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# Improving a cargo consolidation strategy for port-hinterland transport via inland waterways☆

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ABSTRACT

Container logistics is under increasing pressure to deliver efficient and sustainable hinterland transport. Achieving this requires improving the performance of environmentally friendly modes, such as inland waterway transport. This study examines the potential of cargo consolidation as a strategy to tackle suboptimal filling rates of containers, one of the most persistent inefficiencies in the Rhine-Alpine Corridor. We develop an integrated optimization model that holistically accounts for the operational and spatial requirements of consolidation, assessing the sensitivity of the strategy to labor costs, fuel prices, value of time, and vessel costs. The results show that, despite additional handling and coordination costs, consolidation can reduce overall transport costs by up to 4 % and attract as much as 42 % more container volumes to IWT on specific origin-destination connections. Vessel occupation rates emerge as a decisive factor in determining consolidation benefits, while cost parameters such as labor and fuel prices strongly influence outcomes. The research illustrates how optimizing this strategy can contribute to the sustainability of port-hinterland container transport and discusses the conditions required for its realization.

## 1. Introduction

The growing global emphasis on environmental sustainability has intensified the need to address the negative externalities of freight transport, including emissions, congestion, accidents, and land-use impacts. At the same time, the rapid growth of containerized trade in the coming decades demands more efficient freight logistics networks (ITF, 2019). In this context, inland waterway transport (IWT) represents a strategic opportunity, offering an energy-efficient and cost-effective alternative for serving port-hinterland connections (ECA, 2023).

Over the past decades, however, IWT in Europe has faced a series of internal and external disruptions and inefficiencies that have undermined its competitiveness. Internally, the sector has been constrained by bottlenecks that reduce efficiency in the port–hinterland logistics chain. One of the most critical is the suboptimal filling rate of shipments, defined as the ratio of the actual amount of cargo carried to the maximum possible load (McKinnon et al., 2015). In the Rhine-Alpine corridor (RALP, the busiest multimodal port-hinterland transport network in the region), the average container filling rate has been around 55 % (Novimove, 2023), suggesting that most containers transported are Less than Container Load (LCL). This generates cascading effects, such as additional handling time at terminals and increases the external costs per TEU transported (Friedhoff et al., 2023). The persistent challenge of suboptimal container filling rates and fragmented cargo flows in many IWT corridors continues to hinder the realization of the environmental and economic benefits of IWT.

Cargo consolidation (CC) has emerged as a potential solution to the problem of suboptimal container filling rates, yet its adoption in port–hinterland systems via IWT remains limited. This strategy consists of consolidating LCL shipments so that all goods bound for the same location are combined into a full container, ensuring a high filling rate to the destination. At the consolidation facility, various optimization operations can be performed to group goods from different shipments that share a destination, thereby reducing direct costs and externalities (Fan et al., 2019). Unlike the dry port strategy, which essentially replicates seaport functions inland and focuses on offering full intermodal services

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such as customs clearance, storage, and distribution, the CC strategy is solely concerned with optimizing container utilization.

There are three primary distinctions between these strategies. First, the strategic considerations for placing a consolidation center differ from those of a dry port: while dry ports are usually located to extend the seaport functions and provide inland gateways, consolidation centers must consider the geography of navigable waterways and the flow of cargo in specific corridors (Rodrigue and Notteboom, 2012). Second, the operational characteristics of dry ports are considerably broader, encompassing a wide range of logistics and administrative functions (Roso et al., 2009), whereas CC facilities are only focused on optimizing container bundling and vehicle deployment (Olsson and Woxenius, 2014). Third, the sensitivity of CC to operational and market parameters, such as labor costs, can differ substantially from that of dry ports (Rodrigue and Notteboom, 2012). These elements have been overlooked in the emerging literature on consolidation for IWT.

Consequently, this strategy entails two major layers of complexity: spatial and operational. The spatial dimension involves decisions on where and how to implement consolidation facilities, which depend on the geographical distribution of demand, the configuration of multimodal networks, and the proximity of urban and industrial clusters to ports and terminals (Liang et al., 2024; Long and Grasman, 2012). The location selected for the consolidation facility can impact freight flows across regions and redistribute traffic between transport modes (Liang et al., 2024).

While introducing a CC strategy for IWT could influence the overall transport competitiveness in serving hinterlands, the existing literature remains limited in addressing the second layer of complexity: the operational. Specifically, available studies have focused narrowly on cargo flow eligibility and the placement of consolidation centers (Bedoya-Maya et al., 2025; Wang et al., 2023) but have not been able to estimate potential advantages related to optimizing vessel service requirements. Adjustments in vessel capacity to serve consolidated cargo flows could reveal additional cost and emissions savings. This gap in the literature leads to the first research question: to what extent does an optimized CC strategy influence container IWT efficiency in port-hinterland connections?

There is another literature gap regarding the sensitivity of CC strategies to operational parameters. Factors such as labor costs, cargo value of time, fuel prices, and vessel operating costs all influence the effectiveness and cost-efficiency of CC strategies. Yet, the extent to which these parameters affect strategic decision-making in IWT remains underexplored. This prompts the second research question: Under which operational conditions does CC yield benefits for IWT? Addressing this question is important to refine the assessment and align it with current port–hinterland transport realities.

To answer these questions, this study develops an optimization model that addresses both layers of complexity, considering the spatial configuration of cargo flows between origin-destination (OD) locations, transport and handling costs, vessel occupancy rates, and the number of completed trips on critical port–hinterland connections. The model incorporates network characteristics, IWT service data, OD matrices, travel times, and cost structures for each OD pair. Sensitivity analyses are also conducted to assess the impact of critical parameters on the optimal CC strategy. The empirical application focuses on regions connected to the major seaports in the North Sea via IWT within the Rhine–Alpine Corridor (RALP), the busiest port–hinterland transport corridor in Europe.

This research contributes to the literature on port-hinterland transport and intermodality using IWT by bridging transport geography and operational research. It does so by developing a fully integrated optimization framework that assesses CC at both the container and vessel levels, incorporating target filling rates and vessel occupation as decision variables. This enables more precise and realistic cargo consolidation strategies. The rest of the paper is structured as follows. Section 2 reviews the literature. Section 3 outlines the assessment methodology and explains the integrated optimization model. Section 4 reports the results, which are discussed in Section 5. Section 6 concludes the paper.

## 2. Literature review

From the perspective of operational research, a substantial body of work has examined the economic and logistical advantages of the CC strategy. Early studies, such as Beckmann et al. (1953), started to show the economies of scale achievable by reallocating goods moving in the same direction into larger transport units, estimating the cost benefits of aggregating shipments. Jackson (1985) identified cost reduction as the principal driver for adopting CC strategies, while Higginson and Bookbinder (1994) used simulation models to evaluate both cost and time efficiencies, highlighting their joint importance in assessing viability. Çetinkaya and Bookbinder (2003) developed a framework for balancing consolidation timing and cargo volume, offering solutions for different carriage types. A common feature of these early contributions is their emphasis on consolidation at the container level, with less attention given to optimizing shipments within containers.

Subsequent research addressed this gap more explicitly. Qin et al. (2014) formulated a linear programming model for the freight consolidation and containerization problem (FCCP), jointly optimizing shipment routing and container utilization. They showed that balancing delivery costs with container fill rates is critical, as focusing solely on either dimension can lead to inefficiencies. Building on this, Tiwari et al. (2021) incorporated emissions taxes into the FCCP to evaluate environmental impacts alongside costs. Hanbazazah et al. (2018) extended the scope to in-transit consolidation across multiple stations, allowing for mode selection and divisible shipments, while Hanbazazah et al. (2019) generalized this to indivisible shipments and specific delivery windows, reflecting real-world operational constraints, indicating scalability for large problem instances. While these studies introduced shipment-level decision-making, they often omitted key operational targets such as container filling rates and vessel occupation, variables that are essential for designing flexible consolidation strategies in modes like IWT.

From the perspective of transport geography, research has increasingly focused on the spatial dynamics of seaport–hinterland connectivity via IWT. Early conceptual contributions by Notteboom and Konings (2004) and Notteboom and Rodrigue (2005) identified the structural factors shaping IWT, waterway availability, cargo distribution, and economic integration, developing the port regionalization concept that emphasizes seaport–hinterland interdependence (Notteboom and Rodrigue, 2010). From these studies, network optimization approaches have been applied to improve IWT performance. Caris et al. (2011) developed discrete-event simulation models to test bundling strategies, while Zhou et al. (2023) and Deng et al. (2022) applied network analysis to examine hub configurations, economies of scale, and spatial disparities in hinterland connectivity.

This line of research has also considered network optimization to improve performance. For instance, Konings et al. (2013) proposed a hub-and-spoke (HS) model for seaport–hinterland waterway transport, showing cost benefits under certain handling cost conditions. Zheng and Yang (2016) applied a segmented HS approach to the Yangtze River, identifying optimal hub and feeder port locations, while noting limitations for small vessels. Fazi et al. (2015) examined trade-offs between consolidating containers via barges and dispatching by truck, finding that barge-based consolidation is favorable when capacity, scheduling, and docking conditions allow flexibility.

Recent studies have begun linking CC to resilience, as in Wang et al. (2023), who showed that flexible CC on the Yangtze River reduced congestion and costs during COVID-19 disruptions. However, empirical work integrating CC within a multimodal, cross-border IWT network remains limited. Bedoya-Maya et al. (2025) addressed this gap for the first time in Europe, considering the main waterways of the Rhine–Alpine Corridor, testing three locations for the CC strategy. The study found that seaport or multi-terminal deployment generated negative cost savings due to high handling and infrastructure costs, whereas a single strategic hinterland location where flows converge could yield positive savings, conditional on meeting thresholds for eligible cargo and consolidation weight targets.

In sum, research in operational research and transport geography has approached CC from largely independent angles: the former focusing on optimization models and operational efficiency, the latter on port-hinterland cargo flows and context-specific feasibility conditions. This separation has limited the development of integrated assessment frameworks that jointly consider spatial placement, modal competition, operational parameters, and realistic implementation constraints. The present study seeks to bridge this gap in the European IWT context by developing an assessment methodology that accounts for both perspectives, as detailed in the following section.

## 3. Assessment methodology

This section presents the integrated optimization modeling framework for the CC strategy that accounts for both operational and spatial complexity layers. First, an optimization model is formulated to determine the optimal operational conditions of the strategy that minimizes the total cost. Second, the analysis incorporates spatial considerations related to port–hinterland transport via IWT, ensuring that corridor-specific factors are reflected in the evaluation. Finally, the section outlines the input parameters necessary to conduct a comprehensive performance assessment of the proposed strategy.

### 3.1. Optimization model

The decision variables of this problem are as follows: 1) whether a specific OD pair should be assigned to consolidation, 2) the optimal final load factor of the containers for each OD pair if consolidation is undertaken, and 3) the optimal final occupation rate of the vessels for each OD pair if consolidation is undertaken. The idea behind the optimization model is that the additional incurred costs can be compensated for by savings on transport from the consolidation station to the destination because fewer vessels need to be used. If an OD pair is assigned to consolidation, some vessels on this pair only travel the first leg between the origin and the consolidation station, where they unload all their containers and do not proceed with the rest of the trip. In our model, these vessels are called “leg-1” vessels. The model scope does not consider the subsequent activities of these vessels, as they are assumed to be deployed for other productive services beyond the modeling environment; in this case, they could be deployed to transport other cargo types, as they are dry vessels. Containers eligible are consolidated and, along with non-eligible containers, await transportation to the destination. The vessels responsible for this process are termed “whole-trip” vessels, as they cover the entire journey of the OD pair. Starting from the origin, they first stop at the consolidation station to unload eligible containers and reload the consolidated and non-eligible containers left by leg-1 vessels. The sum of leg-1 vessels and whole-trip vessels equals the total number of trips (vessels) over the year. Based on this, some assumptions guiding the principles of the model are specified below:

a. The frequency of the vessels leaving the origin for each OD pair is evenly distributed throughout the year.
b. The consolidation station has unlimited capacity and can handle all the containers that are assigned to it.
c. The occupation rate of the vessel does not affect the vessel cost, which implies that a vessel, empty or fully loaded, costs the same amount to travel the same distance.
d. The highest final occupation rate and container filling rates are both 90 %.
e. The initial occupation rate and container filling should not be over 90 %.
f. The employee efficiency for consolidation is two persons handling two containers per day.
g. One employee works 8 h a day.

Based on these guiding principles, the optimization model can then be developed. The parameters and decision variables used in the model are presented in Table 1.

The overall objective of the integrated optimization model is to minimize the total cost with the consolidation strategy. These costs include the travel costs of both the leg-1 and the whole trip vessels, cargo handling costs at the consolidation station and destination terminals, consolidation costs, cargo waiting at the consolidation station, and labor costs. Each term in the objective function will be explained specifically in the constraints. The model is expressed as:

**Table 1**
Optimization model parameters and decision variables.

| Notation | Unit | Definition |
|---|---|---|
| Sets | | |
| $N$ | – | Terminals (indices: $i, j$) |
| $A$ | – | Arcs $(i, j)$ |
| $K$ | – | Vessel types, $k \in \{0, 1\}$ (0: Leg-1 vessels; 1: Whole-trip vessels) |
| Decision variables | | |
| $y_{ij}$ | – | Binary, equals 1 if OD pair $ij$ is assigned to consolidation; 0, otherwise. |
| $f_{ij}$ | – | Continuous, target load factor of the containers for OD pair $ij$ |
| $r_{ij}$ | – | Continuous, target occupation rate of the vessels for OD pair $ij$ |
| $z_{ijk}$ | – | Integer, number of vessels of type $k$ for OD pair $ij$ |
| Dependent variables | | |
| $v_{ij}^{FILL}$ | TEUs | Continuous, filled volumes after consolidation for OD pair $ij$ |
| $c_{ijk}$ | €/vessel | Continuous, average cost of a type $k$ vessel for OD pair $ij$ |
| $c_{ij}^{HAND}$ | € | Continuous, total container handling cost for OD pair $ij$ |
| $c_{ij}^{CR}$ | € | Continuous, total cargo consolidation cost for OD pair $ij$ |
| $c_{ij}^{VoT}$ | € | Continuous, total value of time of cargos stranding at the consolidation station for transportation to the destinations for OD pair $ij$ |
| $t_{ijk}^{PORT}$ | hr | Continuous, inland port time (include at consolidation station) of a vessel of type $k$ for OD pair $ij$ |
| $t_{ijk}^{IDLE}$ | hr | Continuous, idle time of a vessel of type $k$ for OD pair $ij$ |
| $t_{ijk}^{TOTAL}$ | hr | Continuous, total time of a vessel of type $k$ for OD pair $ij$ |
| Parameters | | |
| $Q$ | TEUs | Capacity of the homogeneous vessels |
| $G_{ij}$ | Vessels | Number of annual trips (vessels) for OD pair $ij$ |
| $D_{ijk}$ | km | Distance sailed by vessel type k for OD pair $ij$ |
| $T_{ijk}^{SAIL}$ | hour | Sailing time of vessel type k for OD pair $ij$ |
| $E_{ij}$ | – | Eligibility rate of containers for consolidation for OD pair $ij$ |
| $V_{ij}$ | TEUs | Total number of initial containers for OD pair $ij$ |
| $LF_{ij}$ | % | Initial average filling rate of containers for OD pair $ij$ |
| $H_{ij}$ | % | Initial average occupation rate of vessels for OD pair $ij$ |
| $T^{HAND}$ | hr/TEU | Container handling time at inland ports |
| $T^{STRAND}$ | hour | Average stranding time of cargos at the consolidation station for transportation for OD pair $ij$ |
| $C^{HAND}$ | €/TEU | Container handling cost |
| $C^{FILL}$ | €/TEU | Container filling cost |
| $C^{EMP}$ | €/TEU | Container emptying cost |
| $C^{FUEL}$ | €/km | Fuel cost per km traveled for a vessel |
| $C^{FIX}$ | €/h | Fixed cost for a vessel |
| $C^{VAR}$ | €/hr | Variable cost for a vessel |
| $W_{ij}$ | € | Yearly labor costs for consolidation on OD pair |
| $VoT$ | €/TEU/hr | Cargo value of time |
| $M$ | – | Large enough number |

$$\text{Min} \sum_{(i,j)\in A}\left(\sum_{k\in K} z_{ijk}c_{ijk} + c_{ij}^{HAND} + c_{ij}^{CR} + c_{ij}^{VoT}\right)$$

Constraints (1) and (2) specify the lower and upper bound of the final vessel occupation rate and load factor for vessels on each OD pair $ij$. The lower bounds are given by their initial values. The upper bound is a rate no greater than 100 %, denoted by M, and depends on whether the OD pair is assigned to consolidation. Constraints (3) express how the final filled volume $v_{ij}^{FILL}$ is calculated.

$$LF_{ij} \le f_{ij} \le My_{ij} \quad \forall(i,j)\in A \tag{1}$$

$$H_{ij} \le r_{ij} \le My_{ij} \quad \forall(i,j)\in A \tag{2}$$

$$v_{ij}^{FILL} = \frac{LF_{ij}V_{ij}E_{ij}}{f_{ij}} \quad \forall(i,j)\in A \tag{3}$$

$$y_{ij} \in \{0,1\} \quad \forall(i,j)\in A \tag{4}$$

$$v_{ij}^{FILL} \ge 0 \quad \forall(i,j)\in A \tag{5}$$

Constraints (6) state that the number of final vessels after consolidation is determined by the volume of unmixable containers and the number of filled containers after consolidation, assuming that vessels are loaded to an optimized occupation rate. Constraints (7) ensure that for each OD pair $ij$, the number of final leg-1 vessels and whole-trip vessels equals the initial number of vessels.

$$y_{ij}\left(\frac{\left(V_{ij}(1-E_{ij}) + v_{ij}^{FILL}\right)}{r_{ij}Q} + 1\right) + \left(1-y_{ij}\right)G_{ij} \ge z_{ijk} \quad \forall(i,j)\in A, k=1 \tag{6}$$

$$\sum_{k\in K} z_{ijk} = G_{ij} \quad \forall(i,j)\in A \tag{7}$$

$$z_{ijk} \in Z_{\ge 0} \quad \forall(i,j)\in A, \quad \forall k\in K \tag{8}$$

The equations below describe how the average vessel cost, $c_{ijk}$, for each OD pair $ij$ of vessel type $k$ is estimated. The port time, idle time, and total vessel time estimation are first described. In describing this, constraints (9) state that the inland port time for a leg-1 vessel of OD pair $ij$ is the time required to unload all containers at the consolidation station. Constraints (10) explain the port time of a whole-trip vessel, which is determined by considering the time needed to unload all eligible volumes on all whole-trip vessels and loading filled volumes at the consolidation station and unloading everything (ineligible and filled volumes) at the destination ports. This estimates the time needed to handle all volumes on an OD pair. This time is then averaged over the number of the final whole-trip vessels to obtain the average port time for a vessel. Constraints (11) express the calculation of total vessel time, which is the sum of sailing time (given as inputs), port time, and idle time, where according to Van Dorsser (2015) the idle time is estimated as $t_{ijk}^{IDLE} = 0.1*\left(t_{ijk}^{PORT} + T_{ijk}^{SAIL}\right)$. With the time estimated, constraints (12) give the average cost of a vessel, which is the sum of fuel cost, fixed cost determined by total vessel time, and variable cost determined by sailing time and port time.

$$t_{ijk}^{PORT} = T^{HAND}H_{ij}Qy_{ij} \quad \forall(i,j)\in A, k=0 \tag{9}$$

$$t_{ijk}^{PORT} = T^{HAND}\frac{\left(y_{ij}\left(V_{ij}E_{ij} + 2v_{ij}^{FILL} + \frac{z_{ijk}}{G_{ij}}V_{ij}\left(1-E_{ij}\right)\right) + \left(1-y_{ij}\right)V_{ij}\right)}{z_{ijk}} \quad \forall(i,j)\in A, k=1 \tag{10}$$

$$t_{ijk}^{TOTAL} = T_{ijk}^{SAIL} + t_{ijk}^{PORT} + t_{ijk}^{IDLE} \quad \forall(i,j)\in A, \quad \forall k\in K \tag{11}$$

$$c_{ijk} = \left(D_{ijk}C^{FUEL} + C^{FIX}t_{ijk}^{TOTAL} + C^{VAR}\left(T_{ijk}^{SAIL} + t_{ijk}^{PORT}\right)\right) \quad \forall(i,j)\in A, \quad \forall k\in K \tag{12}$$

Constraints (13)–(15) describe the calculation of the total cost for container handling, cargo consolidation, and cargo stranding at the consolidation station for each OD pair $ij$, respectively.

$$c_{ij}^{HAND} = C^{HAND}\left(y_{ij}\left(V_{ij}E_{ij} + 2v_{ij}^{FILL} + \frac{z_{ijk}}{G_{ij}}V_{ij}\left(1-E_{ij}\right)\right) + \left(1-y_{ij}\right)V_{ij}\right) \quad \forall(i,j)\in A, k=0 \tag{13}$$

$$c_{ij}^{CR} = \left(C^{FILL}v_{ij}^{FILL} + C^{EMP}\left(V_{ij}E_{ij} - v_{ij}^{FILL}\right) + W_{ij}\right)y_{ij} \quad \forall(i,j)\in A \tag{14}$$

$$c_{ij}^{VoT} = \left(\frac{z_{ijk}}{G_{ij}}V_{ij}\left(1-E_{ij}\right) + v_{ij}^{FILL}\right)T^{STRAND}VoTy_{ij} \quad \forall(i,j)\in A, k=0 \tag{15}$$

### 3.2. Geographical applicability

This section integrates spatial aspects of port–hinterland transport through IWT, ensuring that corridor-specific characteristics are accounted for in the evaluation. The optimization model developed in the previous section is applied to regions linked to the IWT within the Rhine-Alpine Corridor (RALP) (Fig. 1). The RALP stands as Europe's busiest IWT corridor, connecting over forty terminals across Belgium, France, Germany, the Netherlands, and Switzerland to the seaports of Amsterdam, Antwerp, and Rotterdam (European Commission, 2017). Part of the Trans-European Transport Network (TEN-T), the RALP is designated as one of the priority transportation routes to guide Europe toward a sustainable transition in freight transport by 2030 (European Commission, 2020).

The study examines the CC process within the IWT system, specifically focusing on how containers arriving at seaports are transported further inland. As previously noted, containers arriving at seaports are often partially filled. This partial filling can occur for different reasons. Firstly, the containers are often loaded with goods from multiple suppliers, each shipping different cargo volumes to various destinations. Secondly, different cargo shipments might arrive at the seaport at different times, making it difficult to consolidate and fully load containers with goods going to the same inland destination before they need to be dispatched. In addition, some containers are time-sensitive, requiring that they be transported immediately, even if they are not fully loaded.

Once these partially filled containers arrive at the deep sea terminal, they are often moved directly to the hinterland vehicles without consolidation. This is largely because deep sea terminals are typically focused on quickly handling high volumes of containers, with limited space and time to reconstruct these cargoes efficiently. Furthermore, deep sea terminals may lack the specific facilities or infrastructure needed to efficiently reorganize cargo, as their primary function is to facilitate the rapid transfer of containers between different modes of transportation.

As a result, these inefficiencies carry over into the IWT system, where partially filled containers take up more space on vessels than necessary, leading to underutilized capacity and higher transportation costs. This makes the CC process critical for improving efficiency and reducing costs in inland logistics operations.

Consequently, the study evaluates the performance of implementing a CC strategy to enhance the container fill rates (Fig. 2). This evaluation compares the performance of CC against a benchmark scenario (i.e., no CC) using defined Key Performance Indicators (KPIs) such as container fill rate, vessel occupancy rate, transport cost, and trip completion rate of vessels. Following the initial assessment, sensitivity analyses are

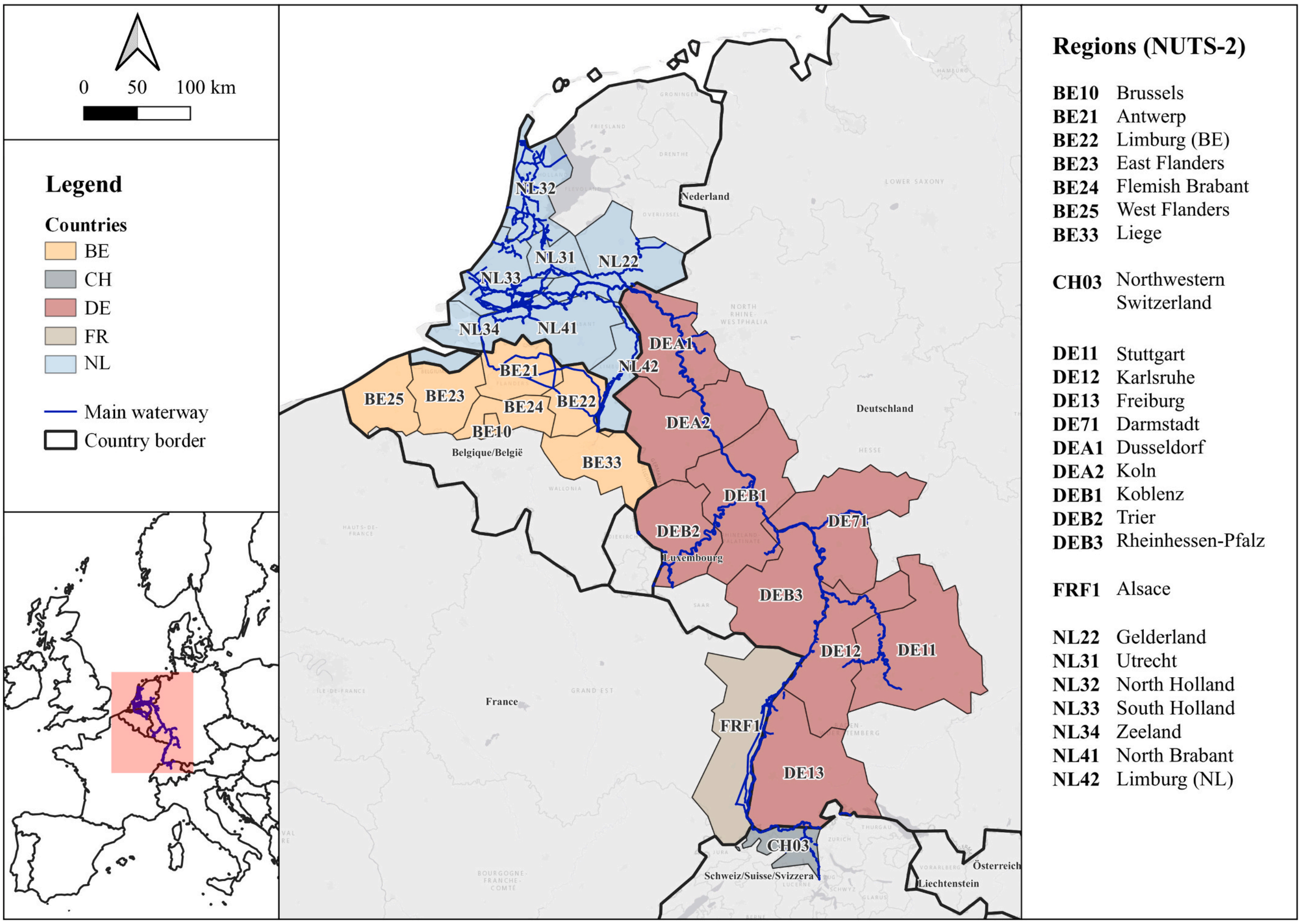



**Fig. 1.** The RALP IWT regions. Source: Bedoya-Maya et al. (2025)

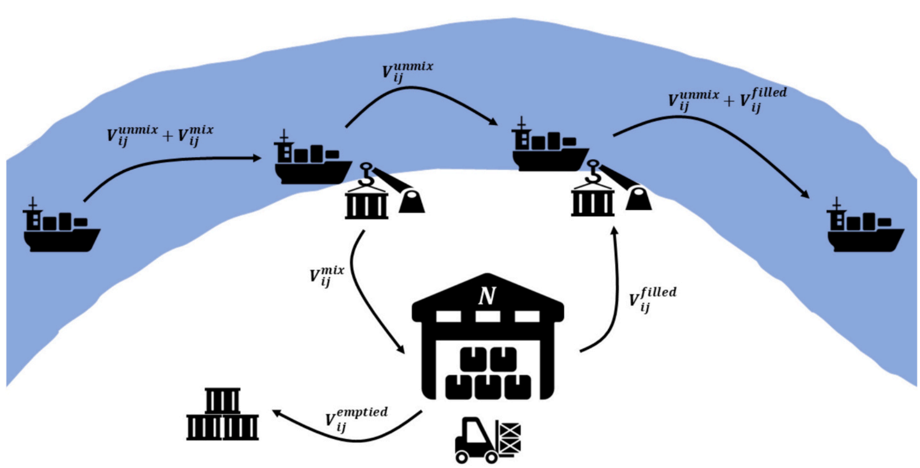



**Fig. 2.** Illustration of the CC strategy. Note: The notations used in the figure are defined in Table 1.

conducted to examine the influence of different parameters on performance evaluation.

As mentioned, the analysis focuses on container transport from seaports – specifically Antwerp and Rotterdam – to different destinations along the IWT Rhine-Alpine corridor. The analysis targets the implementation of the consolidation process within this corridor, requiring a consolidation facility. The existing literature has evaluated the potential cost savings of establishing this facility at three locations: the seaports, the inland terminals, and a single strategic hinterland location (Bedoya-Maya et al., 2025). The findings indicate that the first two options do not result in cost savings, regardless of the volume of container flows to be consolidated. This outcome is primarily due to high implementation costs and capacity constraints. In contrast, the third option—a single strategic hinterland location—demonstrates the potential for positive cost savings.

Nijmegen in the Netherlands was identified as the optimal location for two main reasons. First, its relative proximity to the two seaports of interest reduces the travel distance for vessels to reach the consolidation facility (Fig. 3). Second, it is situated at a key juncture where cargo flows from different seaports converge on the main waterway, enhancing connectivity to other IWT destination regions along the middle and upper Rhine. The envisioned consolidation operation in Nijmegen entails handling and reconstructing eligible LCL containers before onward transport to final destinations. This process involves consolidating various goods destined for the same destination, ensuring containers are fully loaded while adhering to safety and technical requirements. The fully loaded containers are then transported to their final destinations, with empty containers redistributed to the seaports.

### 3.3. Input parameters

The input parameters for the performance evaluation of the CC compared to the benchmark case with no CC are then specified in Table 2. For this, the OD matrix, the number of TEUs transported from each OD pair, the mass volume of the TEUs, the eligibility factor of the containers (this specifies what fraction of the transported TEUs are eligible for CC), the average occupation rate of the vessel, the average filling rate of the containers for each OD pair, the service frequency (number of trips), and the distance from an origin to the consolidation station in Nijmegen, and from the consolidation station to the hinterland destination are specified. These different input parameters are derived previous studies (Bedoya-Maya et al., 2025; Nicolet et al., 2023; Shobayo et al., 2021).

Meanwhile, Table 3 focuses on the vessel and consolidation parameters, such as the cost input, vessel average speed, value of time, and fuel consumption levels. These values are derived from (Ramos et al., 2020; Shobayo et al., 2021; Van Dorsser, 2015). Having specified these parameters, we can then evaluate the performance of the CC strategy against the benchmark and conduct sensitivity analysis to validate the findings. This is described in the next section.

## 4. Results

This section examines the impact of the CC strategy on container IWT performance both at the corridor level and for specific origin-destination connections considering the spatial configuration of port-hinterland transport via IWT in the RALP. To provide a structured presentation of the results, the outcomes of the optimization model are first reported and disaggregated by specific OD connections. Subsequently, the corridor-level impacts are evaluated and discussed.

### 4.1. Optimization results

Table 4 presents the breakdown of the total cost for both the base consolidation case at Nijmegen and the benchmark case. In the latter, no consolidation for any OD pairs is set following the methodology proposed by Majoor et al. (2021). Meanwhile, the base consolidation case utilizes values from Table 3 as base parameter values.

The total cost for the benchmark case is 3.48 million euros higher than that for the case with consolidation. This suggests the economic feasibility of CC. Examining different cost KPIs reveals that while the consolidation strategy involves additional costs such as consolidation

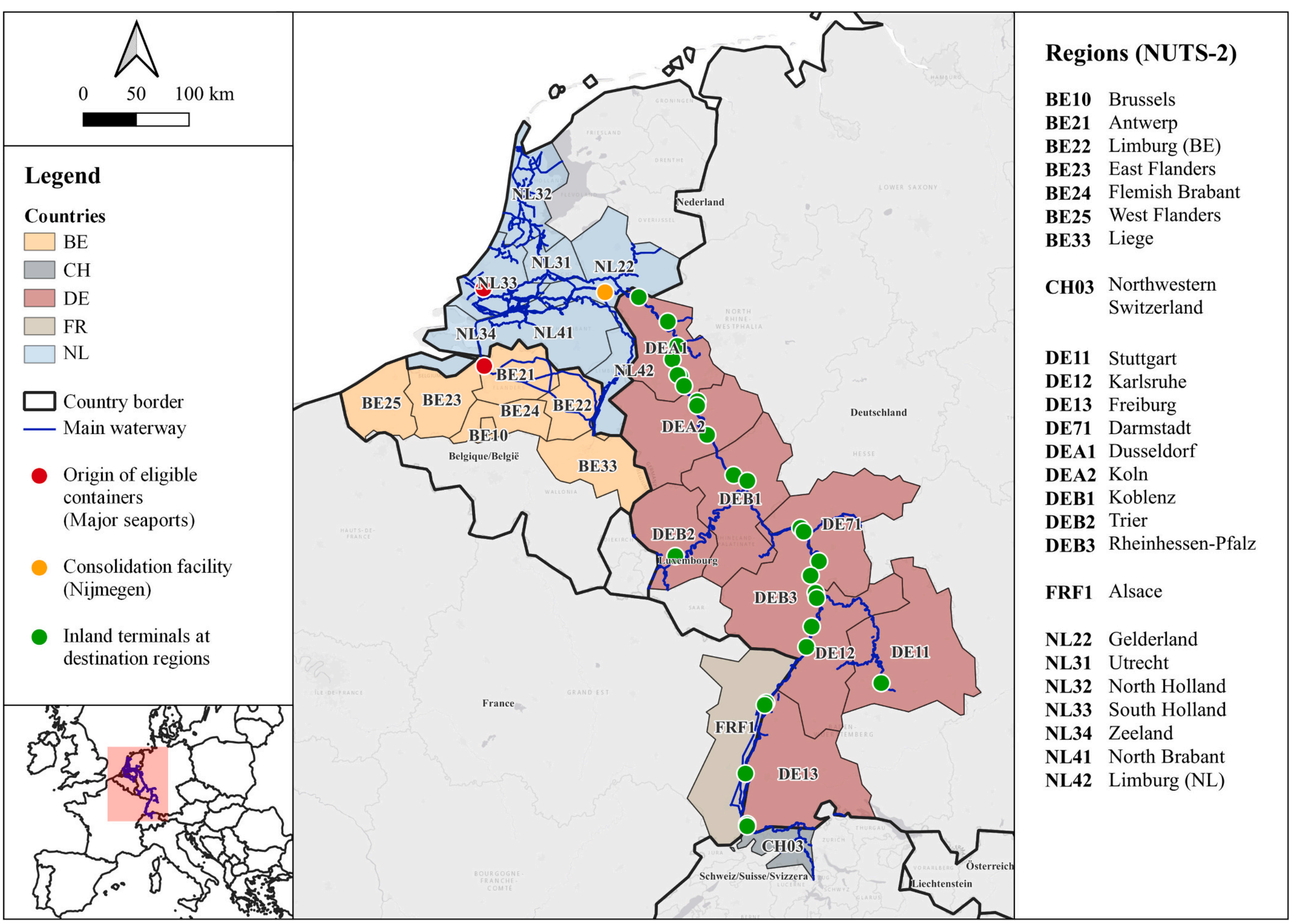



**Fig. 3.** Cargo consolidation at Nijmegen (NL).

**Table 2**
Input parameters.

| Origin | Destination | TEUs | Mass (Tons) | Eligibility (%) | Occupation rate vessels (%) | Filling rate container (%) | Trips (#/year) | Distance Orig.–Nij. (km) | Distance Nij. – Dest. (km) |
|---|---|---|---|---|---|---|---|---|---|
| BE21 | CH03 | 9436.8 | 70,466.7 | 81 % | 20.5 % | 46 % | 180 | 170 | 717 |
| BE21 | DE11 | 3973.75 | 11,875 | 26 % | 8.9 % | 58 % | 175 | 170 | 592 |
| BE21 | DE12 | 29,039.53 | 173,400 | 40 % | 80.5 % | 76 % | 141 | 170 | 529 |
| BE21 | DE13 | 4676.07 | 13,466.67 | 22 % | 18.1 % | 66 % | 101 | 170 | 714 |
| BE21 | DE71 | 19,948.07 | 81,000 | 36 % | 38.4 % | 57 % | 203 | 170 | 385 |
| BE21 | DEA1 | 84,171.8 | 645,000 | 52 % | 37.8 % | 73 % | 870 | 170 | 114 |
| BE21 | DEA2 | 23,455.07 | 152,666.7 | 47 % | 38.0 % | 69 % | 241 | 170 | 187 |
| BE21 | DEB1 | 17,462 | 146,733.3 | 47 % | 37.1 % | 90 % | 184 | 170 | 291 |
| BE21 | DEB3 | 103,604 | 468,066.7 | 48 % | 65.5 % | 47 % | 618 | 170 | 442 |
| BE21 | FRF1 | 8010.2 | 55,200 | 48 % | 12.4 % | 72 % | 252 | 170 | 779 |
| BE21 | NL42 | 15,707.8 | 178,800 | 71 % | 13.6 % | 81 % | 450 | 170 | 114 |
| NL33 | CH03 | 32,974.07 | 244,666.7 | 60 % | 32.2 % | 61 % | 400 | 145 | 717 |
| NL33 | DE11 | 2502 | 9700 | 37 % | 61.1 % | 53 % | 16 | 145 | 592 |
| NL33 | DE12 | 22,032.4 | 109,266.7 | 36 % | 52.8 % | 68 % | 163 | 145 | 529 |
| NL33 | DE13 | 18,544.93 | 125,733.3 | 45 % | 18.1 % | 76 % | 400 | 145 | 714 |
| NL33 | DE71 | 28,593.6 | 141,733.3 | 50 % | 69.8 % | 49 % | 160 | 145 | 385 |
| NL33 | DEA1 | 280,507.7 | 2,190,000 | 67 % | 70.1 % | 58 % | 1563 | 145 | 114 |
| NL33 | DEA2 | 37,852.13 | 238,533.3 | 50 % | 61.6 % | 63 % | 240 | 145 | 187 |
| NL33 | DEB1 | 12,131.73 | 74,733.34 | 42 % | 81.7 % | 73 % | 58 | 145 | 291 |
| NL33 | DEB3 | 102,619.2 | 510,400 | 46 % | 71.3 % | 54 % | 562 | 145 | 442 |
| NL33 | FRF1 | 24,476.2 | 141,000 | 43 % | 65.5 % | 67 % | 146 | 145 | 779 |
| NL33 | NL42 | 107,140.4 | 784,733.3 | 74 % | 41.9 % | 49 % | 1000 | 145 | 114 |

Sources: Bedoya-Maya et al. (2025) and Nicolet et al. (2023).

**Table 3**
Vessel and consolidation cost parameters.

| Parameter | Unit | Value |
|---|---|---|
| Sailing speed | Km/h | 13 |
| Value of time of cargo | € / hour / TEU | 0.30 |
| Labor cost | € / hour | 10 |
| Price of unloading or reloading one TEU | € / TEU | 32.5 |
| Fuel price | € / Liter | 1 |
| Fuel consumption rate when sailing per vessel | Liter / Km | 8.976 |
| Fuel consumption rate when stopping per vessel | Liter/h | 6.66 |
| Fix cost per vessel | € / hour | 86.64 |
| Variable cost per vessel | € / hour | 1.25 |

Sources: Shobayo et al. (2021) and Van Dorsser (2015).

**Table 4**
Aggregated cost composition (in million euros) of the benchmark case vs. the base case of the CC.

| | Recon. cost (labour + empty + fill) | Transport cost | Handle cost (Nijmegen + dest) | Cargo VoT cost | Total cost |
|---|---|---|---|---|---|
| Benchmark (without recon.) | 0.00 | 68.72 | 19.78 | 0.00 | 88.49 |
| Recon. base case | 3.94 | 58.16 | 21.16 | 1.75 | 85.01 |

cost, additional handling cost, and VoT cost, there is a notable reduction in transport cost. This reduction is significant enough to offset the additional costs, resulting in an overall cost reduction with the implementation of the CC strategy.

The reduction in transport cost can be attributed to a decrease in the number of vessels required for the transport service compared to the benchmark case. This decrease reduces the total transport costs for transporting LCL containers, and the empty vessels can be effectively utilized for other transport services in different OD pairs within the corridor.

The comparison of costs in Table 5 focuses on the seaports under study (Antwerp and Rotterdam) to evaluate the performance of each origin seaport concerning the CC strategy. The analysis suggests that

**Table 5**
Aggregated cost performance (in million euros) for each seaport.

| | Cost base case (with Recon.) | Cost benchmark (without Recon.) | Cost difference |
|---|---|---|---|
| Total | 85.01 | 88.49 | −3.93 % |
| Antwerp Port | 34.42 | 36.85 | −6.59 % |
| Rotterdam Port | 50.59 | 51.64 | −2.03 % |

Antwerp stands to benefit more from the consolidation strategy. This is most likely due to the spatial configuration of inland waterways in the transport corridor, since there are longer distances from Antwerp to the destination regions in the Middle and Upper Rhine compared to Rotterdam. This is evident in the distribution of OD pairs assigned to the consolidation station in Table 6, where the regions linked to Antwerp are poised to gain more advantages than those connected to Rotterdam. Specifically, the travel time savings range from 29 % to 49 % compared to the baseline case, as illustrated in Fig. 4, and the vessels required to transport the same amount of cargo could be reduced by up to 20 %.

Furthermore, the results reveal that routes benefiting from CC generally exhibit a relatively low initial vessel occupation rate, ranking among the three lowest rates compared to other routes. However, it is noteworthy that when comparing the container filling rate among these connected routes, only BE21-CH03 records a below-average container filling rate by 46 %, suggesting that the filling rate of containers is not the only variable influencing the selection of OD pairs in the CC strategy.

The primary observed variable affecting OD pair selection decisions is the initial occupation rate of vessels. This implies that the vessel occupation rate influences whether the OD pair should be assigned to consolidation. A lower initial occupation rate corresponds to a higher

**Table 6**
Connected OD pairs and their optimal conditions.

| Origin | Dest. | Initial load factor | Optimal load factor | Initial occupation rate | Optimal occupation rate | Vessels required |
|---|---|---|---|---|---|---|
| BE21 | CH03 | 46 % | 90 % | 20.50 % | 90 % | 86.11 % |
| BE21 | DE11 | 58 % | 90 % | 8.90 % | 90 % | 90.86 % |
| BE21 | DE13 | 66 % | 90 % | 18.10 % | 90 % | 80.20 % |
| BE21 | FRF1 | 72 % | 90 % | 12.40 % | 90 % | 87.30 % |
| NL33 | DE13 | 76 % | 90 % | 18.10 % | 90 % | 81.25 % |

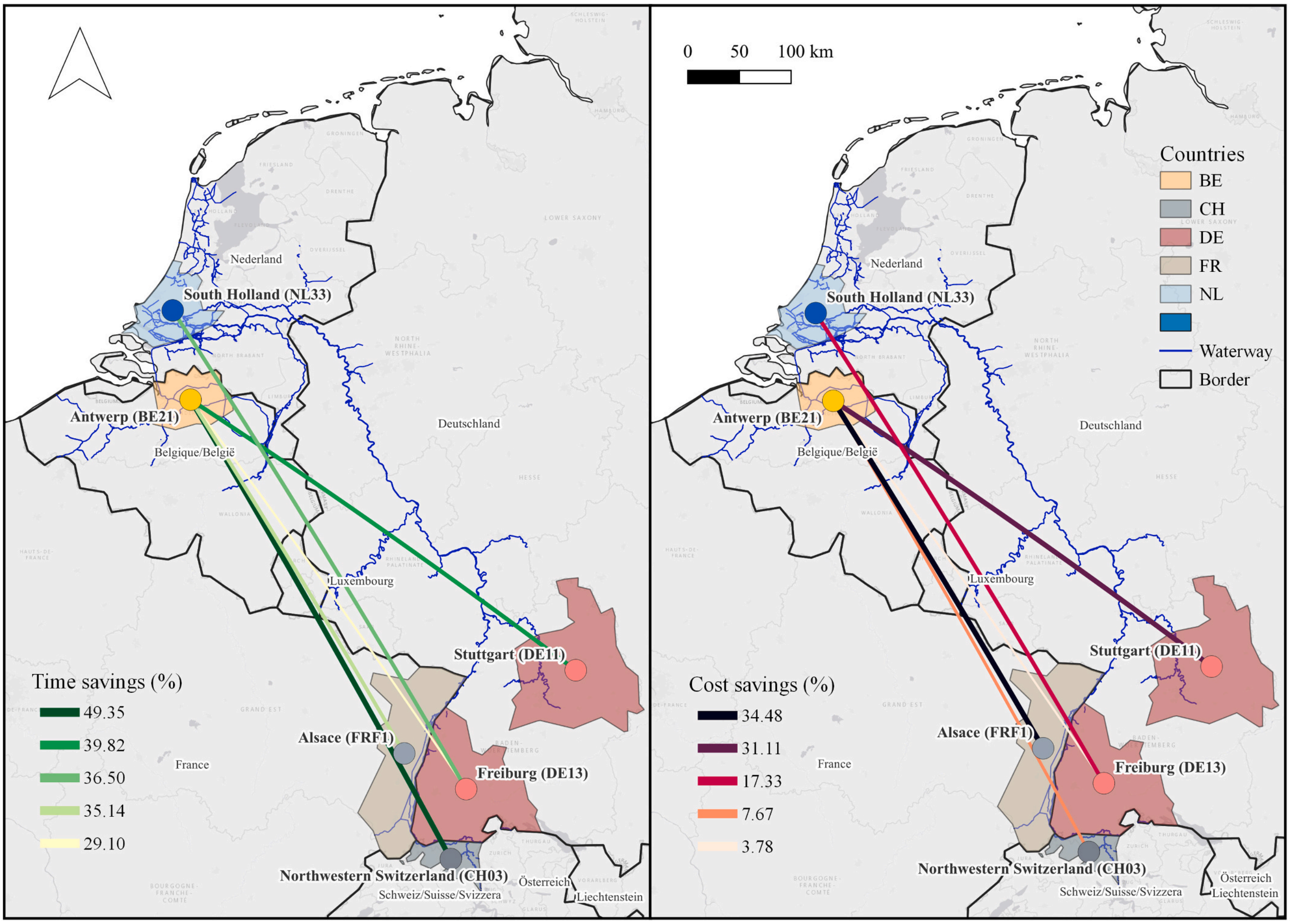



**Fig. 4.** Cost and time savings.

potential for assignment to consolidation. The final container load factor and vessel occupation rate for these OD pairs all reach the upper bound (90 %), indicating full utilization of the vessel's capacity on these routes.

The number of OD pairs to be included in the consolidation strategy can be influenced by various sensitivity parameters, with labor cost, cargo VoT, fuel price, fixed vessel cost, and variable vessel cost being the most important. Individual sensitivity analyses are performed on these parameters to assess their impact on optimal decisions. The parameters outlined in Table 3 serve as the base case for consolidation, with the load factor and occupation rate capped at 90 %. In each parameter sensitivity analysis, the remaining parameters are held constant at their base case values, and the total cost for all OD pairs is computed. Fig. 5 depicts how the total cost responds to variations in each parameter.

The findings indicate that when other parameters remain constant, increases in labor cost and cargo VoT lead to a reduction in the number of OD pairs assigned to consolidation and an overall increase in the total cost. This outcome is intuitive, as higher labor cost and cargo VoT translate to increased consolidation costs for each OD pair at Nijmegen. Once these parameters surpass certain thresholds (35 euros/h for labor cost and 1.6 euros/h for cargo VoT), the consolidation cost escalates to a point where no OD pair is recommended for consolidation, and the total cost aligns with the benchmark case where no consolidation occurs. Conversely, fuel price exhibits a different trend. As fuel prices rise, OD pairs are incentivized to opt for consolidation because of cost savings from reducing vessels for the leg after Nijmegen, with higher fuel prices yielding more substantial cost savings. Fixed and variable vessel costs do not significantly influence the optimal decision in the number of OD pairs assigned to consolidation.

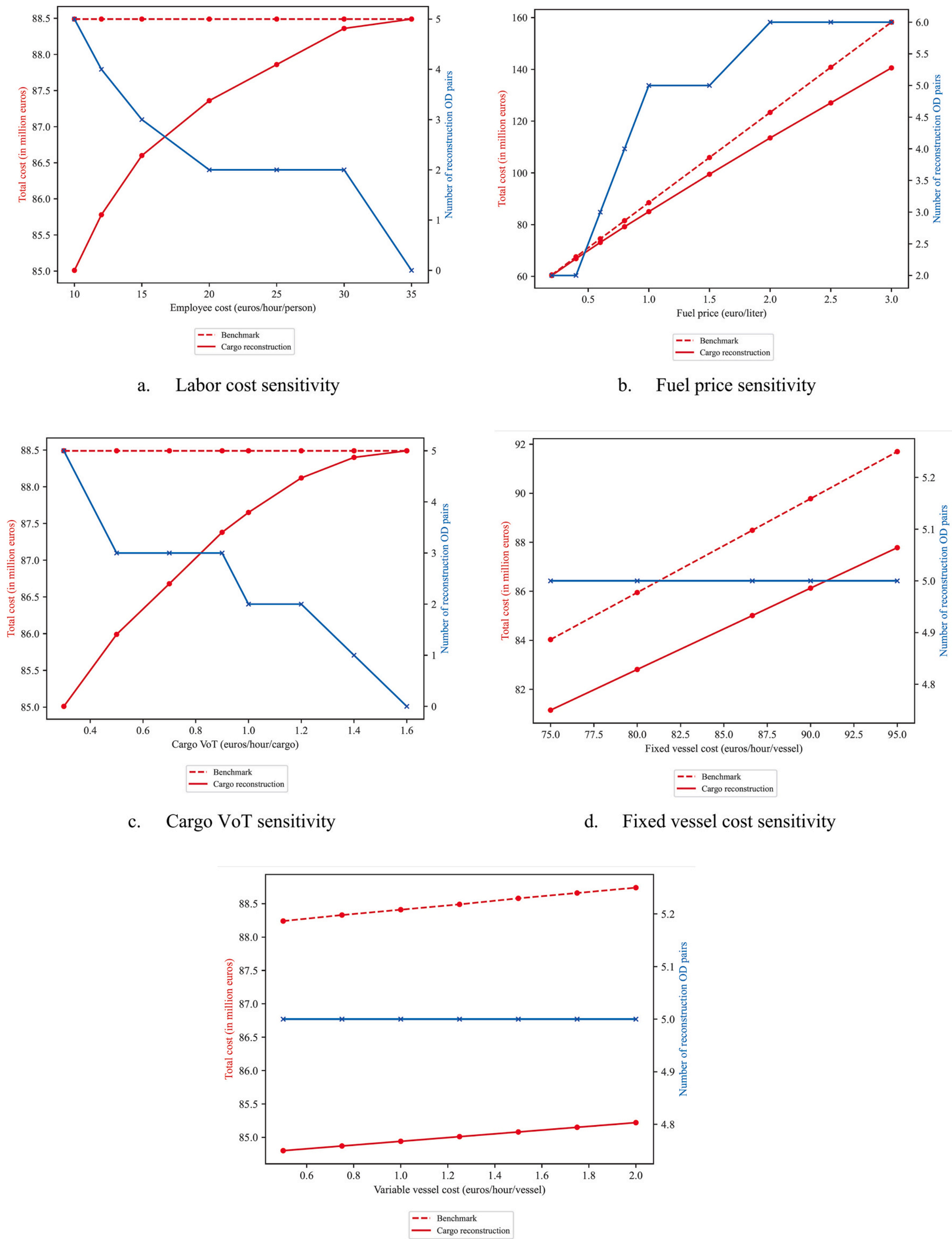
The above results are based on optimizing individual OD pairs with the CC strategy. Based on this, it becomes essential to examine how the optimization strategy will improve the overall performance of container IWT in the feasible routes, considering the competition from road and rail in these OD pairs. This evaluation is conducted in the following section.

### *4.2. Impact assessment at the corridor level*

Based on preceding analyses, this section examines the impact of the CC strategy on container IWT performance at the corridor level. This impact is evaluated across KPIs such as operating time, cargo volume increase, occupation rate, vessel counts, mode share influence, emissions, and cost impacts (Nicolet et al., 2022; Shobayo et al., 2024). These KPIs are developed within a DES model that evaluates the impact of different innovations on the performance of container IWT logistics along the RALP (Shobayo et al., 2024).

The DES model details the container IWT logistics system and its interactions with other transport modes, such as road and rail. These interactions encompass the relationships between cost and time calculations, transport mode selection based on specific parameters, transport flow assignment to a network based on the chosen modes, and evaluation of current and future transport performance using a defined set of KPIs (Shobayo et al., 2024). The model further incorporates a framework for integrating various innovation initiatives to assess their impacts on present and future performance across multiple scenarios.

Thus, to test the overall impact of the CC strategy specified above, the key optimization results achieved in Section 4.1 were integrated




a. Labor cost sensitivity

b. Fuel price sensitivity

c. Cargo VoT sensitivity

d. Fixed vessel cost sensitivity

e. Variable vessel cost sensitivity

**Fig. 5.** Sensitivity analysis.

within this global DES model to determine the overall performance of container IWT in selected feasible OD pairs from the optimization strategy. The outcomes of these KPIs are illustrated in Fig. 6, where multiple KPIs are compared for each entity, represented by OD pairs in this context. Notably, only three OD pairs (i.e., BE21-CH03, BE21-DE13, and BE21-FRF1) are depicted in the figure, deviating from the optimization output table, which suggested the feasibility of CC for five routes (i.e., BE21-CH03, BE21-DE11, BE21-DE13, BE21-FRF1, and NL33-DE13).

The exclusion of BE21-DE11 and NL33-DE13 from the simulation is attributed to the absence of container transport services for these pairs within the simulation model, influenced by factors such as generalized costs, mode share, and assignment parameters of container IWT compared to road and rail transport, and relative to total container volumes transported in each OD pair. Consequently, only three of the five feasible routes in the optimization output generate transport

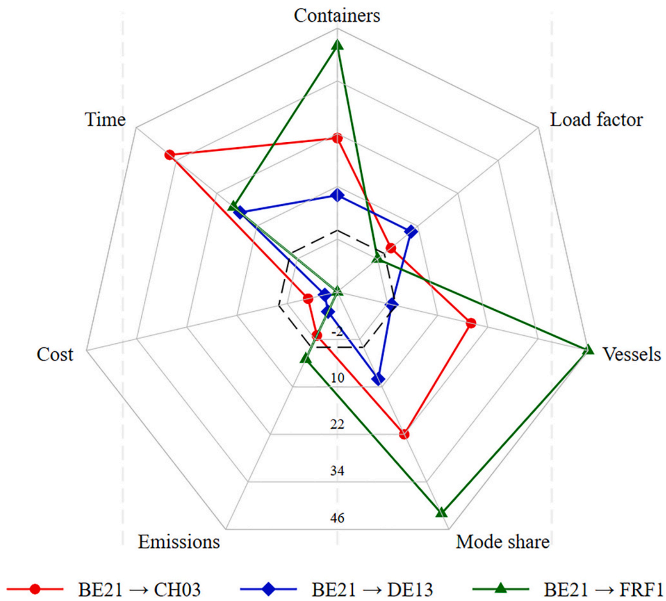



**Fig. 6.** KPI assessment.
Notes: Values denote percentage changes. The center is positioned at –14. The black dashed line represents the no-variation reference.

services within the simulation model.

In line with this, starting with the TEUs KPI, Fig. 6 reveals the impact of the CC strategy on augmenting container volumes transported via IWT across the analyzed routes. It demonstrates that implementing the CC innovation would attract more volumes to IWT. Specifically, container volumes via IWT are projected to increase by 42 % in the BE21-FRF1 pair, 21 % in the BE21-CH03 pair, and 8 % in the BE21-DE13 pair compared to scenarios without this innovation. This is closely associated with the mode share KPI, exhibiting similar percentage increases for the OD pairs.

Regarding the vessel counts KPI, regions BE21-FRF1 and BE21-CH03 are estimated to experience a vessel service increase by 46 % and 18 %, respectively, along these pairs, whereas BE21-DE13 is estimated to experience a reduction of 1 % in the vessel count service. This reduction can be explained by the marginal increase in volumes handled, facilitating an augmentation in the vessel load factor of vessels already operational within the system. Particularly, BE21-DE13 estimates the highest percentage load factor increase, with an 8 % rise compared to scenarios without the innovation. Conversely, BE21-CH03 witnesses a 2 % load factor increase with the CC strategy, whereas the BE21-FRF1 pair records a 2 % reduction in vessel load factor. This reduction can be linked to the variance between the cargo volume and the vessel count increase. In this case, the vessel counts increases by 46 %, while the cargo volume only increases by 42 %.

Regarding the time KPI, all three pairs undergo an increase in vessel operating time, attributable to the additional leg of the waiting and container handling process at the consolidation station in Nijmegen. In this regard, BE21-CH03 is estimated to experience the most significant time increase, estimated at 36 %, compared to scenarios without innovation. Meanwhile, BE21-DE13 and BE21-FRF1 are also anticipated to encounter some increase in operating and handling time, estimated at 15 % and 17 %, respectively, with the implementation of CC in these routes.

Despite the anticipated significant increase in operating time for vessels and containers utilizing CC, this increase is expected to be offset by a reduction in generalized transport costs of containers in these pairs. As illustrated in Fig. 6, transport costs per TEU are projected to decrease by 14 % in the BE21-FRF1 pair compared to scenarios without the consolidation strategy. A similar trend is observed for BE21-CH03 and BE21-DE13 pairs, with cost reductions of 7 % and 11 % respectively. However, the magnitude of this reduction is expected to be influenced by the sensitivity parameters, as disclosed in Fig. 5.

Finally, emission impact analysis revealed reductions for the BE21-CH03 and BE21-DE13 pairs at 3 % and 9 %, respectively, with the CC strategy. In comparison, the BE21-FRF1 pair is expected to experience a 3 % increase in emissions. This increase is attributed to the close association with the vessel count increase KPI, where the significant rise in deployed vessels for service would lead to additional emissions in the transport link. However, considering that a 46 % increase in vessels would only result in a 30 % emission increase and that the vessels are primarily deployed to handle and transport the additional cargo volumes attracted from the other modes, it can be argued that there could be an overall net reduction in emissions per TEU transported in this pair.

## 5. Discussion

The optimization conducted in this study bridges operational research with transport geography by linking container-level operational efficiencies to broader corridor-level spatial dynamics, advancing understanding of how consolidation strategies can reshape port–hinterland connections via IWT. Notably, the results point to important trade-offs that must be considered in both academic and policy debates. While consolidation reduces average costs and emissions per container, it also introduces additional handling time and, in specific origin-destination pairs, negative savings. This underlines the need for a nuanced approach to evaluating IWT innovations, recognizing that their effectiveness is spatially dependent and sensitive to cost parameters such as labor costs and fuel prices.

These findings contribute to the broader discussion on strategies to enhance the competitiveness of container IWT by estimating that a CC strategy can improve operational performance while offsetting the higher coordination costs associated with its implementation. Importantly, vessel occupation rates emerge as a decisive factor in determining the potential benefits of consolidation, suggesting that underutilized routes represent the greatest opportunities for optimization. From a policy perspective, the results indicate that targeted support for consolidation could strengthen the role of IWT in sustainable multimodal transport, but such measures should be carefully designed to balance efficiency gains with the spatial and operational conditions of specific port-hinterland connections.

It is critically important to acknowledge that cost-efficiency improvements alone are insufficient to secure a lasting modal shift toward IWT if the system is not also resilient and reliable. Reliability has long been identified as a primary concern for shippers, often outweighing cost considerations, and remains a barrier to the full exploitation of IWT's sustainable advantages. The sector still faces multiple challenges, including long waiting times at seaports, bridges, and locks, on top of the inefficiency address in this paper (i.e., suboptimal filling rates of containers), which reduce competitiveness relative to road and rail (Novimove, 2023).

These inefficiencies are further compounded by external disruptions, most notably low water levels in the main waterways of the RALP, which have significantly undermined the operational performance of IWT and was related to a decline in its modal share. Between 2007 and 2021, IWT's market share decreased by around 14 percentage points, falling to 5.6 %, while road transport exceeded 75 % (Eurostat, 2024), underscoring the urgency of addressing resilience alongside efficiency. Therefore, optimizing container filling rates through consolidation is only one contribution to the overall solution. External disruptions such as critical water level episodes, expected to intensify with climate change, can quickly erode the feasibility and attractiveness of a CC strategy. More specifically, during prolonged droughts, reduced barge capacity diminishes the practicality of consolidation, regardless of its modeled cost savings.

These challenges highlight the importance of coordinating consolidation strategies with complementary innovation initiatives, such as resilient vessel design, adaptive infrastructure, digitalization of navigation processes, and improved hydrological forecasting. Future research should therefore extend beyond the assessment of a single inefficiency to model combined strategies that address both internal inefficiencies (e.g., suboptimal loading factors) and exogenous disruptions (e.g., water-level fluctuations). Such integrated approaches will be critical to ensuring that IWT is not only cost-competitive but also sufficiently reliable to sustain long-term modal shift ambitions.

## 6. Conclusions

This study examined the potential of cargo consolidation to address one persistent inefficiency in inland waterway transport, focusing on the Rhine–Alpine Corridor. The results show that by increasing container filling rates and vessel utilization, consolidation can minimize average transport costs and emissions per TEU while attracting additional cargo volumes to IWT. These findings confirm that operational innovations at the container level can influence corridor-level freight dynamics, improving the competitiveness of IWT in port–hinterland transport.

The analysis highlights three main implications for transport geography and policy. First, the benefits of consolidation are highly spatially dependent: longer-distance hinterland connections, such as those from Antwerp to the Upper Rhine capture greater cost savings than shorter routes to the Netherlands or the Lower Rhine, underscoring the need for targeted strategies. Second, vessel occupation rates emerge as a decisive factor in determining where consolidation is most effective, pointing to the importance of monitoring and managing corridor-level capacity utilization. Third, while consolidation improves efficiency, its effectiveness is constrained by broader system vulnerabilities, particularly reliability issues linked to water-level fluctuations and other external disruptions. Without addressing these challenges, cost-efficiency improvements alone are unlikely to secure a lasting modal shift to IWT.

The findings suggest that a consolidation strategy could help strengthen IWT's role within multimodal transport systems, but such measures must be carefully designed to account for route-specific conditions and resilience needs. Complementary innovation initiatives, such as resilient vessel design, adaptive infrastructure, and digitalization, will be essential to ensure that IWT becomes not only cost-competitive but also reliable enough to retain shipper confidence. Future research should therefore move beyond single-innovation assessments to explore how combined strategies can jointly enhance efficiency, resilience, and ultimately reliability.

## CRediT authorship contribution statement

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

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## Data availability

Data will be made available on request.

## References

Beckmann, M.J., Koopmans, T.C., McGuire, C.B., Winsten, C.B., 1953. The allocation of switching work in a system of classification yards. In: Proceedings of Winter Meeting of the Railway Systems and Procedures Association, University of Chicago, IL., 94a–94j. https://www.rand.org/pubs/papers/P448.html.

Bedoya-Maya, F., Shobayo, P., Nicolet, A., Christopoulou, E., Majoor, I., van Hassel, E., Vanelslander, T., 2025. Cargo consolidation in port-hinterland container transport: a spatial economic assessment for inland waterways. Res. Transp. Bus. Manag. 59, 101254. https://doi.org/10.1016/j.rtbm.2024.101254.

Caris, A., Macharis, C., Janssens, G.K., 2011. Network analysis of container barge transport in the port of Antwerp by means of simulation. J. Transp. Geogr. 19 (1), 125–133. https://doi.org/10.1016/J.JTRANGEO.2009.12.002.

Çetinkaya, S., Bookbinder, J.H., 2003. Stochastic models for the dispatch of consolidated shipments. Transp. Res. B Methodol. 37 (8), 747–768. https://doi.org/10.1016/S0191-2615(02)00060-7.

Deng, P., Song, L., Xiao, R., Huang, C., 2022. Evaluation of logistics and port connectivity in the Yangtze River Economic Belt of China. Transp. Policy 126, 249–267. https://doi.org/10.1016/j.tranpol.2022.07.019.

ECA, 2023. Intermodal Freight Transport: EU Still Far From Getting Freight Off the Road. https://www.eca.europa.eu/en/publications/SR-2023-08.

European Commission, 2017. Study on the TEN-T Core Network Corridor Rhine-Alpine. https://transport.ec.europa.eu/system/files/2022-02/ralp_corridor_final_report_2017.pdf.

European Commission, 2020. Study on the Rhine-Alpine TEN-T Core Network Corridor and support to Coordinator. https://transport.ec.europa.eu/system/files/2022-02/ralp_corridor_final_report_2020.pdf.

Eurostat. *Modal split of inland freight transport.* https://ec.europa.eu/eurostat/databrowser/view/TRAN_HV_FRMOD__custom_6044915/default/table?lang=en.

Fan, Y., Behdani, B., Bloemhof-Ruwaard, J., Zuidwijk, R., 2019. Flow consolidation in hinterland container transport: an analysis for perishable and dry cargo. Transp. Res. E 130, 128–160. https://doi.org/10.1016/j.tre.2019.08.011.

Fazi, S., Fransoo, J.C., Van Woensel, T., 2015. A decision support system tool for the transportation by barge of import containers: a case study. Decis. Support. Syst. 79, 33–45. https://doi.org/10.1016/j.dss.2015.08.001.

Friedhoff, B., Ramne, B., Alias, C., van Hassel, E., Martens, S.E., Felde, J., zum, & Samuel, L., 2023. Elevating the logistics resilience of the Rhine-Alpine Corridor with the help of innovative vessel and cargo handling concepts. Transp. Res. Proc. 72, 1998–2005. https://doi.org/10.1016/j.trpro.2023.11.681.

Hanbazazah, A.S., Abril, L.E., Shaikh, N.I., Erkoc, M., 2018. A redesigned benders decomposition approach for large-scale in-transit freight consolidation operations. Int. J. Inf. Syst. Supply Chain Manag. 11 (2), 1–15. https://doi.org/10.4018/IJISSCM.2018040101.

Hanbazazah, A.S., Abril, L., Erkoc, M., Shaikh, N., 2019. Freight consolidation with divisible shipments, delivery time windows, and piecewise transportation costs. Eur. J. Oper. Res. 276 (1), 187–201. https://doi.org/10.1016/j.ejor.2018.12.043.

Higginson, J., Bookbinder, J.H., 1994. Policy recommendations for a shipment-consolidation program. J. Bus. Logist. 15 (1). https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2695467.

ITF, 2019. ITF Transport Outlook 2019. https://doi.org/10.1787/transp_outlook-en-2019-en.

Jackson, G.C., 1985. A survey of freight consolidation practices. J. Bus. Logist. 6 (1). https://trid.trb.org/view/223308.

Konings, R., Kreutzberger, E., Maraš, V., 2013. Major considerations in developing a hub-and-spoke network to improve the cost performance of container barge transport in the hinterland: the case of the port of Rotterdam. J. Transp. Geogr. 29, 63–73. https://doi.org/10.1016/j.jtrangeo.2012.12.015.

Liang, F., Verhoeven, K., Brunelli, M., Rezaei, J., 2024. Inland terminal location selection using the multi-stakeholder best-worst method. Int J Log Res Appl 27 (3), 363–385. https://doi.org/10.1080/13675567.2021.1885634.

Long, S., Grasman, S.E., 2012. A strategic decision model for evaluating inland freight hub locations. Res. Transp. Bus. Manag. 5, 92–98. https://doi.org/10.1016/j.rtbm.2012.11.004.

Majoor, I., Ramos, C., Burgess, A., Van der Geest, W., Hendriks, I., van Hassel, E., Shobayo, P., Samuel, L., Nicolet, A., Atasoy, B., van Doorser, C., Bijlsma, R., Hofman, P., 2021. NOVIMOVE Transport Model Architecture and Data Collection. Technical Report. https://novimove.eu/downloads/.

McKinnon, A., Browne, M., Whiteing, A., Piecyk, M. (Eds.), 2015. Green Logistics: Improving the Environmental Sustainability of Logistics. Kogan Page Publishers.

Nicolet, A., Negenborn, R.R., Atasoy, B., 2022. A logit mixture model estimating the heterogeneous mode choice preferences of shippers based on aggregate data. IEEE Open J. Intell. Transp. Syst. 3, 650–661. https://doi.org/10.1109/OJITS.2022.3208379.

Nicolet, A., Shobayo, P., van Hassel, E., Atasoy, B., 2023. An assessment methodology for a modular terminal concept for container barging in seaports. Case Stud. Transp. Policy 14, 101103. https://doi.org/10.1016/j.cstp.2023.101103.

Notteboom, T., Konings, R., 2004. Network dynamics in container transport by barge. Belgeo 4, 461–478. https://doi.org/10.4000/belgeo.13402.
Notteboom, T., Rodrigue, J., 2005. Port regionalization: towards a new phase in port development. Marit. Policy Manag. 32 (3), 297–313. https://doi.org/10.1080/03088830500139885.
Notteboom, T., Rodrigue, J., 2010. Foreland-based regionalization: integrating intermediate hubs with port hinterlands. Res. Transp. Econ. https://doi.org/10.1016/j.retrec.2009.12.004.
Novimove, 2023. Solving Inefficiencies on the IWT Rhine-Alpine Corridor. Novel Inland Waterway Transport Concepts for Moving Freight Effectively. https://novimove.eu/?cn-reloaded=1.
Olsson, J., Woxenius, J., 2014. Localisation of freight consolidation centres serving small road hauliers in a wider urban area: barriers for more efficient freight deliveries in Gothenburg. J. Transp. Geogr. 34, 25–33. https://doi.org/10.1016/j.jtrangeo.2013.10.016.
Qin, H., Zhang, Z., Qi, Z., Lim, A., 2014. The freight consolidation and containerization problem. Eur. J. Operat. Res. 234 (1), 37–48. https://doi.org/10.1016/j.ejor.2013.09.015.
Ramos, C., Burges, A., van der Geest, W., Hendriks, I., van Hassel, E., Shobayo, P., Samuel, L., Atasoy, B., van Doorser, C., Bijlsma, R., Macquart, A., Pedersen, J.T., Eiten, J., Grunder, D., Alias, C., 2020. D.2.1: Detailed Requirements of the NOVIMOVE Transport Model. Technical Report. https://novimove.eu/downloads/.
Rodrigue, J., Notteboom, T., 2012. Dry ports in European and North American intermodal rail systems: two of a kind? Res. Transp. Bus. Manag. 5, 4–15. https://doi.org/10.1016/j.rtbm.2012.10.003.
Roso, V., Woxenius, J., Lumsden, K., 2009. The dry port concept: connecting container seaports with the hinterland. J. Transp. Geogr. 17 (5), 338–345. https://doi.org/10.1016/j.jtrangeo.2008.10.008.
Shobayo, P., Nicolet, A., van Hassel, E., Atasoy, B., Vanelslander, T., 2021. Conceptual Development of the Logistics Chain Flow of Container Transport Within the Rhine-Alpine Corridor. https://doi.org/10.5281/zenodo.5638762.
Shobayo, P., Bedoya-Maya, F., van Hassel, E., Vanelslander, T., Christopoulou, E., Majoor, I., 2024. Assessing inland waterway transport (IWT) container logistics on the Rhine Alpine corridor: a discrete event simulation approach. Res. Transp. Econ. 107, 101475. https://doi.org/10.1016/j.retrec.2024.101475.
Tiwari, S., Wee, H.M., Zhou, Y., Tjoeng, L., 2021. Freight consolidation and containerization strategy under business as usual scenario & carbon tax regulation. J. Clean. Prod. 279, 123270. https://doi.org/10.1016/j.jclepro.2020.123270.
Van Dorsser, J.C.M., 2015. *Very Long Term Development of the Dutch Inland Waterway Transport System* [TU Delft]. https://doi.org/10.4233/uuid:d9cd85d4-2647-49e4-8e7c-df66e27681d3.
Wang, M., Tan, Z., Chen, J., 2023. Improving the resilience of the inland river transportation chain with flexible freight consolidation strategy under epidemic. Ocean Coast. Manag. 243, 106757. https://doi.org/10.1016/j.ocecoaman.2023.106757.
Zheng, J., Yang, D., 2016. Hub-and-spoke network design for container shipping along the Yangtze River. J. Transp. Geogr. 55, 51–57. https://doi.org/10.1016/j.jtrangeo.2016.07.001.
Zhou, S., Ji, B., Song, Y., Yu, S.S., Zhang, D., Van Woensel, T., 2023. Hub-and-spoke network design for container shipping in inland waterways. Expert Syst. Appl. 223, 119850. https://doi.org/10.1016/j.eswa.2023.119850.