Optimising Cargo Consolidation for Port-Hinterland Inland Waterway Transportation

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Short summary

Despite being a sustainable and cost-effective mode of transportation, Inland Waterway Transportation (IWT) has experienced a decline in its market share within the EU over the years. The IWT system faces certain inefficiencies, including low occupancy rates of vessels and low load factors of containers. To address these challenges, this research proposes a Cargo Consolidation (CC) strategy to optimize the utilization of available transport capacity. We develop a mixed integer programming model that considers the trade-off between cost savings from more efficient vessel capacity use and increased container handling costs, aiming to determine the optimal consolidation assignment. A case study conducted on the Rhine-Alpine corridor IWT network demonstrates the feasibility of the CC strategy. The results indicate that a low vessel occupancy rate is the key factor influencing the profitability of the CC concept.
Keywords: Cargo consolidation, Inland waterway transport, Network modelling, Capacity optimization.

1 Introduction and problem description

Inland Waterway Transportation (IWT) is widely recognized as a sustainable and cost-efficient mode of transportation, yet it has been experiencing a decline in market share. According to Eurostat (2024), from 2012 to 2020, there has been an 18.8% decrease in total ton-kilometers for IWT within the EU. One significant factor contributing to the reduced competitiveness of IWT is the often low container load factor and vessel occupancy rate (Ramos et al., 2020). However, only a limited amount of work studied this issue in the literature. Konings et al. (2013) propose a hub-and-spoke network (HS) for seaport-hinterland waterway transport to improve the barge performance. They develop a cost model to compare the performance of different HS network settings, and highlight the importance of hub design and location in achieving cost-effective operations and maximizing benefits. Building on their work, Zheng & Yang (2016) design an HS network on the Yangtze River, taking into account the typology of IWT of the Yangtze River. They propose a mixed integer linear programming to solve the optimal ship assignments and weekly shipping operations. Their results show that for river shipping using small ships, containers are seldom transshipped and consolidated due to the additional handling costs. Fazi et al. (2015) consider the port-hinterland barge transportation and propose a heterogeneous fleet vehicle routing problem formulation to explore the trade-off between consolidating containers for cost efficiency and dispatching single containers via trucks. The current literature mainly focuses on IWT network reorganization and containers consolidation to enhance barge efficiency. The literature does not examine the economic potential for further consolidating containerized cargo in the IWT network. Although it is widely studied in other transportation contexts, such as air transport or urban logistics (Qin et al., 2014), (Melo & Ribeiro, 2015), (Zhu et al., 2022), the concept of Cargo Consolidation (CC) for the port-hinterland IWT has not been extensively researched. To bridge this gap, we propose a CC strategy for IWT that considers consolidating both barge containers and containerized cargo simultaneously.
Our main contributions are :

1. We systematically consider the CC strategy through a mixed integer programming (MIP) model to decide the optimal consolidation assignment.

2. We test this approach through a real-world case study on the Rhine-Alpine corridor IWT network using realistic cost estimations.

Problem description

The CC strategy features the use of a dedicated station located between seaports and hinterland terminals to consolidate containerized cargo. Containers are categorized as eligible or non-eligible based on whether the cargo inside can be consolidated. The proposed consolidation process is that some of the eligible containers are emptied, and their cargo will be transferred to the remaining eligible containers. When a seaport-hinterland terminal pair is assigned to consolidation, a vessel trip on this origin-destination (OD) pair is cut into two legs: the first leg between the seaport and the CC station and the second leg from the CC station to the destination. Some vessels on this OD pair will only travel the first leg. We assume they unload all their containers at the CC station and will be deployed for other purposes; therefore, their subsequent activities are not taken into consideration. These vessels are referred to as "Leg-1" vessels. The eligible containers from these vessels are consolidated and, along with non-eligible containers, await transportation to the destination. The vessels responsible for this process are termed "Whole-Trip" vessels, which cover the entire journey of the OD pair. Starting from the seaport, they first stop at the CC station to unload their eligible containers and reload the containers waiting at the CC station, then these vessels continue their trip to the final destination.
The potential cost savings of CC arise from the reduction in the number of vessels on the second leg. However, this may incur increased container handling costs and additional time at the CC station. As a result, there is a trade-off between the cost savings achieved through vessel reduction and the additional costs incurred. The viability of this strategy depends on whether the cost savings outweigh the additional costs. In this regard, we propose a mixed integer programming model for the optimal consolidation assignment.
We consider an IWT network consisting of multiple seaports as origins and inland ports as destinations with a consolidation station in between. We consider for each OD pair: the number of yearly trips, total cargo volumes, consolidation eligibility, average container load factor and vessel occupation rate, and the time and cost of container handling and consolidating. The goal is to find the optimal OD pairs consolidation assignment and a target load factor and occupation rate for each OD pair, with the objective to minimize the total annual cost on the studied transport network.

2 Methodology

This section presents the mathematical formulation of our proposed mixed integer programming model for the CC strategy on an IWT network. Table 1 lists the notations used in the model.

$$\text{Min} \quad \sum_{(i,j)\in A} \left(\sum_{l\in L} z_{ijl} c_{ijl} + c_{ij}^{handle} + y_{ij} (c_{ij}^{CC} + c_{ij}^{strand}) \right) \tag{1}$$

s.t.

$$y_{ij} \left(\frac{\left(V_{ij}^{unmix} + v_{ij}^{\text{fill}}\right)}{r_{ij} Q} + 1 \right) + (1 - y_{ij})\, G_{ij} \geq z_{ijl} \quad \forall (i,j) \in A, l = 1 \tag{2}$$

$$z_{ijl} \geq y_{ij} \frac{\left(V_{ij}^{unmix} + v_{ij}^{\text{fill}}\right)}{r_{ij} Q} + (1 - y_{ij})\, G_{ij} \quad \forall (i,j) \in A, l = 1 \tag{3}$$

$$\sum_{l\in L} z_{ijl} = G_{ij} \quad \forall (i,j) \in A \tag{4}$$

The objective (1) is to minimize the total cost for all OD pairs, including costs of the vessels, handling at both the CC station and destination ports, consolidation and the value of time cargo stranding at the consolidation station. Constraints (2) (3) specify the quantity of the final Whole-trip vessels z_{ijl}, where $l = 1$. If OD pair (i, j) is assigned to consolidation, z_{ij1} is determined by the total non-eligible and filled TEUs, the capacity of a single vessel and the optimal vessel occupation rate. Constraints (4) regulate that the sum of Leg-1 and Whole-trip vessels should be equal to the initial total trips for this OD pair.

Table 1: Notations

Sets:	
N	Terminals (indices: i, j)
A	Arcs (i, j)
L	Vessel types $l \in \{0, 1\}$ (0: Leg-1 vessels; 1: Whole-trip vessels)
Parameters:	
G_{ij}	Annual trips for OD pair ij [Vessels]
D_{ijl}	Distance for OD pair ij for vessel type l [Km]
E_{ij}	Consolidation eligibility rate for OD pair ij
V_{ij}	Total volume for OD pair ij [TEUs]
V_{ij}^{unmix}	Non-eligible TEUs for OD pair ij [TEUs]
LF_{ij}	Average container load factor for OD pair ij
O_{ij}	Average vessel occupation rate for OD pair ij
Q	Single vessel capacity [TEUs]
TS_{ijl}	Sailing time for a single vessel of type l for OD pair ij [hr]
T^{handle}	Handling time per TEU at the CC station [hr/TEU]
T^{strand}	Average stranding time at CC station per TEU for OD pair ij [hr/TEU]
C^{handle}	Handling cost per TEU [€/TEU]
C^{fill}	Filling cost per TEU [€/TEU]
C^{emp}	Emptying cost per TEU [€/TEU]
C^{fuel}	Fuel cost per km traveled for a single vessel [€/km]
C^{fix}	Fixed cost for a single vessel [€/hr]
C^{var}	Variable cost for a single vessel [€/hr]
W_{ij}	Yearly labor costs for consolidation on OD pair ij [€]
VoT	Cargo value of time [€/TEU/hr]
Decision Variables:	
y_{ij}	Binary, equals to 1 if OD pair ij is assigned to consolidation; 0, otherwise
f_{ij}	Continuous, target container load factor for OD pair ij
r_{ij}	Continuous, target vessel occupation rate for OD pair ij
z_{ijl}	Integer, optimal number of vessels of type l for OD pair ij
Dependent Variables:	
v_{ij}^{fill}	Number of filled containers after consolidation for OD pair ij [TEUs]
c_{ijl}	Average vessel costs of type l for OD pair ij [€/vessel]
c_{ij}^{handle}	Total handling cost for OD pair ij [€]
c_{ij}^{CC}	Total consolidation cost for OD pair ij [€]
c_{ij}^{strand}	Total cargo stranding cost at CC station for OD pair ij [€]
tP_{ijl}	Port time for a single vessel of type l for OD pair ij [hr]
tI_{ijl}	Idle time for a single vessel of type l for OD pair ij [hr]
tT_{ijl}	Total time for a single vessel of type l for OD pair ij [hr]

$$c_{ijl} = \left(D_{ijl}C^{fuel} + C^{fix}tT_{ijl} + C^{var}(TS_{ijl} + tP_{ijl})\right) \quad \forall (i,j) \in A, \quad \forall l \in L \tag{5}$$

$$c_{ij}^{handle} = C^{handle}\left(y_{ij}\left(V_{ij} + 2v_{ij}^{fill} + 2\frac{z_{ijl}}{G_{ij}}V_{ij}^{unmix}\right) + (1 - y_{ij})V_{ij}\right) \quad \forall (i,j) \in A, l = 0 \tag{6}$$

$$c_{ij}^{CC} = C^{fill} * v_{ij}^{fill} + C^{emp}(V_{ij}E_{ij} - v_{ij}^{fill}) + W_{ij} \quad \forall (i,j) \in A \tag{7}$$

$$c_{ij}^{strand} = T^{strand}VOT\left(\frac{z_{ijl}}{G_{ij}}V_{ij}^{unmix} + v_{ij}^{fill}\right) \quad \forall (i,j) \in A, l = 0 \tag{8}$$

Constraints (5) define the average individual vessel cost c_{ijl}, including fuel cost, fixed costs determined by total vessel time, and variable costs based on sailing time and inland port time.

Constraints (6) present the total handling cost c_{ij}^{handle} takes into account Leg-1 vessels unloading all containers, and Whole-trip vessels unloading eligible containers and reloading the filled and the non-eligible containers from Leg-1 vessels at CC station, and Whole-trip vessels unloading all non-eligible and filled containers at the destination. Constraints (7) denote the total consolidation cost c_{ij}^{CC}, which includes container emptying and filling expenses, and labor costs for consolidation. Constraints (8) specify the total cargo stranding cost at the CC station.

$$tT_{ijl} = TS_{ijl} + tP_{ijl} + tI_{ijl} \quad \forall (i,j) \in A \quad \forall l \in L \tag{9}$$

$$tP_{ijl} = y_{ij} T^{handle} O_{ij} Q \quad \forall (i,j) \in A, l = 0 \tag{10}$$

$$tP_{ijl} = T^{handle} \frac{\left(y_{ij} \left(V_{ij} + 2v_{ij}^{fill} + 2\frac{z_{ijl}}{G_{ij}} V_{ij}^{unmix} \right) + (1 - y_{ij}) V_{ij} \right)}{z_{ijl}} \quad \forall (i,j) \in A, l = 1 \tag{11}$$

Constraints (9) specify the relationship between the total time, sailing time, inland port time, and the idle time. Constraints (10) define the inland port time for individual Leg-1 vessels, representing the time required for unloading all containers. Constraints (11) present the inland port time for a single Whole-trip vessel. It is calculated by: first estimating the time needed for handling all volumes on this OD pair, and then averaging it over the quantity of Whole-trip vessels.

$$v_{ij}^{fill} = \frac{LF_{ij} V_{ij} E_{ij}}{f_{ij}} \quad \forall (i,j) \in A \tag{12}$$

$$f_{ij} \leq LF_{ij} + y_{ij} M \quad \forall (i,j) \in A \tag{13}$$

Constraints (12) specify the final filled volume and constraints (13) restrict that when OD pair (i,j) is not assigned to consolidation, the final load factor of this OD pair should not exceed the initial value.

$$LF_{ij} \leq f_{ij} \leq 0.9 \quad \forall (i,j) \in A \tag{14}$$

$$O_{ij} \leq r_{ij} \leq 0.9 \quad \forall (i,j) \in A \tag{15}$$

$$z_{ijl} \in \mathbb{Z}_{\geq 0} \quad \forall (i,j) \in A \quad \forall l \in L \tag{16}$$

$$y_{ij} \in \{0,1\} \quad \forall (i,j) \in A \tag{17}$$

The range of f_{ij} and r_{ij} is specified by constraints (14) and (15). The lower bounds are given by their initial values, while the upper bound is set at 90% for both variables. This is because achieving a 100% container load factor and vessel occupation rate is unrealistic in real-world practice. Constraints (16) restrict z_{ijl} to be non-negative integers, and constraints (17) specify y_{ij} as binary variables.

3 Results and discussion

In order to assess the effectiveness of the cargo consolidation strategy, we apply the model to the Rhine-Alpine corridor, which is a prominent IWT corridor in Europe with 2 seaports (Antwerp and Rotterdam) and 11 selected hinterland terminals located across Germany, the Netherlands, France, and Switzerland. The input values and the parameters are obtained from (Majoor et al., 2021). We assume that the consolidation station is located in Nijmegen (Atasoy et al., 2023) and the container barge has a maximal capacity of 250 Twenty-Foot Equivalent Units (TEUs). The consolidation station is assumed to have unlimited capacity. i.e., is capable of handling all containers assigned to it. Vessel departure frequency from the origin is evenly distributed throughout the year for each OD pair. The integrated average vessel cost is not influenced by the vessel's occupation rate; i.e., a vessel, whether empty or fully loaded, incurs the same cost for traveling the same distance. The efficiency of employees for consolidation is defined as two persons handling two containers per day, with each employee working an 8-hour shift. The optimal results derived from the model are compared with the benchmark scenario in which no consolidation takes place for any OD pair. To

Table 2: Optimal load factor, occupation rate and vessel reduction

		Load Factor		**Occupation Rate**		**Vessel reduction**
Origin	Dest.	Initial	Optimal	Initial	Optimal	-
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%

Table 3: Cost composition (in million euros) of the Benchmark and the consolidation.

	Consolidation	Vessel	Handling	Cargo VoT	**Total cost**
Benchmark	0.00	68.72	19.78	0.00	88.49
Consolidation (CC)	3.94	58.16	21.16	1.75	85.01
Difference	+3.94	-10.56	+1.38	+1.75	-3.48

Table 4: Total Cost (in million euros) and Vessel Time (hr) comparison

		Cost			**Time**		
Origin	Dest.	CC	Benchmark	**Difference**	CC	Benchmark	**Difference**
BE21	CH03	2.64	2.86	**-7.67%**	116.40	77.94	**49.35%**
BE21	DE11	1.58	2.29	**-31.11%**	91.90	65.73	**39.82%**
BE21	DE13	1.53	1.59	**-3.78%**	99.85	77.35	**29.10%**
BE21	FRF1	2.71	4.14	**-34.48%**	110.89	82.05	**35.15%**
NL33	DE13	5.06	6.12	**-17.33%**	102.70	75.23	**36.50%**

set up the benchmark case, the binary variables y_{ij} are set to 0, while the remaining variables and parameters remain unchanged.

The optimal solution indicates that 5 out of 22 OD pairs should be assigned to cargo consolidation in order to achieve the lowest total cost. Table 2 presents the optimal load factor, occupation rate, and vessel reduction rate on these selected OD pairs. The final load factors and vessel occupation rates all reach their upper bound (90%), indicating that it is encouraged to utilize the vessel capacity as much as possible to reduce the costs. These OD pairs are also the five with the lowest initial occupancy rates among all 22 OD pairs. The initial load factors on the selected OD pairs are comparable to the unassigned ones, indicating that the initial vessel occupation rate is the key factor in determining whether the OD pair should be assigned to consolidation or not. As the capacity utilization of the vessels on these OD pairs is very low, cargo consolidation helps to make efficient use of the unused capacity, leading to a significant reduction in the number of vessels required for the second leg. The vessel reduction for these OD pairs is above 80% for all. To sum up, OD pairs with lower initial occupation rates have a higher potential of being assigned to consolidation.

Table 3 presents the comparison of costs for the benchmark case and consolidation. The results show that the implementation of the proposed cargo consolidation strategy yields a total annual cost reduction of 3.48 million euros. As indicated in the difference in each cost category, the reason behind the cost savings is that the reduction in vessel costs outweighs the marginal cost increase in other categories due to the implementation of the strategy. Table 4 presents a breakdown of the cost and vessel's inland port time differences for OD pairs assigned to consolidation. The results suggest that the cost reduction of the CC strategy comes at the expense of increased vessel transport time. This is because the vessel needs to dock at the CC station to unload cargo to be consolidated, as well as reload the already consolidated cargo waiting at the station, thus greatly increasing the time needed to complete the trip. Therefore, for time-sensitive transport, such as perishable products, the CC strategy may not be advisable. However, for situations where cost is a priority, the CC strategy is recommended for cost-saving purposes.

4 Conclusions

Our research investigates the feasibility of implementing the cargo consolidation concept in inland waterway transport. In this study, we propose a mixed integer programming model to determine the optimal consolidation assignment for OD pairs based on a realistic cost estimate for the involved operations. The case study on the Rhine-Alpine corridor shows the potential profitability of the CC strategy and highlights the significant influence of the initial vessel occupation rate on consolidation assignment decisions. Additionally, the findings confirm that while the CC strategy offers cost savings, it also leads to a substantial increase in the total inland port time of vessels. For the next step, we plan to conduct a more detailed simulation at the vessel level, with a heterogeneous fleet and variable demand. Further research can explore the integration of this strategy into the intermodal transportation system and determine the optimal location for the CC station(s).

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