frequency, rail is not necessarily more attractive than IWT as α_{RAIL} is not statistically significant. Conversely, the results indicate that road is more attractive than IWT due to the relatively high value of α_{ROAD} and its *p*-value.

The discrete event simulation enables the determination of the modal share of IWT for each OD pair (NUTS-2 regions) to calibrate the baseline scenario before the CC strategy. Fig. 6 depicts the results for container flows originating from the seaports and passing through the SHL (Nijmegen), organized by quartiles of the modal share (Q1-Q4). In these flows, IWT predominates over road and rail transport, a contrast observed in OD pairs with shorter travel distances. The results show that simulated IWT originating from Antwerp has a higher modal share in flows unloaded in Düsseldorf (DEA1), Karlsruhe (DE12), and Trier (DEB2). In comparison, IWT has a larger market share in flows originating from Rotterdam and unloaded in Koblenz (DEB1), Darmstadt (DE71), and Freiburg (DE13).

After establishing the baseline scenario, we proceed to the second component of the analysis framework (Fig. 1) to conduct an economic assessment of the CC strategy. Fig. 7 shows the negative relationship between transport cost per TEU and load factor. It can be noted that the highest costs are associated with those OD pairs covering longer distances. The slope of the trend is more pronounced in the group of connections from the seaports to the hinterland and in the opposite direction, reporting the highest costs on two destinations in Germany (Rheinhessen-Pfalz, DEB3, and Stuttgart, DE11), and the Swiss destination (Basel, CH03). In contrast, the load factor in short distance connection is relatively high, such as those within the Netherlands and between the Netherlands and Belgium. These are also the regions in which road transport has a dominant role over intermodal transport.

Considering the regions in which IWT offers a competitive position in the baseline scenario, the eligibility criteria are analyzed. Fig. 8 reports the percentage of eligible container flows and load factors. We observe a negative correlation between the variables, indicating that OD pairs with higher eligibility tend to have lower average load factors. Similarly, this pattern is more pronounced for flows originating in Antwerp (BE21, Fig. 8a), especially for flows below 40 % eligibility. The highest percentage of eligible containers, at 81 %, is found in the connection with Basel in Northwestern Switzerland (CH03), which also reports the lowest load factor of 47 %. Conversely, the lowest eligibility is observed in the flows toward Trier (DEB2), with a loading factor of 70 %. Notably, Koblenz (DEB1) exhibits the highest load factor at 90 %.

In the case of flows originating from Rotterdam (NL33, as shown in Fig. 8b), the inverse relationship between eligibility and load factors is

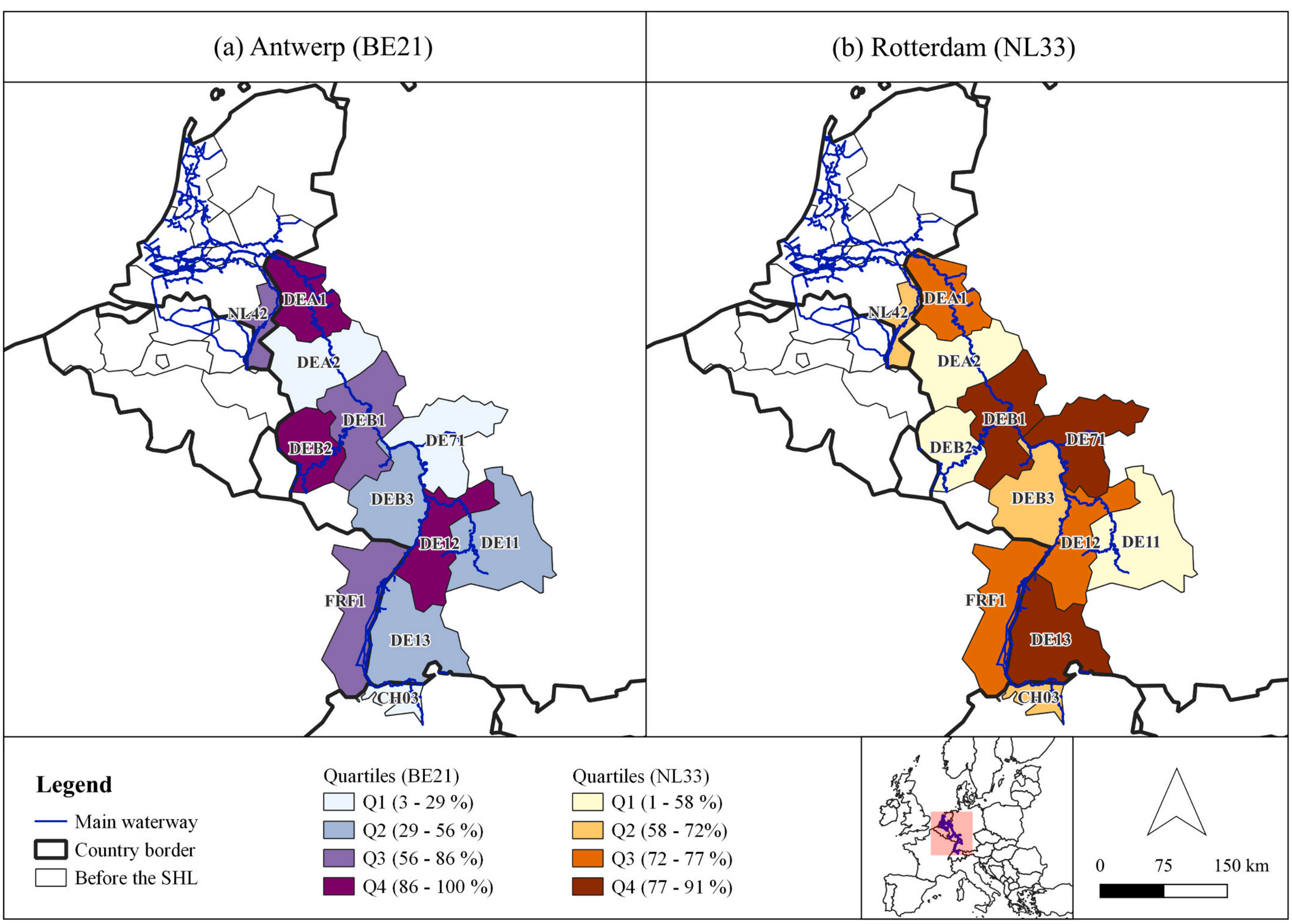

Fig. 6. Simulated mode share in regions passing through the SHL according to seaport of origin.

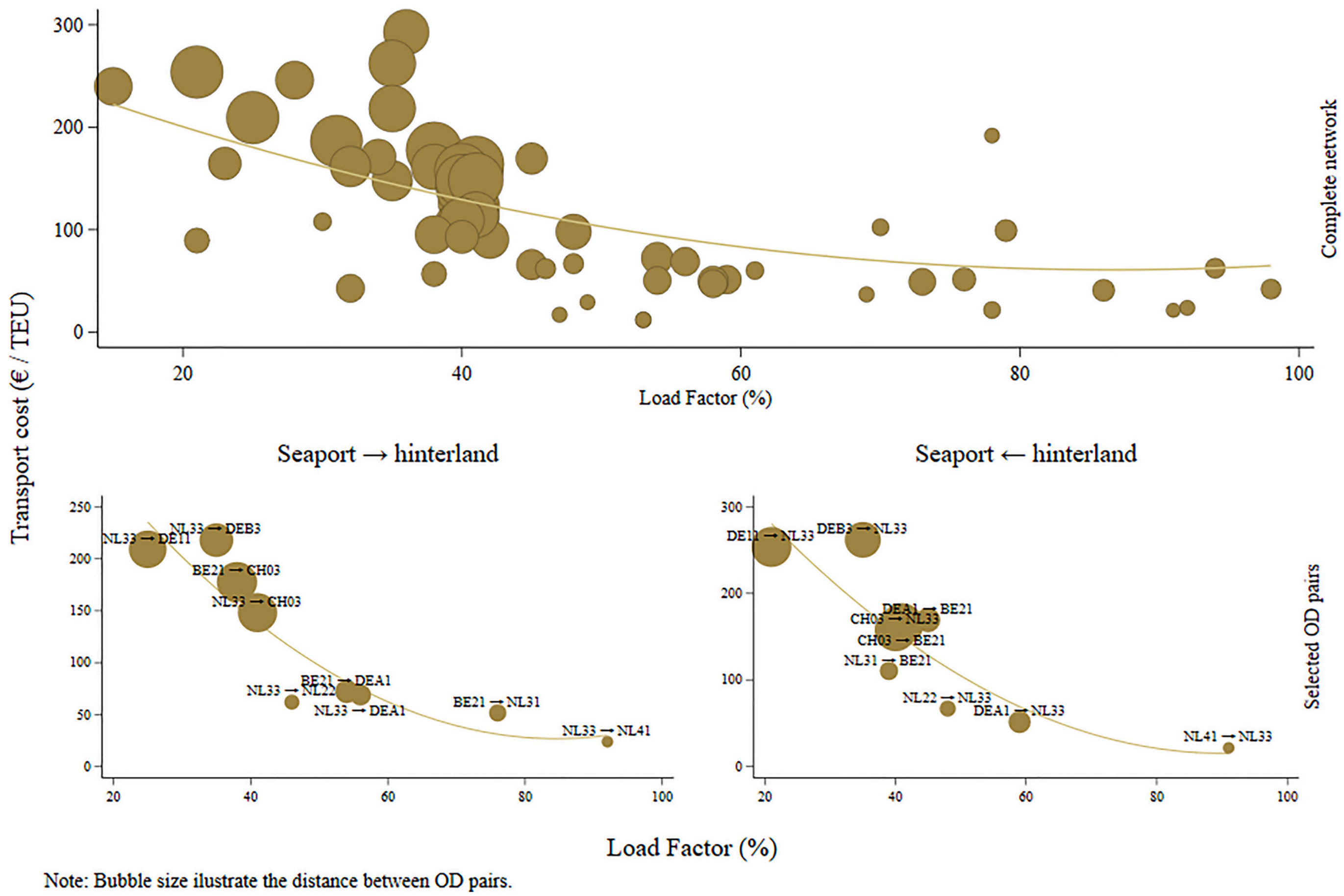

Fig. 7. Relation of costs per TEU and load factor.

more pronounced for flows exceeding 50 % eligibility. Cologne (DEA2) serves as a reference case in this context. Container flows toward Limburg (NL42) exhibit the highest eligibility at 71 % and a load factor of 49 %. Conversely, Freiburg (DE13) shows the highest load factor at 76 %, with an eligibility of 45 %.

Within this framework, LCL containers are identified as those units that meet the eligibility criteria while exhibiting sub-optimal loading factors. The historical average of LCL containers is presented in Fig. 9. For each OD pair. Considering the combination of flows originating in Antwerp and Rotterdam, the greatest potential for optimization is observed in flows destined to be unloaded in Düsseldorf (DEA1) and Rheinhessen-Pfalz (DEB3). The former is particularly significant for flows originating from Rotterdam, while the latter is for those from Antwerp. Within the Netherlands, a significant number of containers eligible for consolidation are noted in flows from Rotterdam to Limburg (NL42). Compared to the rest of the network, each of these three destinations has more than 25 thousand containers eligible for consolidation on average, as noted by the dashed line in Fig. 9.

While these figures represent historical averages, the net benefits and cost savings per TEU are highly dependent on the proportion of LCL containers in a given year. To account for this variability, a sensitivity analysis was conducted, considering a range of 35 % to 90 % for LCL containers relative to the total eligible cargo. The results, illustrated in Fig. 10, indicate that the CC strategy does not yield benefits when the CFS is deployed at the seaport or an inland terminal in any scenario, with a reduction in cost savings intensifying as the proportion of LCL containers increases. In the case of the SHL (Nijmegen), the CC strategy reports positive cost savings if the proportion of LCL containers is above 53 %. Below that threshold, implementing the policy is not advantageous.

Notably, a different trend is observed among the three strategies. The cost savings from CC implemented at the SHL (Nijmegen) increase with a higher proportion of LCL containers, whereas implementing CC at the seaport becomes more costly. In the beneficial case, the savings surpasses €20 per TEU when the potential reduction is 90 %. In comparison, the cost savings drop below €-150 per TEU if CC is implemented at the seaports. The scenario for CC at the inland terminals remains negative and relatively constant.

These results are also sensitive to critical parameters considered in the simulation. On one hand, they depend on the payload of a TEU considered for the consolidation process. On average, a vessel carries containers with a load of approximately 14 t per TEU (MPC, 2024). However, the objective is to maximize container payload, which could reach up to 28 t per TEU (Hapag-Lloyd., 2024). Fig. 11 illustrates the sensitivity of the results to this parameter, showing that the strategy is not cost-effective if the consolidation process achieves only the average weight (14 t per TEU). The strategy starts to show benefits at a weight of 20 t per TEU, as referenced by the dashed line in red, and could achieve cost savings of up to €20 per TEU if the consolidation process reaches the payload of 28 t per TEU.

On the other hand, the final benefits of the CC strategy will depend on the values of VoT and VoR assumed in the baseline cost estimation. While these values were derived from existing literature (de Jong et al., 2014), they can vary significantly over time. Such variations will affect

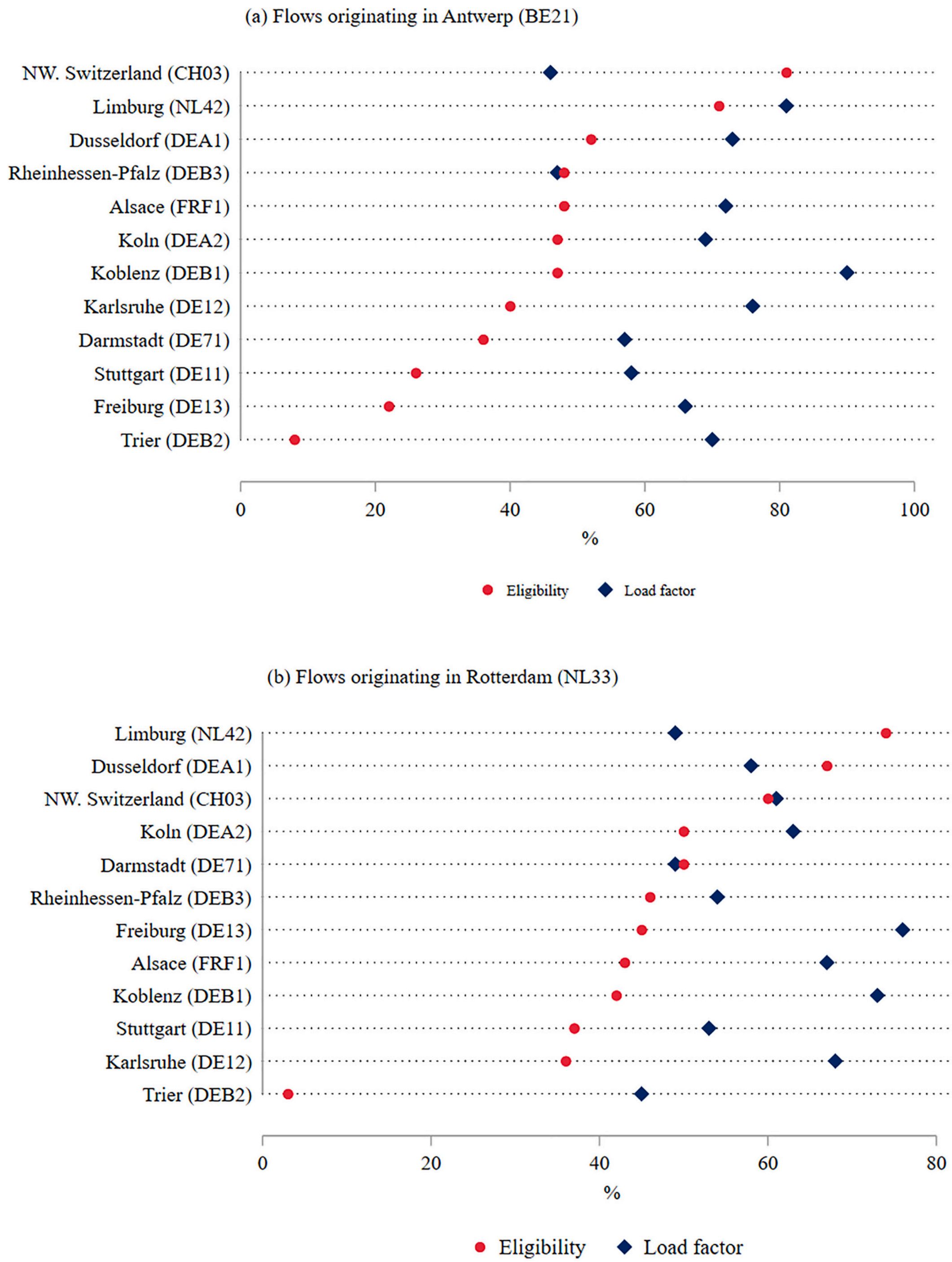

Fig. 8. Average eligibility and loading factors of container flows.

the cost and time submodel, ultimately influencing the final benefits derived from the CC strategy.

To address this uncertainty, Fig. 11 presents a sensitivity analysis based on a two-step framework. First, the relationship between VoT, VoR, and generalized costs of IWT in the baseline scenario is evaluated for the longest port-hinterland connections (i.e., Antwerp and Rotterdam to Basel), as detailed in Appendix B. These origin-destination pairs are selected because they best capture the dynamics within the cost submodel. The results reveal a linear relationship between these variables in both cases within the simulation model.

Consequently, the second step involves applying linear variations to baseline transport and handling costs for IWT across all origin-destination pairs and re-estimating the cost savings per TEU resulting from the consolidation strategy. The analysis reveals that reducing the number of containers requiring transportation leads to greater cost savings as baseline costs increase, driven by variations on VoT and VoR values associated with the initially transported containers, as reference by the red dashed line. Coherently, a negative cost saving would be reported in the opposite case. These savings are particularly pronounced when the payload is maximized at 28 t per TEU, reaching around 20 €

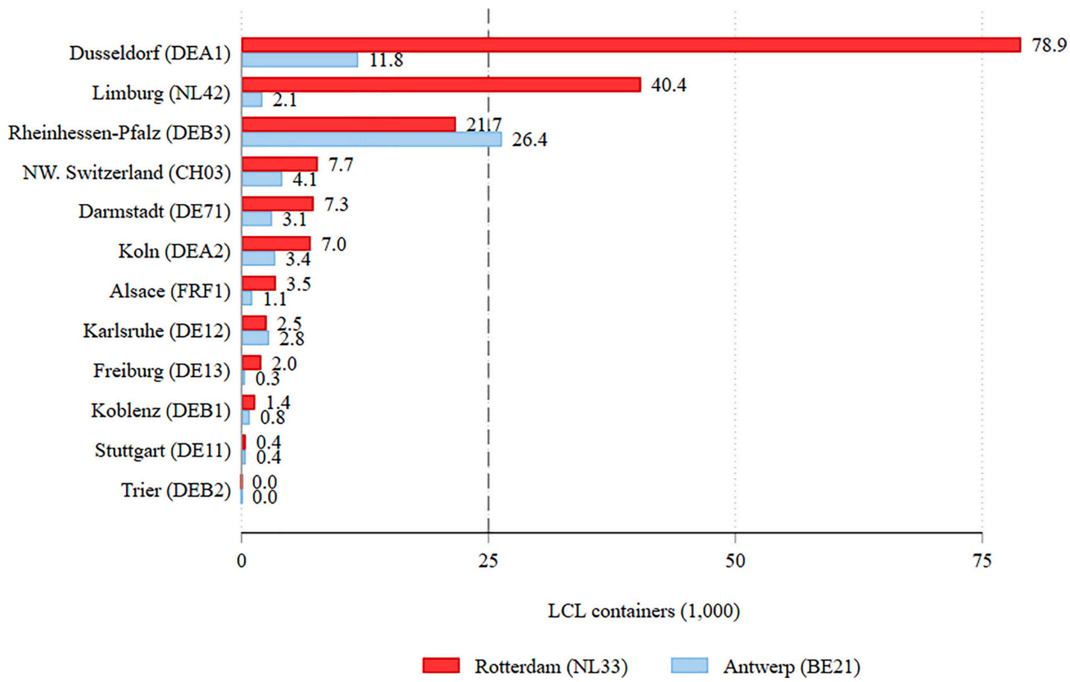

Fig. 9. Average of LCL containers originating in Antwerp and Rotterdam.

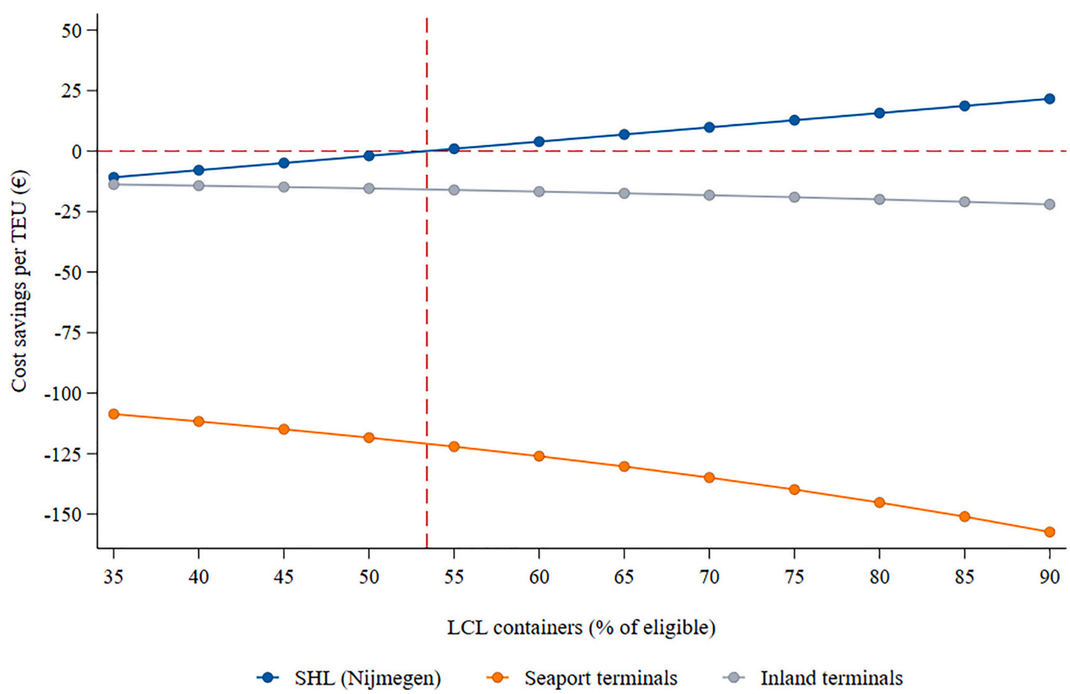

Fig. 10. Sensitivity to LCL containers.

per TEU.

5. Discussion and conclusions

Our literature review reveals that the CC strategy has yielded positive results for diverse transport modes; however, it indicates scant evidence regarding its potential for IWT, especially within an international corridor like the European one where IWT serves as a competitive alternative to road and rail for container cargo. Reducing inefficiencies in the RALP corridor could directly influence the performance of inland terminals across 24 European NUTS-2 regions from 5 countries. In this regard, the findings of our research complement the studies of Fan et al. (2019) and Wang et al. (2023) by simulating a CC strategy for the entire RALP navigable network intending to maximize container loading factors.

The central contribution of this study is the development of a spatial economic framework to assess the feasibility of the strategy. This framework can be applied to major inland rivers in other regions to analyze incurred costs and potential savings per TEU, considering various potential locations for the consolidation center. Consistent with

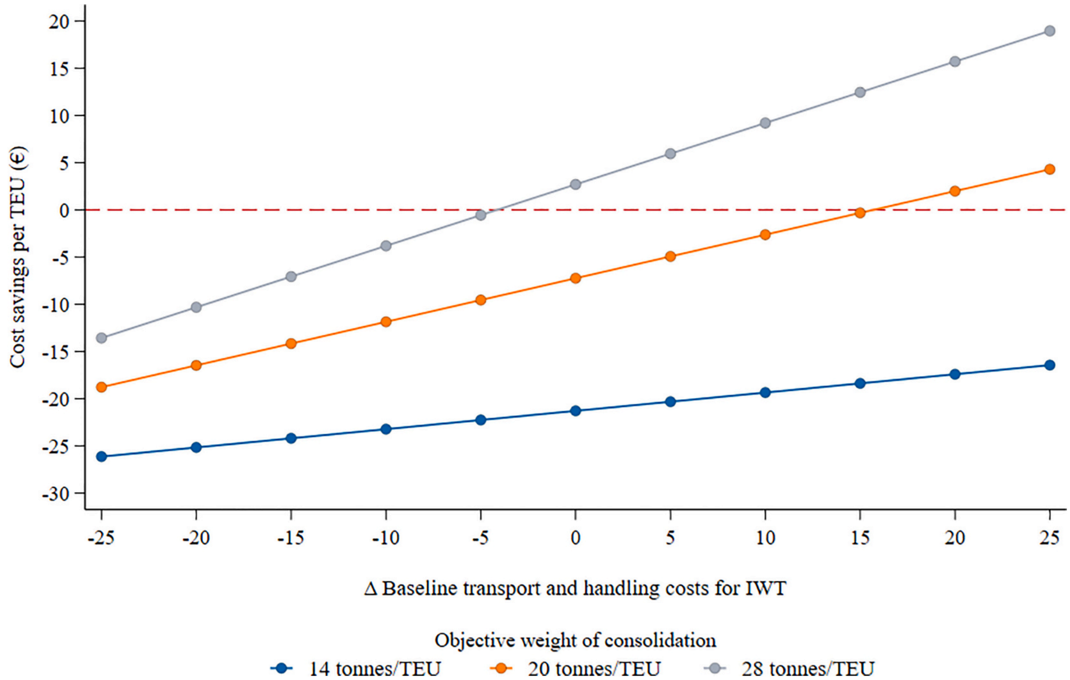

Fig. 11. Sensitivity to objective weight of consolidation and baseline cost parameters.

findings by Long and Grasman (2012) and Liang et al. (2024), this case study highlights the importance of market potential as container flows originating from the seaports of Antwerp and Rotterdam that are transported toward hinterland regions within the RALP. Intuitively, one might expect higher benefits if CC is implemented directly at the seaports to reduce transport costs over longer distances. However, our study's findings indicate that cost savings are not realized in any scenario when this option is chosen. This outcome can be attributed to the incurred costs at the ports of Antwerp and Rotterdam, which are linked to high handling costs at the seaport terminals.

Alternatively, hinterland hubs have gained increasing importance in recent years for intermodal transport originating from the ports of Antwerp and Rotterdam. For instance, the inland port of Duisburg has become a crucial hinterland hub with regular container barge traffic in the RALP. Notably, our results suggest that deploying and operating the CFS at all inland terminals would be costly and result in negative cost savings in all scenarios. This outcome could be attributed to the logistics capacity required to consolidate containers at each inland terminal, involving the need for multiple CFSs for the CC strategy.

The remaining scenario involves deploying the CFS at a specific hinterland location. Nijmegen is preferred over Duisburg and other options as a strategic point for consolidating container flows originating from the ports of Antwerp and Rotterdam. Specifically, this location offers the benefits of a hinterland hub situated as close as possible to the seaports where flows from different origins converge in route to the hinterland. Unlike other locations, consolidated cargo here would be transported along the busiest segment of the RALP inland network.

Notably, the results further suggest that merely selecting a strategic location such as Nijmegen for the CC strategy does not guarantee cost savings benefits. The proportion of LCL containers relative to the total eligible must exceed the 53 % threshold for the policy to be considered worthwhile. This indicates that the profitability of the strategy may vary annually, contingent on the proportion of eligible containers. Considering historical averages, it must be noted that the expected cost savings may be relatively modest compared to barge freight rates. Nonetheless, the sensitivity analysis revealed that these savings could reach up to €15/TEU when this proportion is 80 % of eligible cargo flows.

While such high eligibility is uncommon across the network, it might be worthy to implement the strategy on specific OD connections. For instance, the average proportion of LCL containers from Antwerp to Basel and Rheinhessen-Pfalz -two of the longest port-hinterland connections- was above 50 % from 2007 to 2021. However, these figures are based on historical averages, and the study does not account for future eligibility numbers. Therefore, before moving toward implementation, it would be crucial to gather input from various stakeholders to ensure the strategy's value and to identify which origin-destination connections would benefit from the approach, given the expected cargo flows.

It's also important to note that exogenous factors can influence the loading factors and the appeal of a CC strategy. For instance, the frequency and duration of critical water level episodes in the RALP, related to climate change, can disrupt the logic of the assessment. Specifically, during critically low water level events loading factors would decrease, and the proportion of LCL containers susceptible to consolidation might meet the economic feasibility threshold. However, under such navigability constraints, a CC strategy would not be practical. Consequently, it is essential to coordinate the CC strategy with other innovations in the RALP to alleviate transport inefficiencies. These innovations might include designing resilient infrastructure and vessels to cope with water level fluctuations, advancing digitalization to enhance navigation, and improving weather forecasting (CCNR, 2023).

We acknowledge that the economic feasibility of a CC strategy depends on the specific evaluation context, and the findings from this study should not be regarded as directly transferable to other regions. For instance, placing the consolidation center at a single hinterland site may not be the optimal solution for other major inland networks; in some cases, locating it directly at seaports or at multiple hinterland sites might achieve greater cost savings. However, the methodology developed here, combining the DES model with economic evaluation, can be replicated with data from diverse inland networks in other regions. The RALP case study serves as a valuable reference point for conducting these assessments and provides a basis for comparing the contextual factors that may influence optimal location selection in different settings.

To replicate the assessment of a CC strategy for major river systems in other regions, three essential conditions must be met. First, at least one seaport should generate demand for IWT services, facilitating port-hinterland connections. Second, the inland network should be sufficiently developed to support the strategy without significant additional investment. Finally, a sufficient number of eligible containers with suboptimal loading factors should be available to ensure the economic viability of the strategy. For major rivers in other regions, such as the Yangtze and the Mississippi, the first two conditions are generally met, and the third can be evaluated using the methodological approach proposed in this research.

Several limitations of this study must be acknowledged. First, the impact on travel time remains uncertain. On the one hand, the consolidation process may add travel time for a portion of containers compared to the baseline scenario without intervention. On the other hand, it can improve operational efficiency at inland terminals by alleviating pressure on handling infrastructure, reducing the number of unloading operations. Additionally, it benefits the rest of the transport chain by requiring fewer containers to be transported by road from the terminal to the final destination.

Second, the strategy may have implications for external costs that are not accounted for. For instance, CO_2 emissions and other external costs could potentially be reduced by transporting fewer containers—and possibly fewer barges—from the CFS to the final destination. Third, this approach may have broader implications, as enhanced competitiveness could increase the appeal of IWT over road-only or rail options. By lowering costs per TEU, this strategy might alter the mode choice for cargo originating from the seaports, potentially increasing the market share of IWT.

Finally, while this study focuses on the economic benefits of the CC strategy for IWT, it does not address the optimization of its implementation in terms of operational aspects such as service scheduling, cost-time minimization, or managing fluctuating water levels. Future research exploring these operational factors could assess improvements in transport efficiency and capacity utilization, and extend the analysis to the other discussed key performance indicators, including the potential impacts of the CC strategy on travel time, external costs, and market share.

There are three main conclusions from the study. First, the potential cost savings achieved by implementing a consolidation strategy in the RALP are highly sensitive on the location in which the CFS is deployed and the proportion of LCL containers relative to the total eligible. Second, executing the CC strategy directly at the seaport or at the inland terminal of each hinterland results in negative cost savings under all cases. The strategy can yield benefits if a CFS is established in a terminal proximate to the seaports where container flows converge in their route to the hinterland. Third, selecting the optimal location for the CFS is a necessary condition but not sufficient to ensure positive cost savings. Specifically, the annual flow of LCL containers must be substantial enough to justify the policy. In the context of the RALP, the study found that the flow should surpass 53 % of eligible containers and set an objective weight of consolidation of at least 20 t per TEU for the strategy to be considered worthwhile.

Increasing the use of IWT for container cargo can support regional sustainability goals on freight transport networks. Addressing suboptimal container loading factors would contribute in that regard by enhancing its market appeal to stakeholders, promoting IWT as a competitive option for port-hinterland connections. While this study focused on the RALP, the proposed assessment approach can be applied to address similar inefficiencies in major inland waterways in other regions.

CRediT authorship contribution statement

Felipe Bedoya-Maya: Conceptualization, Methodology, Formal analysis, Software, Investigation, Validation, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Peter Shobayo:** Conceptualization, Methodology, Formal analysis, Software, Investigation, Validation, Data curation, Writing – review & editing. **Adrien Nicolet:** Conceptualization, Methodology, Formal analysis, Software, Investigation, Validation, Data curation, Writing – review & editing. **Eva Christopoulou:** Conceptualization, Methodology, Software, Investigation, Validation. **Ivo Majoor:** Conceptualization, Methodology, Software, Investigation, Validation. **Edwin van Hassel:** Conceptualization, Methodology, Validation, Resources, Supervision, Writing – review & editing, Project administration, Funding acquisition. **Thierry Vanelslander:** Resources, Supervision, Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare no conflicts of interest.

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Appendix A

A.1. Detailed notations of the cost and time sub-model

Notation	Definition	Unit
D	Distance of the route	km
T^m_{drive}	Driving time of mode *m*	hr
T_{dwell}	Dwell time	hr
C^m_{fixed}	Fixed maintenance cost of mode *m*	€/m3
FC_{idle}	Fuel consumption during idle time of the vessel class	l/h
FC_{sail}	Fuel consumption during sailing	l/h
P_{fuel}	Fuel price	€/l
C_m	Generalized cost of mode *m*	€
C^m_{hr}	Hour cost of mode *m*	€/kr
T_{idle}	Idle time, including port waiting and lock passage times	hr
P_{inst}	Installed engine power	KW

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Notation	Definition	Unit
Cap_m	Load capacity of mode *m*	–
T_{lock}	Lock passage time	hr
C_o^m	Operative cost of mode *m*	€/km
PD_{trip}	Port dues per trip	€
S_m	Speed of mode *m*	km/h
$T_{terminal}^{wait}$	Terminal waiting time	hr
T_{port}^{hand}	Port handling time	hr
$T_{terminal}^{hand}$	Terminal handling time	hr
T_{port}	Time at port	hr
T_{lock}^{tran}	Time crossing the lock	hr
T_{lock}^{wait}	Time waiting at lock	hr
T_{port}^{wait}	Time waiting at port	hr
C_{trans}^m	Transport cost of mode *m*	€
T_{cong}	Trucking congestion time	hr
T_{rest}	Trucking resting time	hr
u_m	Utilization rate of mode *m*	%
VOR_m	Value of reliability for mode *m*	€
VOT_m	Value of time for mode *m*	€
C_{var}	Variable maintenance cost	€/kWh
L	Vessel breadth	m
B	Vessel draught	m
T	Vessel length	m
C_v	Voyage costs	€

A.2. Detailed costs and time submodel

$$C_{IWT} = \left[C_{trans}^{IWT} + \left(T_{oper}^{IWT} * VOT_{IWT}\right) + \left(T_{lock} + T_{port}\right) * VOR_{IWT}\right] \Big/ \left(Cap_{IWT} * u_{IWT}\right) \tag{11a}$$

$$C_{trans}^{IWT} = C_o^{IWT} + C_v^{IWT} \tag{11b}$$

$$C_v = \left[P_{fuel} * \left([FC_{idle} * T_{idle}] + [FC_{sail} * T_{sail}]\right)\right] + PD_{trip} \tag{11c}$$

$$C_o = \left[\left(C_{fixed}^{IWT} * L * B * T\right) + \left(C_{var} * T_{sail} * P_{inst}\right)\right] + \left(T_{oper}^{IWT} * C_{hr}^{IWT}\right) \tag{11d}$$

$$T_{oper}^{IWT} = T_{sailing} + N_{lock} * \left(T_{lock}^{wait} + T_{lock}^{tran}\right) + \left(T_{port}^{hand} + T_{port}^{wait}\right) \tag{11e}$$

$$T_{sailing} = D \big/ S_{IWT} \tag{11f}$$

$$C_{road} = \left[\left(C_{trans}^{road}\right) + \left(T_{drive}^{road} + T_{cong}\right) * VOT_{road} + \left(T_{cong} + T_{terminal}^{wait}\right) * VOR_{road}\right] / \left(Cap_{road} * u_{road}\right) \tag{11g}$$

$$C_{trans}^{road} = \left(C_{km}^{road} * D\right) + \left(C_{hr}^{road} * T_{oper}^{road}\right) + \left(C_{hr}^{road} / 2 * T_{rest}\right) \tag{11h}$$

$$T_{oper}^{road} = T_{drive}^{road} + T_{cong} + T_{terminal}^{wait} + T_{terminal}^{hand} + T_{rest} \tag{11i}$$

$$T_{drive}^{road} = D \big/ S_{road} \tag{11j}$$

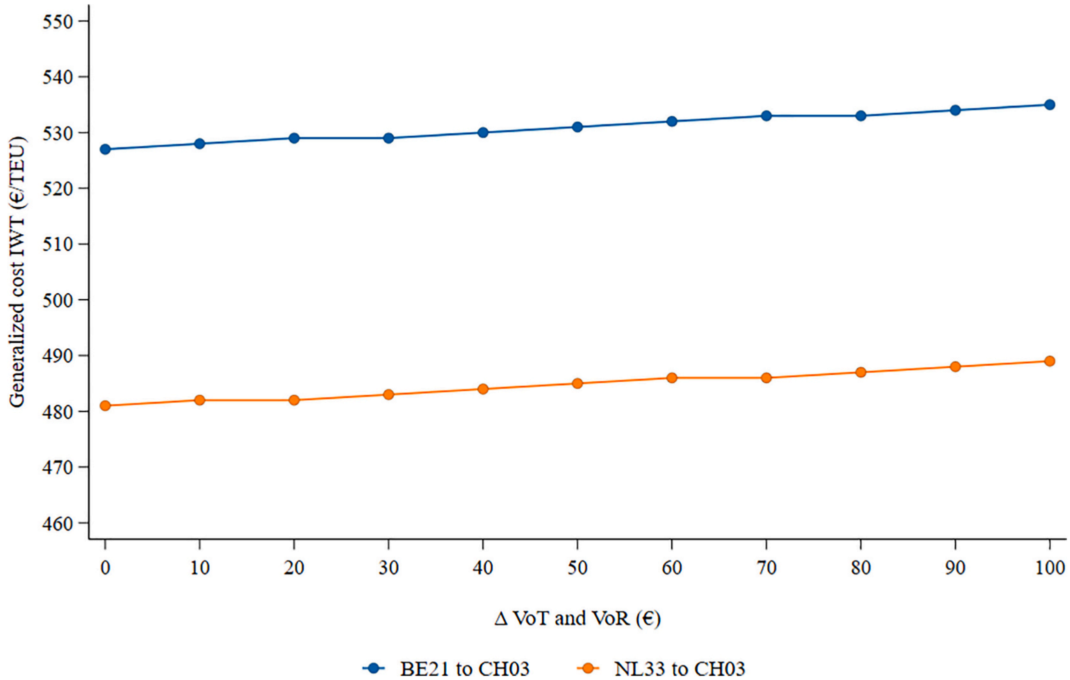
$$C_{rail} = \left[C_{trans}^{rail} + \left(T_{oper}^{rail} * VOT_{rail}\right) + \left(T_{dwell} * VOR_{rail}\right)\right] \Big/ \left(Cap_{rail} * u_{rail}\right) \tag{11k}$$

$$C_{trans}^{rail} = C_{fixed}^{rail} + \left(C_{km}^{rail} * D\right) + \left(C_{hr}^{rail} + T_{oper}^{rail}\right) \tag{11l}$$

$$T_{oper}^{rail} = T_{drive}^{rail} + T_{terminal}^{hand} + T_{terminal}^{wait} \tag{11m}$$

$$T_{drive}^{rail} = D \big/ S_{rail} \tag{11o}$$

Appendix B. Sensitivity of IWT generalized cost to VoT and VoR



Note: Prov. Antwerp (BE21, region hosting the Port of Antwerp), South Holland (NL33, region hosting the Port of Rotterdam), Northwestern Switzerland (CH03, region hosting the Port of Basel)

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