



Examining the Logistics Performance of a Decentralized Waterborne Container Transportation Service in the West German Canal Network with the Help of Discrete-Event Simulation

Cyril Alias^{1(✉)}, Jonas Zum Felde¹, and Sven Severin²

¹ DST – Development Centre for Ship Technology and Transport Systems, Duisburg, Germany

{Alias, ZumFelde}@dst-org.de

² RIF Institut für Forschung und Transfer e. V., Dortmund, Germany

Sven.Severin@rt.rif-ev.de

Abstract. In order to alleviate road traffic congestion, a logistics concept based on small inland vessels in the West German canal network has been developed for the distribution of containers. The service concept rests on multiple transshipment points throughout the considered geographic area as potential origins and destinations of transport legs. After safeguarding the technical feasibility, the resulting service concept needs to be examined in order to assess its economic viability. Only with promising outcomes resulting from this assessment can potential operators be convinced to transfer the concept into reality, set up the decentralized waterborne container transportation service, and deploy actual inland vessels to be operated in the German waterways. Discrete-event simulation has established itself as an important analysis method in logistics and is suitable for the examination of logistics systems at an operational and tactical level. In the present setting, various scenarios have been selected as the most promising ones and simulated with appropriate models. Eventually, DES will help to determine the routes to be operated, the ports and transshipment points to be included in the respective routes, the vessels to be used, including their type and number, the manning regulation of the inland vessels to be selected, and the transshipment concept to be pursued. Ultimately, the logistics simulation reveals which scenarios turn out to be the most and least promising ones and allows overall statements on the expectable profitability of the service. Furthermore, it helps to identify utilization peaks of the examined inland vessels and transshipment points.

Keywords: Inland waterway transportation · Discrete-event simulation · Decentralized container transport · Transshipment · Logistics · Economic performance

1 Introduction

Reliable, safe and environmentally compatible transport is an elementary prerequisite for a competitive and sustainable economy. To ensure that the transport sector does not become a bottleneck to economic development, the available resources must be used efficiently. However, the road and rail modes of transport are increasingly reaching their limits, and the heavy traffic load, especially on the roads, leads to high emissions of pollutants and greenhouse gases. At the same time, inland waterway transportation (IWT) is characterized by high reliability and energy efficiency and has considerable unused capacity reserves, especially in Northwestern and Central Europe¹. It therefore lends itself to relieving the burden on road and rail.

Traditionally, IWT has focused on direct long-distance transports, such as bulk transports between two locations of up to several hundred kilometers. In view of the eroding volumes of bulk cargo in continental Europe, IWT is urgently required to open up new market segments and, in doing so, to exploit the opportunities offered by technological progress to the greatest possible extent for its benefit.

In order to utilize the unused transport capacities and develop new market segments for IWT, a decentralized waterborne container transportation service can be a viable solution. While the conception of such a service has already been described in previous publications, the configuration of the service in terms of the inland vessels to be used and the transshipment points to be served as well as an assessment of the expected economic key figures are still pending.

2 Transport Service Concept

The examined transport service concept encompasses a decentralized waterborne container transportation service operating in the hinterland of the European seaports in the range between Le Havre, France, and Hamburg, Germany. Specifically, it serves the hinterland areas of the ports in Hamburg and Bremerhaven (both Germany), Zeebrugge and Antwerp (both Belgium) as well as Rotterdam and Amsterdam (both the Netherlands).

The service foos on four sub-concepts, i.e., the logistics service design, the envisaged inland vessels, the designated transshipment operations, and – lastly – the integration of the envisioned service into the landscape of existing logistics services. Details of the four sub-concepts have been published earlier and are, thus, only briefly described in the following.

2.1 Vessel Concept

The inland vessels designed for the transport service have been developed specifically for the use in the West German canal network. As part of this, the decision in favor of

¹ An area between Eastern and Western Europe, generally accepted as comprising Austria, the Czech Republic, Germany, Hungary, Liechtenstein, Poland, Slovakia, Slovenia, and Switzerland (see Collins Dictionary).

small inland vessels was made deliberately to account for the different capacity demands expected for different stretches of the transport network. As such, the considered inland vessels can carry between eight and 30 TEU each. Due to structural restrictions in terms of bridge heights in the area of operation, the transport of only a single layer of containers can be considered realistically. Taking into account the remaining factors of the clearance profile, such as lock chamber dimensions and waterways drafts, the inland vessels measure between 50 and 95 m in length and 6.80 and 9.50 m in width and feature a draft of up to 1.12 m (Alias et al. 2021).

The previous examination failed to prove the economic viability of such a service due to the lack of freight volume to utilize the envisioned vehicle capacity fully. Inland barges of up to 96 TEU. In the RuhrCargo research project, a push train between the inland ports of Dortmund (at the end of the Dortmund-Ems Canal) and Duisburg (at the junction of the river Rhine and the Rhine-Herne Canal) was planned with a potential single-layer transport capacity of up to 96 TEU (DST 2013).

As the inland vessels are planned for operation in the canal network without any waterway currents to overcome, the power requirements for the vehicles can be covered by hybrid-electrical propulsion as the expected power consumption of the different inland vessels ranges between 43 and 196 kilowatt-hours, respectively, at a velocity of 12 km per hour, the maximum velocity permitted on the considered waterways. In addition, the inland vessels were hydrodynamically optimized with the help of CFD and model testing experiments (Ley et al. 2022). During the vessel design process, it was also considered to keep the construction as modular as possible and, thereby, allow for easily scalable and cost-effective production.

The inland vessels are also planned in a way that future modes of operation, such as one-person operation, remote control, and even fully automated operation, are enabled. By this, the potential for further cost reduction in the future is included. At the moment, such modes of operation are not recognized by the German waterway authority, while it is already permitted in the Netherlands.

As the inland vessels are designed for single-layer container transports only, they can be equipped with a mobile onboard crane to tie into the transshipment concept.

2.2 Transshipment Concept

The service area of the decentralized waterborne container transportation service extends over a geographic area between the river Rhine in the west and the river Weser in the northeast of the German state of North Rhine-Westphalia, the economically strongest and most densely populated region in the country. Apart from the existing container ports in the considered area, additional decentralized transshipment points have been taken into consideration. These additional transshipment points include active ports without any container handling business to date as well as abandoned transshipment points from the former era of coal, iron, and steel production in the considered geographic area (Alias et al. 2021).

Usually, either a container crane or a reach stacker is available at those transshipment points already engaged in the container business so that there is no further investment required to participate in the transport service. However, this applies to a small minority of the considered locations only. These remaining transshipment points

will need to invest in container handling infrastructure, mainly reach stackers, once such an investment appears economically viable and rewarding. However, in order to develop a container business, even smaller investments may pose an obstacle for many locations, so a concept in which all required equipment will be provided by the inland vessel operator appears more promising. Hence, a mobile onboard crane can help include additional locations with initially low cargo volume but a sufficient growth potential and, thus, eliminate a potential entry barrier.

Designed as a mobile gantry crane running along the side passage of the inland vessel, the mobile onboard crane is operated by the inland vessel operator. In order to limit the usage of space, the control stand of the crane is co-located with the control station of the inland vessel. From its home position at the ship's bow, the crane is capable of traversing the inland vessel along its entire length. Additional details about the transshipment concept can be found in earlier publications.

2.3 Logistics Concept

In order to determine the logistics concept underlying the proposed transport service, both the demand and supply sides have been considered in the design process. The supply side is represented by the service area, which has been defined with the help of the waterways that are to be covered. The service area represents the aforementioned geographic area with five canals, i. e., the Datteln-Hamm Canal, the Dortmund-Ems Canal, the Mittelland Canal, the Rhine-Herne Canal, the Wesel-Datteln Canal, as well as the navigable part of the river Ruhr and a small portion of the river Weser (Alias et al. 2021).

The first level of transshipment point taken into consideration comprises those ports already actively participating in container transshipment. Only two ports, Minden and Dortmund, fit this criterion. As the next step, all active ports in the examined service area were added to the list of transshipment points – resulting in a total of 42 additional port locations. Lastly, yet another 61 formerly active ports and transshipment points have been identified as potential transshipment points on the third level. Many of these inactive and abandoned sites still fit the regulatory requirements for port operations. All three levels combined represent the complete set of 105 total destinations to be potentially used by the proposed service. To enable a comprehensive calculation of travel times, additional points of interest, such as locks, bridges, turning basins and waterway junctions, were included in the network (Alias et al. 2020).

The demand for such a service was derived in two ways. Firstly, the cargo already known to be transported with the proposed waterborne transport process was determined. In addition, a potential modal shift effect due to the introduction of the new service was quantified and added to the already determined volumes. The freight volumes were determined using publicly available information on container freight volumes and calculated at the municipal level before being allocated to ports (Alias et al. 2020). In addition, the determined volumes the values were validated on a sample basis by identifying real cases of potential users of the service.

Eventually, three service concepts were identified as possible solutions for the service: direct transport, scheduled liner service, and a hub-and-spoke system with a transshipment hub in the center of the service area.

2.4 Integration Concept

As has been mentioned before, the designated decentralized waterborne container transportation service operates in the hinterlands of the seaports in Belgium, Germany, and the Netherlands. More precisely, it is designed as serves as a feeder shuttle service between the hinterland hubs. The feeder shuttle bidirectionally serves the inland ports of Duisburg and Wesel on the Rhine and the port of Minden at the waterway junction of Mittelland Canal and the river Weser. In all three termini, the containers are transhipped onto the larger liner services to the seaports in Belgium and the Netherlands, and northern Germany, respectively.

Direct service to the seaports as a single inland vessel or as a push train had been considered earlier and is principally possible, although the reduced vehicle capacity compared to the existing liner services makes this option economically unattractive. Therefore, the options have been discarded during the examination and the service area of the envisioned transport service restricted to the above-mentioned geographic area.

In addition, the proposed decentralized waterborne container transport network must be designed with the international supply chains in mind in order to become an integral part of the intermodal transport chains. The need for this integration has been deliberately taken into account in the planning and booking processes for the proposed service, so that they are compatible with those used for the preceding and subsequent transport phases. This also applies to the control tools required to monitor and control the transport execution.

3 Research Methodology

For the detailed examination of the logistics performance of the decentralized waterborne container transportation service, discrete-event simulation (DES) has been chosen as the examination method of choice because it has established itself as a frequently adopted examination method in logistics when it comes to the multiple flows in complex technical systems. In a discrete-event simulation, the system under consideration is represented by events, activities and processes. As it uses random numbers, a sufficient number of replications is required to achieve statistical certainty of the results the DES study. DES has been selected to account for the complexity of the envisioned transport service operation as it has already been applied to a wide range of applications across multiple areas within the transportation and logistics domain (and beyond) (Kuhn et al. 2008, p. 73). Moreover, DES enables process transparency and, thereby, the comparative assessment of several decision alternatives (März et al. 2011, pp. 3–5).

In IWT, however, the application of DES is still a rarity and gains momentum only slowly. Therefore, a dedicated simulation tool and model had to be developed in order to examine and assess the predefined scenarios of the decentralized waterborne container transportation service in an effective manner.

3.1 Simulation Tool

A DES tool for the proposed waterborne transport service was created based on the VEROSIM toolbox to evaluate and compare different scenarios that could be envisioned as part of the decentralized waterborne container transportation service. VEROSIM is a software system originally designed for 3D simulations, virtual test environments, and simulation-based development in robotics and engineering. This foundation for the DES tool allowed for the abstraction of a two-dimensional model. Based on this, the necessary functionality for modeling an IWT simulation system had to be programmed to create a new tool tailored to the actual case (zum Felde et al., 2022). Although the development was strongly oriented towards the specifications of the particular case study, the flexibility of the toolbox allows for a complete representation of IWT in general, including further case studies.

3.2 Simulation Model

The discrete-event simulation model is based on the points of interest identified as relevant to the network. The points of interest, such as ports, locks and nodes, are located on a map covering the entire service area described above. Each point of interest is considered a node in the network connected by edges representing the waterway segments between two points of interest. Travel times are based on the distance of the waterways between each point of interest and the related inland vessel characteristics, such as maximum permissible speed and acceleration behavior. Each point is given the necessary attributes to represent its specific functionality. For instance, a lock node is provided with attributes that indicate the width and length of the chamber as well as the respective lock operation time, whereas a port node is defined by its number of available berths and handling facilities and the pertaining processing times.

In order to generate the container volumes to be processed in the model, the predetermined cargo volumes are fed into the simulation model based on the municipality of origin. The model determines the costs of road-based transportation on the first or last mile, i. e., between the respective municipality and the assigned canal port. In this study, only loaded containers were considered as the focus lay on load trips. In terms of inland vessel utilization, a significant increase can be expected once empty containers are included in the examination.

When creating a specific scenario, the DES model allows the creation of routes from the set of considered ports. The only restriction is that the route must serve a port with the ability to transfer containers onto a container liner service, i. e., Duisburg, Wesel, and Minden, as the transport service is designed as a feeder shuttle between the inland hubs. In addition to the freedom in route design, the DES model allows the specification of a minimum time between visits to improve the timing of the route. Further, it allows a combination of minimum utilization and maximum waiting time. While designing a route, the DES model automatically computes the length of the route and determines the smallest lock and lowest bridge that limit use by certain vessels. After a route is created, the required vehicles must be deployed on the route. Inland vessels can be added and configured according to available vessel types, crew

specifications, and a home port for the vessel. The required vessel manning specifications are available according to both the Regulations for Rhine navigation personnel (RheinSchPersV) and German regulations for inland navigation personnel (BinSchPersV), which were both integrated in the German Inland Waterway Vessels Safety Ordinance (BinSchUO) formerly. Apart from lock size, waterway draft, and bridge height, there are no restrictive factors to the use of inland vessels so that any combination of type, crew and home port for each vessel used on a route is allowed.

In order to determine the resulting key performance indicators (KPI), additional data is required as input. This applies in particular to the calculation of the costs incurred by the envisaged transport system. Within the simulation model of the decentralized waterborne container transportation system, a large number of input parameters are variable. These input parameters include, but are not limited to, many of the costs associated with vessel operation, the capital investments of the ports, and the temporary storage of containers at the ports. The most detailed calculation is performed for vessel operations. Besides the wages for the crew required for the specific manning specification, further time-related costs, e. g., insurance and regular tasks of maintenance, repair, and overhaul (MRO) required to operate a vessel, and the distance-related cost of energy, which were determined by calculating accurate consumption based on vessel movements and collected from the experimental evaluation during the vessel design phase, are included.

To be precise, the energy costs caused by vessel movements are determined by calculating accurate values for the energy consumed. These values foot on previously collected data from the experimental results of the model tests of the designed inland vessels. The energy consumption determined for each barge is also used to calculate the CO₂ emissions caused by the service using a CO₂ conversion factor.

In addition, the costs of road-based pre-haul, i. e., from the consignor to the canal port, and the ones of the liner services between an inland hub and the seaport, e. g., between Duisburg and Rotterdam or between Minden and Hamburg, are included. By including these costs in the DES model, the costs incurred for the total transportation service between the consignor and the seaport can be determined. Thereby, it is possible to effectively compare the new decentralized waterborne container transportation service with its main competitor, i. e., the direct road transportation from the consignor to the seaport. In this way, both the costs per TEU kilometer of the new transport service on the West German canal network and the ones of the total transport leg can be determined and compared throughout the examined scenarios.

Furthermore, the DES model computes a port-related service level based on the container dwell time in a particular port. This interpretation of the service level differs from the classic definition of service level, which refers to shipments received on time and in full. Such an accurate calculation of the level of service cannot be determined because no order data is available to measure the punctuality factor and the damage freedom.

The DES model stores the events in an external database, which allows easy access to the simulation results for further analysis with external tools. For the most important KPI analyzed in each scenario, the DES model has a built-in option for evaluating and visualizing the KPI over time.

4 Simulation-Based Examination

4.1 Examined Scenarios

With the help of discrete-event simulation, the logistics performance of the envisioned decentralized waterborne container transportation service is examined. In total, the comparative examination comprises eight different scenarios, all of which are based on different configurations of the system. Figure 1 illustrates the different routes of the decentralized waterborne container transportation service as a network map, while Table 2 shows the number of routes served and inland vessels deployed for each of the ten considered scenarios.

Labelled as the baseline case, Scenario 1 represents the original configuration of the transport service, i. e., a feeder service of the hinterland hubs Duisburg and Wesel serving the seven biggest ports in the canal network with liner services operating on seven different routes with 28 inland vessels of different types and capacities. The assignment of the inland vessels to the routes is determined by the volume of cargo to be hauled and handled. The inland vessels are crewed following the BinSchPersV regulations in such a way that 24-h operation is allowed by regular shift changes of the crew.

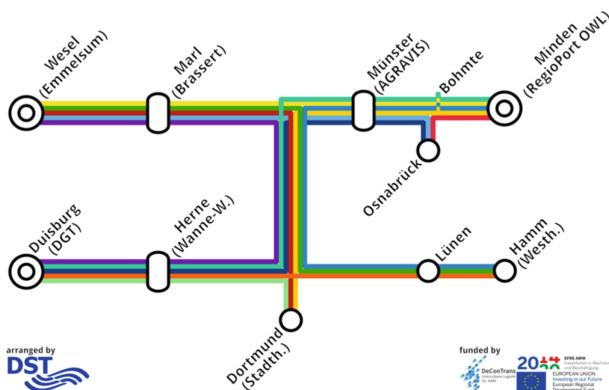


Fig. 1. Network map of the decentralized waterborne container transportation service with termini in Duisburg (DUI), Wesel (WES), Dortmund (DTM), Hamm (HMM), and Minden (MID).

Scenario 2 is a slight modification of the first one, with one stop at the Mittelland Canal being replaced by another one. Precisely, the inland port of Osnabrück has replaced the container terminal in Bohmte and led to the inclusion of additional operational challenges as the inland port of Osnabrück is situated at the end of a branch canal, which again is limited by two small locks restricting the vessel size to a maximum length of 82 m. This fact results in two additional routes being serviced by two inland vessels each, elevating the total number of routes to nine, and the number of ships to 32. Based on the baseline scenario, the two subsequent scenarios observe the

impact of an increase in transshipment points to be served. Scenarios 3 and 4 increase the number of ports to 44 and 105, respectively. In both scenarios, the seven routes are served by a total of 39 inland vessels in order to compensate for the higher number of stops. Scenario 5 examines the effect of the baseline scenario operating in shuttle mode and results in a configuration of 16 routes with 37 inland vessels. An examination of more ports served by a shuttle service is refrained from because the number of required inland vessels and routes would exceed any realistic expectations. Table 1 shows an exemplary overview of the configuration results for the Scenarios 1 to 4.

Table 1. Overview of served routes, deployed vessels and allocated capacities for the scenarios 1 to 4. (colors and termini correspond to the lines in the network map in Fig. 1).

		Route 1	Route 2	Route 3	Route 4	Route 5	Route 6	Route 7	Route 8	Route 9
Scenario 1	transport relation [start - end]	DUI - WES	DUI - DTM	DUI - HMM	DUI - MID	WES - DTM	WES - HMM	WES - MID		
	no. of vessels	7	3	3	5	3	2	5		
	vessel type (TEU)	VI (30)	VI (30)	IV (24)	I (8)	III (18)	III (18)	I (8)		
Scenario 2	transport relation [start - end]	DUI - WES	DUI - DTM	DUI - HMM	DUI - MID	DUI - OSN	WES - DTM	WES - HMM	WES - MID	WES - OSN
	no. of vessels	7	3	3	4	3	3	2	4	3
	vessel type (TEU)	VI (30)	VI (30)	IV (24)	I (8)	I (8)	III (18)	III (18)	I (8)	I (8)
Scenario 3	transport relation [start - end]	DUI - WES	DUI - DTM	DUI - HMM	DUI - MID	WES - DTM	WES - HMM	WES - MID		
	no. of vessels	9	3	5	8	3	3	8		
	vessel type (TEU)	VI (30)	VI (30)	III (18)	I (8)	II (12)	III (18)	I (8)		
Scenario 4	transport relation [start - end]	DUI - WES	DUI - DTM	DUI - HMM	DUI - MID	WES - DTM	WES - HMM	WES - MID		
	no. of vessels	9	3	5	8	3	3	8		
	vessel type (TEU)	VI (30)	VI (30)	III (18)	I (8)	II (12)	III (18)	I (8)		

Apart from liner services and direct haulage, a third traffic concept, i. e., a hub-and-spoke system, is examined in Scenarios 6 and 7. Both scenarios assume a fictional hub in the center of the West German canal network, precisely at the transshipment in Datteln, and differ in the inclusion of Bohmte and Osnabrück, respectively. While six routes are required for the earlier case, seven are required for the latter.

Another variation of the scenarios is the extension of the service area to the hinterland of North German seaports and, thus, the consideration of northbound cargo volumes towards the ports of Hamburg and Bremerhaven. This variation considers Minden as an additional inland hub because it is already served by regular liner services to the seaports. This variation is examined with three scenarios: Scenario 8 is based on the baseline scenario, while Scenario 9 foots on Scenario 2. Scenario 8 results in nine routes and 30 inland vessels, while Scenario 9 requires twelve routes and 35 inland vessels. Scenario 10, designed analogously to Scenario 5, requires an additional seven routes, leading to 23 routes with 46 inland vessels in total. All increases in routes and inland vessels are the necessary result of serving a third destination port and connecting the complete network.

4.2 Simulation Study

The results of the aforementioned scenario configurations are presented as average values of the results collected from over a hundred simulation runs of each scenario. This is done to account for the statistical variation induced by the model. Four key performance indicators will be observed to compare the scenarios and determine the quality of each of them: the costs per TEU-kilometer, the service level, the capacity utilization of the inland vessels, and the productive time shares of each inland vessel.

The most relevant performance indicator is the costs per TEU-kilometer as it is needed to determine the economic viability of the service and to compare it with existing transport alternatives. The costs are analyzed for both the IWT leg with the outlined service as well as the complete transport leg between seaport and consignor (and vice versa).

Additionally, a service level is calculated for each port. Subsequently, both the minimum service level at each location and an aggregated average service level are determined. The minimum service level is set up to act as a threshold that all ports need to accomplish in order to ensure that containers are not being stored in ports for excessive amounts of time. Else, this would lead consignors to refrain from using such a service. To ensure all ports have a decent level of connectivity within the new transport service, a minimum service level of 75% has been established. This translates into 50% of the containers being picked up within the first 24 h after their arrival at a port.

From the operator's perspective, the major performance indicator is the capacity utilization of the inland vessels used. With respect to the DES model, this metric guarantees that the port-related service level is not increased by simply running a multitude of underutilized inland vessels and, thereby, minimizing the container dwell times in the canal ports. It is to be noted again that vessel utilization refers to load runs of containers only. The empty container cycle has not been simulated and needs to be considered as extra volumes on top of the given capacity utilization.

Eventually, the productive time shares of each vessel include the time of transport and locking operations as well as loading and unloading processes. They are used to compare traffic flow in each scenario.

4.3 Simulation Results

After running a hundred simulation runs of each of the ten scenarios, the results have been collected and compiled. Table 2 shows an overview of the results of all scenarios considered in this article.

The baseline scenario, Scenario 1, reaches a service level of 90.78% while just about achieving the required minimal service level of merely 75.3%. Moreover, the baseline scenario yields an average vessel utilization of 47.69% and a productive time share of 66.39%. The costs for the new service amount to 1.07 EUR per TEU-kilometer for the canal leg, and 0.68 EUR for the total leg, respectively.

The other scenarios, including westbound liner service concepts, i. e., Scenarios 2 to 4, feature similar results in terms of port-related service level and vessel utilization albeit costs per TEU-km do increase quite significantly with an increasing number of

transshipment points to be served. The service levels vary between 87.03% and 91.61% and vessel utilization ranges between 43.69% and 48.19% whereas costs per TEU-kilometer for the canal leg grow from 1.09 EUR (Scenario 2) to 1.31 EUR (Scenario 4). All three scenarios miss the minimum service level threshold. While the results of Scenario 2 are close to the one of the baseline scenario, the differences become more pronounced as the number of transshipment increases. This is mostly the result of the increased numbers of stops resulting in longer roundtrip times for routes while boosting the productive time shares.

The first scenario with a direct traffic concept, Scenario 5, almost reaches the service level of the baseline scenario with 90.45%. However, the minimum service level, on the other hand, only reaches 71.77% and, thus, misses the threshold of 75%. The productive time share of the vessels is on the same level as the baseline scenario as well, averaging at 66.7%. Vessel utilization comes in a little short with only 44.94%. In essence, the transport costs are quite comparable with 1.09 EUR per TEU-kilometer for the canal leg and 0.72 EUR for the total leg, respectively.

Table 2. Overview of logistics performance results of the scenarios 1 to 10.

	Scen 1	Scen 2	Scen 3	Scen 4	Scen 5	Scen 6	Scen 7	Scen 8	Scen 9	Scen 10
no. of routes served	7	9	7	7	16	6	7	9	12	23
no. of inland vessels deployed	28	32	39	39	37	13	14	30	35	46
service level (in percent)	90.78	91.07	91.61	87.03	90.45	25.19	16.28	90.95	91.27	93.57
minimum service level (in percent)	75.30	74.63	66.42	62.42	71.77	0.24	0.17	82.25	82.58	78.18
productive time share (in percent)	66.39	66.42	69.14	74.33	66.70	51.53	61.44	71.54	71.59	72.58
vessel utilization (in percent)	47.69	46.85	43.69	48.19	44.94	82.98	80.38	48.41	46.00	39.62
annual emissions per vessel (in tons CO ₂)	168.13	150.81	133.55	119.69	126.23	161.70	164.07	165.05	148.36	121.88
costs per TEU-km (canal only) (in EUR)	1.07	1.09	1.29	1.31	1.09	1.03	0.93	1.09	1.11	1.14
costs per TEU-km (total leg) (in EUR)	0.68	0.70	0.74	0.75	0.72	2.00	2.02	0.68	0.71	0.77

The scenarios with the hub-and-spoke concept, Scenarios 6 and 7, return remarkable results of capacity utilization with 82.98% and 80.38%, respectively. This result is only possible at the expense of the service level with only 25.19% and 16.28%, respectively, as well marginal results for the minimum service level with less than 0.5% for either scenario. Likewise, the productive time shares dropped in either scenario with 51.53% and 61.44%, respectively. The main reason behind these results is the limited transshipment capacity at the hub port (Datteln). This again leads to disadvantageous costs per TEU-kilometer because the penalties for long storage times portside drive these upward.

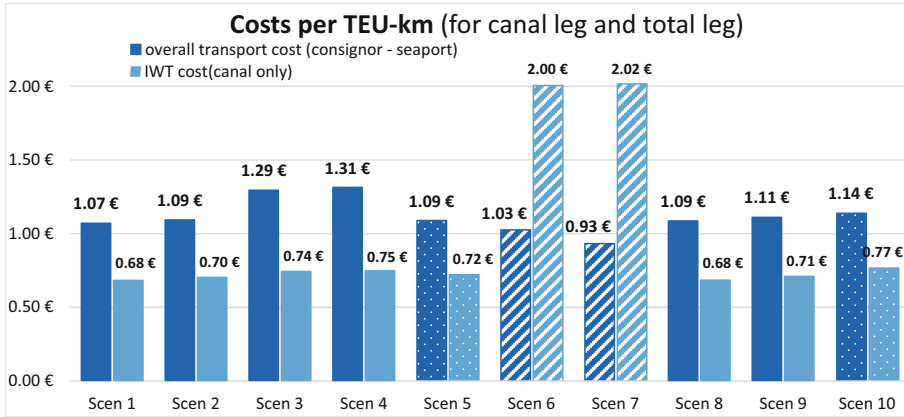


Fig. 2. Comparison of costs per TEU-kilometer for the canal leg and the total leg in the scenarios 1 to 10

When extending the westbound service area by a northbound orientation, as represented in Scenarios 8 to 10, the additional container volumes lead to a stabilization of the service level and particularly the minimum service level. On comparing Scenario 8 with the baseline scenario, the delta between average and minimum service level has shrunk to 8.7% (as opposed to 15.49% in the baseline scenario). Similarly, the vessel utilization and the productive times shares profited from the extension of the service area. The costs per TEU-kilometer remained stable with a slight increase by 0.02 EUR to 1.09 EUR for the canal leg. For the total leg, the costs per TEU-kilometer amount to 0.68 EUR – exactly the same as in the baseline scenario. Similar to the comparison of Scenario 2 with the baseline scenario, Scenarios 8 and 9 feature similar results with 0.71 EUR per TEU-kilometer. This leads to the assessment that the selection of Bohmte or Osnabrück has only a minor impact on the logistics performance of the transport service. The effect of the northbound extension of the service concept is reflected in the results of Scenario 10 as well. However, the scenario with the most routes served and inland vessels used among all observed scenarios shows that the costs per TEU-kilometer are 0.77 EUR for the overall transport and 1.14 EUR for the envisaged IWT service only. In a direct comparison with Scenario 5, the port-related results improve due to the additional freight volume, whereas the vessel-oriented indicators see a downturn with reduced utilization rates (39.62%) and lower productive time shares.

Figure 2 provides an overview of the costs per TEU-kilometer computed for each scenario, while Fig. 3 exhibits the economic KPI of the examined ten scenarios.

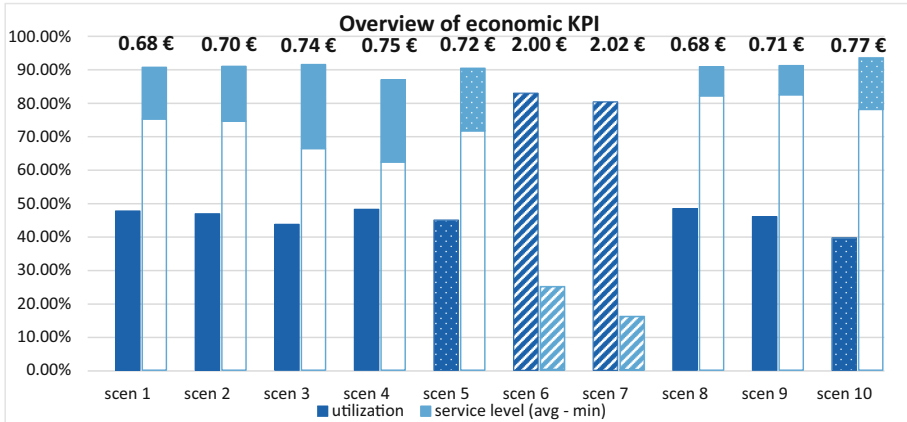


Fig. 3. Comparison of vessel utilization and port service levels in the scenarios 1 to 10.

4.4 Discussion

First, the costs determined in the considered scenarios need to be put into perspective. On the one hand, the designated transportation service still improves on the costs per TEU-kilometer of 2.30 EUR for road transportation, the main competitor for the considered transport leg. The only major deviation from these observations results from the hub-and-spoke scenarios. On the other hand, the costs for operating such a service remain significantly higher than the liner services operated on the river Rhine which can achieve costs as low as 0.18 EUR per TEU-kilometer through its significantly larger economies of scale.

Considering the different service types, the liner services prove to be the best performing and most cost-efficient service type (see Fig. 2 and Fig. 3). Even throughout the synopsis of all considered scenarios, the liner serves yield the best results in comparison with the residual service types.

However, the direct traffic scenarios prove to be competitive despite their relatively high number of routes and the massive increase in the number of inland vessels for the northbound extension of the service area. It is capable of offering high average service levels while remaining economically competitive enough with a noticeable advantage over road transportation (see Fig. 2 and Fig. 3).

The hub-and-spoke system, on the contrary, is severely limited in its operation. A realistic potential hub in the center of the canal network has only limited availability of berths as the majority of transshipment points in the central region have not been designed for the number of simultaneous transshipment operations required of the hub. The identified hub location is realistically capable of handling merely three vessels at a time and, thus, cannot provide the needed transshipment capacity. Additionally, the routes between the hub and the destination ports at the Rhine need to handle almost the entire transport volume as they are limited by the vehicle capacity and the high number

of inland vessels. This again puts additional strain on the central hub. All these reasons lead to a reversed structure of the key performance indicators for the hub-focused scenarios, as can be seen in Fig. 3. This is reflected in the disadvantageous cost structure. Consequently, the overall costs per TEU-kilometer rise significantly as penalty charges are applied for long storage times in ports.

Another aspect worth discussing is the effect of accommodating both westbound and northbound containers (instead of westbound containers only). While the service with westbound container flows already shows good results, the service improves even further with the expansion. Thus, the introduction of additional liner services toward the inland hub of Minden results in a performance stabilization or even improvement, e. g., regarding vehicle capacity utilization and minimum service level. In Scenarios 8 and 9, this improvement is achieved through the introduction of additional routes and vessels as the additional container volume is sufficient to offset the additional costs and eventually result in a small increase in the costs of the canal leg and no effect on the costs of the total leg.

5 Conclusion

The article presents the case of decentralized waterborne container transportation service in the West German canal network designed as a feeder shuttle between the inland hubs in the hinterlands of the seaports of Belgium, the Netherlands, and Germany. The service concept needs to be examined in order to determine the best-performing scenario among multiple conceivable scenarios and to assess its respective economic viability. With the help of discrete-event simulation, various scenarios have been selected as the most promising ones and examined with an appropriate DES model of the envisioned transport service in order to determine operational parameters, such as routes and ports to be served, vessel types and related capacities to be used, manning regimes to be applied, and transshipment concepts to be pursued.

Various alternative configurations have been examined and compared with each other so that the effects of the variations of service type, i. e., liner service, direct traffic, and hub-and-spoke system, service area, i. e., only for westbound containers or also for northbound ones, operation modes, or manning regimes on the vessel can be derived from the multitude of simulation runs.

The results reveal that a bidirectional liner service between the destination ports at the Rhine and the Weser serving, ideally for both west- and northbound containers, with a 24-h operation appears to be the best scenario from an economic perspective.

6 Outlook

Based on the results, the scenarios need further variation in order to move away from the exclusive consideration of a particular service type on all routes and destinations and to replace the approach with a blend of a different, relation-specific configuration of the transport routes.

Furthermore, the effect of future operation modes, such as one-person operation, remote control, and fully automated operation, needs to be examined as they appear as promising next evolutionary steps of the concept.

Likewise, the integration of waterborne container transportation with more sustainable and emission-reduced modes of transport on the first or last leg in order to achieve a better ecological footprint deserves further attention and examination. For instance, the use of heavy-duty electric vehicles could be an option.

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