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Elevating the logistics resilience of the Rhine-Alpine Corridor with the help of innovative vessel and cargo handling concepts

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Abstract

The Rhine-Alpine Corridor connects 70 million inhabitants and is home to Europe's biggest sea and inland ports and the Rhine as its most important waterway. Recent developments and events, such as the extreme low-water period in 2018 and the aggravating barge congestion in the seaports, have deteriorated the trust in the inland waterway network capacity of the Corridor. Hence, the availability and trustworthiness of IWT as a reliable transport mode is diminishing – possibly endangering the ambitious modal shift goals. In order to elevate logistics resilience, the challenges of low-water navigability and barge congestion are to be tackled with new solutions from naval architecture and marine engineering, i. e. innovative vessel concepts to ensure low-water navigability on the Rhine and a modular mobile terminal for additional transhipment capacity in the ports. The resulting concepts will be further examined regarding their operational verification and economic validation before being developed and deployed in their real settings.

Keywords: Inland waterway transport; inland vessel; low water navigation; cargo handling; logistics resilience; transport efficiency;

1. Introduction

With increasing global trade and the steadily increasing size of the seagoing container vessels, the ports had to grow themselves and improve their hinterland connectivity. The two biggest seaports of Europe are part of the Rhine-Alpine Corridor, which is the spine of the so-called Blue Banana, an urbanized corridor from Northwest England to Northern Italy with approx. 111 million residents in total.

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The Rhine-Alpine Corridor features an annual cargo throughput of 1 billion tonnes and an efficient traffic network for road, rail, and inland waterway transport (IWT), which forms the base for efficient transport of such large volumes. Apart from the Rhine as the central traffic artery of continental Europe, the IWT network consists of a series of tributaries, such as the rivers Meuse, Moselle, Main, and Neckar, and is connected to adjacent waterway regions, such as the Danube, the Seine, and the West German canal network including the Mittelland Canal.

Recent developments and events, however, have deteriorated the trust in the inland waterway network capacity of the Rhine-Alpine Corridor. The extreme water periods in the past years, particularly in 2018, belong to the most severe developments among them. Same applies to the pressing problem of long waiting times of inland vessels in seaports due to congestion. The waiting times of inland vessels in the ports of Rotterdam and Antwerp can amount to 120 hours and 70 hours, respectively. As a consequence, availability, and trustworthiness of IWT as a reliable transport mode is diminishing – possibly leading to adverse effects in terms of achieving the ambitious goals in modal shift, emission reduction, and climate protection.

2. Problem statements

2.1. Extreme low-water conditions on the waterway stretches

The European network of inland waterways has a total length of almost 40,000 kilometres. These waterways are divided into navigable rivers, which may be free-flowing or regulated with weirs and locks, lakes, and artificial canals. The Rhine-Alpine Corridor covers waterways of about 1,700 kilometres, mostly unregulated rivers. In contrast to the infrastructure of other modes of transport, waterways take on an essential additional task in the form of drainage of precipitation water. The related fluctuations in the water levels are significant. For example, the highest navigable water level at the Duisburg Ruhrort gauge is 1130 cm, and in October 2018, the lowest water level was reached at 153 cm. Both extremes affect inland waterway transport performance when navigation is suspended or the cargo capacity of the inland waterway vessels (IWV) is reduced.

Fluctuating water levels are in the nature of free-flowing rivers. Extreme low water periods, which are the focus of the NOVIMOVE project, have been observed at irregular intervals since records began. In the period from 1971 to 2018, however, the equivalent discharge was only undershot on a below-average number of days per year. This equivalent discharge represents a statistically determined reference water level (GlW) which is undercut on 20 ice-free days in a 10-year average. For each section of the river's discharge and associated gauge, readings with the target depth of the fairway are defined. They are reviewed and adjusted, if necessary, about every 10 years.

For the Rhine, detailed hydrologic data including spatial resolution and time series was made available by the German Federal Institute of Hydrology (BfG). This dataset is part of the raw data, which is further aggregated at the BfG for the "climate level". It is generated from a meteorological data collective (Metstat) using an in-house water balance model called LARSIM-ME, a 1D hydrodynamic model (SOBEK), and a high-resolution digital terrain model (DGM-W) (Nilson et al., 2020; Notteboom & Konings, 2004). The year 2018 with extreme low water levels was selected for an in-depth analysis. Along the section from Krefeld-Uerdingen (km 763) to the Dutch border (km 857.7) this target depth has its highest value at 2.8 m. In 2018, however, the GlW was undercut for more than 140 days. This consisted of an average of around 20 days between 2.8 m and 2.5 m, 80 days between 2.5 m and 2.1 m and 25 days between 2.1 m, and 1.9 m. On the shallowest spots of the fairway, the water depth fell below 1.9 m for up to 25 days.

The section from Koblenz (km 592) to Krefeld-Uerdingen (km 763) has a target depth of 2.5 m. The corresponding water level here was undercut on almost 140 days as well. Focusing on the shallowest sections, the fairway depth was below 1.7 m for up to 40 days. From Iffezheim to Mainz (kms 334 to 497) as well as St. Goar to Koblenz (kms 557 to 592), the Rhine is indicated with a target depth of 2.1 m. Here again, the corresponding GlW was undercut for more than 140 days at the shallowest spots. In four places, the depth of 1.7 m was undercut for almost 100 days. Fig. 1 illustrates the undercutting days in 2018 for selected bottlenecks and locations. It can be seen that upstream of Duisburg-Ruhrort the probability of shallow water is significantly higher. From the German-Dutch border, the Waal is the major waterway connecting the Port of Rotterdam. For cargo flows up to Duisburg like the large pushed convoys that supply the steelworks in Duisburg with coal and iron ore, the critical stretch is the Waal where significantly lower water depths than targeted based on the discharge were observed in 2018 (Centraal Overleg Vaarwegen, 2018).

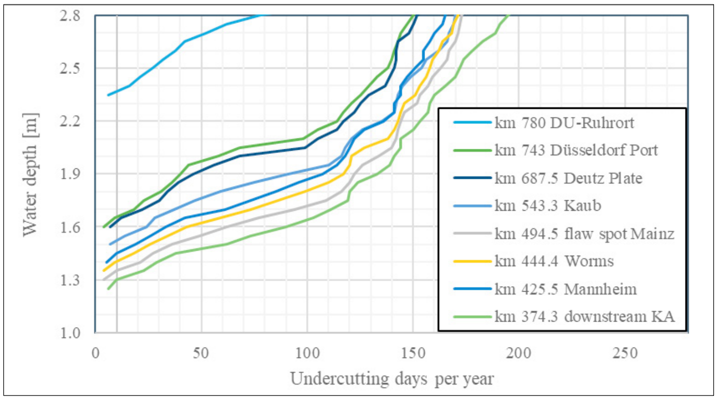

Fig. 1. Detailed view of water depth per days in 2018 at selected bottlenecks.

In addition to the irregular fluctuations in discharge and water depths known from history, climate change is expected to influence precipitation distributions. Earlier snowmelt in the mountains alone may lead to a prolongation of summer low-water periods.

2.2. Seaport congestion

The waiting times of inland vessels in the ports of Rotterdam and Antwerp can amount to 120 hours and 70 hours, respectively, which leads to invalid schedules and delayed hinterland transport for pick-up and delivery purposes. These excessive and highly volatile waiting times are a result of a series of influential factors. To these belong long waiting times of inland vessels at the various seaport terminals, long handling times at the terminals, long dwell times in a port, and lacking scheduling across the various seaport terminals (BAG, 2019, p. 8; Contargo GmbH & Co. KG, 2021; van der Horst et al., 2019).

One major reason behind the long waiting times of inland vessels at the terminals is the limited berthing and handling capacity at seaports for which several ships, i. e., large ocean-going vessels, feeder vessels, and smaller inland vessels, compete at the same time. All these vessels are usually loaded and unloaded at the same quayside. Especially during peak times, when several large seagoing vessels have to be served at the same time, peak loads occur at the terminals. In the event of existing bottlenecks in handling capacity, ocean-going and feeders' vessels are generally given priority ahead of inland vessels as larger vessels have higher operating costs. Further, the pick-up and drop-off time slots for inland vessels are being tightened due to aggravating trend of increasing sizes of ocean container vessels. (BAG, 2019, pp. 8, 11; Contargo GmbH & Co. KG, 2018).

In addition, the long handling times are rooted in the more difficult and, therefore, more time-consuming processes of precise loading and unloading of inland vessels due to the large distance between the operator of the high and expensive container gantry cranes on the quay and the inland vessel (BAG, 2019, p. 8). Separate inland quays with specialized, less high cranes used exclusively for handling inland and coastal vessels promise to speed up vessel handling but are a modern phenomenon in its infancy so far.

The dwell time of inland vessels in a seaport is strongly linked to the large number of seaport terminals it has to call at. In Rotterdam, for instance, the average number of visited terminals per vessel ranges between six and eight. As a result of various new openings of seaport terminals, the complexity of throughput planning for inland vessels has increased accordingly (BAG, 2019, pp. 8–10). In order to avoid providing valuable and scarce capacity for minimum volumes, terminals define certain numbers of containers as minimum batch sizes in order to achieve a bundling effect.

Likewise, the lacking scheduling of incoming and outgoing inland vessels across the various seaport terminals remains an unsolved issue. During their stay in Rotterdam and Antwerp, inland vessels typically call at several container terminals for loading and unloading. A delay at one terminal affects all other terminals on the itinerary of a vessel because agreed time slots cannot be met due to the delays incurred earlier and substitute capacity is not always available. This leads to an exacerbating domino effect on waiting times of inland vessels (BAG, 2019, pp. 8–9).

In order to underpin the above-mentioned challenges with data, geospatial analysis of the movement of the inland vessels in the seaports of Rotterdam and Antwerp has been conducted (van Hassel et al., 2021). Both in terms of waiting times of inland vessels and further challenges, e.g., the level of inter-terminal transfers within ports, can be made visible by means of geographical models. In the present case, the AIS data has been retrieved from a German vendor of data on global (historical and real-time) vessel position tracking information.

With the help of detailed event logs and timestamps of AIS data for inland vessels visiting the ports, light is cast on time profiles of waiting times and operational times, such as sailing inside the port, waiting for a berth, operation at the berth, or lock operation.

The following heat maps (see Fig. 2a) illustrate the situation for inland vessels between Oct 2020 – May 2021. Red sections indicate a higher number of vessel instances recorded at each of these positions, e. g., while waiting at a particular location or during berth operations. In the case of Antwerp, the heat map shows the hot spots around the Deurganckdok terminal and the Noordzee terminal, both of which are frequented by container vessels calling at the port. However, the plot is also red at two other locations – east of Doel and south of Lillo, both of which were identified as designated waiting areas for vessels. It can be concluded that the average waiting time for the considered vessel was 19.72 hours per port visit, while the average number of terminal calls per port visit was four. It can also be observed that if the number of terminal visits per port call increases, then the berth time at the terminals will increase.

Based on the same dataset also the port of Rotterdam was analysed (see Fig. 2b). The heat map shows hot spots around Maasvlakte (APMT, RCT, and Delta terminals) in the west and Eemhaven on the east end. It can be seen that there are large concentrations of vessels waiting at Maasvlakte. It can be concluded that the average time at a terminal amount to five to six hours in Maasvlakte and above 2.5 hours in Eems- and Waalhaven, respectively. With six to eight terminal calls per port visit, one port call in Rotterdam can hence take over 24 hours.

Fig. 2. Inland container vessel positions in the ports of (a) Antwerp (left) and (b) Rotterdam (right)

3. Solutions

3.1. Innovative vessel concepts to address extreme low-water conditions on the critical waterway stretches

During the last 50 years, economies of scale and several decades without extreme low water periods before 2018 led to larger ships. In the event of overcapacity, mainly small ships were scrapped based on economic efficiency. The freight structure effect of the transition from bulk goods to general cargo and the increasing share of time-critical unitized cargo additionally led to an increased vulnerability of inland navigation. Most IWVs were optimised for maximum cargo carrying capacity as well as safe and efficient propulsion. With ducted propellers, as the most common propulsion, a power of about 400 kW/m² and a thrust at bollard pull conditions of about 70 kN/m² can be transmitted into the water. This results in a physical lower limit of the propeller diameter. Reducing the thrust load by increasing the propulsor area leads to higher propulsive efficiency. According to these principles, the propeller diameter is usually larger than the empty draught. Without sufficient cargo, ships are ballasted. For large Rhine vessels, propeller diameters of 1.75 m for single-screw ships and 1.6 m for twin-screw ships are common. Depending on the shape of the aft body and the propeller diameter, every IWV has a minimum draught for safe navigation. If the draught is too low, too much ventilation occurs, and the required thrust cannot be generated. Modern inland ship designs with optimised propeller tunnels allow a minimum draught of approximately 75% of the propeller diameter.

To improve the low-water navigability of the fleet, several options exist: A permanent ship design optimized solely for low water levels, a ship design capable of being adapted to low-water conditions for days or weeks, an inland vessel able to adapt (i. e., reducing draught) for shallow parts of a journey, and a local solution for short distances like the use of a dock ship. Due to the extremely long lifecycles of inland vessels, above 60 years on average in some fleet segments, retrofittable solutions are of utmost importance. Based on the cargo flow analysis and the existing fleet, it was decided to use the large Rhine ships (CEMT Va) with 110 meter in length and 11.4 meter in width as the base case vessel. The minimum draught of an existing IWV can be slightly reduced by local changes to the aft hull and the propulsor. The cargo capacity at this draught, however, can be increased by adding buoyancy.

Temporary adjustment of ship buoyancy is no new idea. While previous projects already considered approaches like so-called steel side blisters, inflatable blisters and foldable buoyancy elements as theoretical concepts, NOVIMOVE has the ambition to bring added-buoyancy concepts to a higher TRL (Zigic et al., 2012). The corresponding work includes iterative detailing of hydrodynamic characteristics, regulatory and operational aspects, related investment costs (CAPEX) and operating cost (OPEX), as well as structural design.

A transforming Surface Effect Ship, with two demi-hulls that can be separated to accommodate an air cushion to reduce draught, was developed. However, due to the high complexity, the related costs and the lack of business case, the work is refocused on more promising concepts. For newly built IWVs, these are retractable side boxes, which are stored on the sides in normal operation. In low water periods, they are unfolded, locked in place, and filled with air. For the existing fleet, so-called pipe-based buoyancy (PBB) and inflatable buoyancy, comparable to existing salvage bags, are considered. Fig. 3 shows a scale model of a CEMT Va ship in the large shallow water basin at DST with one PBB on each side. Here, the added resistance was reduced with faired front ends and sufficient thrust was generated despite ventilation. The achievable speed is limited by the small under-keel clearance and the associated risk of grounding. This results in a power demand significantly below the values with loaded draught and at higher speed.

Fig. 3. Impressions from extensive hydrodynamic model tests with added buoyancy (left) and ventilating propulsors (right).

3.2. Modular mobile terminals to tackle barge congestion in seaports

Principally, the approaches to solve the barge congestion problem in seaports can be categorized into four major categories: feeder and influx control, consolidation, inter-terminal transfer, and further isolated measures. In order to coordinate the feeder loops and to control the influx of inland vessels into a port area, a digital feeder and berth management system is implemented in a number of western European ports. By means of available berths, the timely coordination of the vessels according to the respective utilization status is possible, whereas a lack of such berths puts the system easily under pressure. These digital platforms involve nearly all stakeholders and offer far more services than only the sheer berth allocation (BAG, 2019, pp. 14–17).

Another approach to tackle the congestion issue of inland vessels in seaports is consolidation which can take place in different forms in the hinterland terminals of the seaports, e. g. the destination-specific pre-soring to achieve minimum quantities, the modal shift of hinterland traffic, the development of inland ports as hinterland hubs, the cooperation of inland ports to achieve scale economies, the bundling of cargo on floating or moving terminals, or the cooperation between intermodal operators (BAG, 2019, pp. 17–19).

Directly linked to the consolidation idea is the introduction of so-called inter-terminal transfer (ITT) services allowing customers to visit one or several decentralized transhipment points and to leave the further haulage to the respective destination terminal to a service provider in the port ecosystem. Thereby, inland vessels can avoid having to call at multiple port terminals. However, only a few of these services have been realized into practical use yet, as it remained unclear who was to invest and who would gain the profit (Hu et al., 2018; Hu et al., 2019).

The aspects described above for improving barge handling in seaports can be supplemented by a wide range of further isolated measures – such as dedicated quay and crane capacity for inland vessel transhipment, improved communication between all stakeholders, or the use of the opportunities offered by digital applications and platforms (BAG, 2019, pp. 19–20; Kotowska et al., 2018; Shobayo & van Hassel, 2019).

In the NOVIMAR project, the concept of a modular mobile terminal (MMT) was conceived as a potential solution to reduce the waiting time for IWVs at the busy seaports (Ramne & Fagerlund, 2019). The concept is further developed in the follow-up NOVIMOVE project (Ramne et al., 2021). The envisaged operation is that an IWV collects cargo from inland waterway terminals, where the cargo has different destinations, i. e., different seaport terminals. Currently, when the IWV reaches the seaport, it calls at all the terminals required to drop off the cargo aboard and, possibly, visit additional terminals to collect the import cargo for the subsequent upstream journey.

By providing a consolidation and distribution station, it will be possible to eliminate the need for the IWVs to call multiple terminals and also reduce the waiting time. The mobile terminal will be the interface for the inland waterway vessel when delivering and collecting containers to and from the seaport terminals. This will reduce the number of calls for the IWV. The containers will be shuttled from the mobile terminal handling area to the seaport terminal in barges that constitute modular units of the mobile terminal. Each barge will make a dedicated call at a seaport terminal carrying a, more or less full, barge load to be unloaded and, thereby, being prioritized as opposed to today.

The modules of the terminal have different configurations. The simplest version is the base module which is a simple barge that is pushed or towed between the mobile terminal handling area and the seaport terminal (see Fig. 4). The base module has the main dimensions of 54.06 meter in length, 17 meter in width, and a max. draught of 3.2 meter. For the handling of containers at the MMT, at least one crane module is required (see Fig. 5). The IWV is moored against the MMT block, and the containers are transferred between the vessel and the barges by the crane barge. The MMT can be used both for export and import flows. At the export MMT, the containers on the IWV are unloaded to the barges, one barge for each of the terminals to be served. When a barge is full, it is transferred to the corresponding terminal immediately or according to a predetermined schedule. For the import flow, each import MMT has a number of inland terminals that it serves. The containers in the different seaport terminals with destination to any of these inland terminals, are loaded onto a barge and transferred to the MMT location. At the MMT, the containers on the barges are distributed to vessels with the relevant destination.

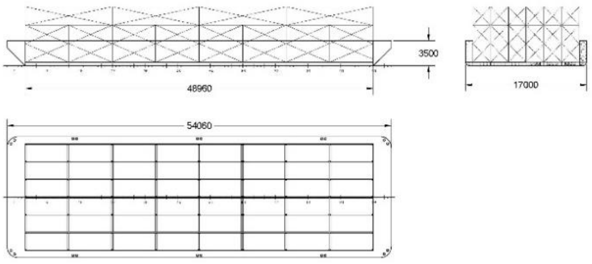

Fig. 4. Base module of the modular mobile terminal

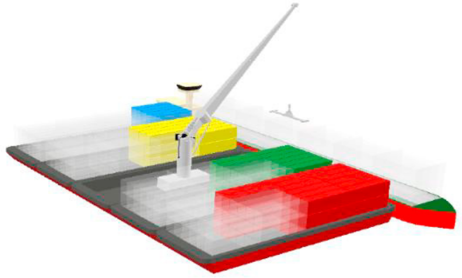

Fig. 5. Typical MMT configuration of the modular mobile terminal

For the transfer of the barges between the seaport terminal and the MMT, the barge can be pushed or towed by a harbour tug, or it can be equipped with a propulsion unit. The propulsion unit is a self-sustained unit with the size of a 20-feet container. The containerized propulsion units (CPU) will contain the power unit and possibly also the energy storage. The thruster will be attached to the aft end of the CPU and reach down into the water aft of the transom of the barge. The CPU will be positioned on the aft deck towards the centre line, leaving space for mooring equipment towards the sides.

The MMT provides an additional degree of freedom for seaport logistics. Moreover, the benefits of the MMT are reduced waiting times for the IWV and increased efficiency of the seaport terminals by reducing the number of calls of barges with (too) small lot sizes. The concept, however, will induce additional cargo handling operations and costs.

4. Related Work

Strengthening IWT services in the hinterland is a focal activity of many seaports with a suitable hinterland waterway network (Notteboom, 2007). Therefore, opportunities for better hinterland access via waterways must be exploited. One of the opportunities lies in greater cooperation and coordination among inland terminals, leading to the optimization of container flows to seaports. (Caris et al., 2011; Caris et al., 2014; Langen et al., 2006). Another way to improve waterborne seaport hinterland traffic is to rethink the supply chain and integrate IWT into existing planning and monitoring solutions (Caris et al., 2014; Platz, 2009).

Seaports have already highlighted the inland waterway reliability issues resulting from barge congestion at seaports, particularly along the Rhine-Alpine Corridor (Konings, 2007; Oganesian et al., 2021; van der Horst et al., 2019). Multiple solutions have been developed and implemented in the seaports to alleviate the situation noticeably (Caris et al., 2011; Oganesian et al., 2021). In addition, there are numerous approaches to optimizing terminal operations across all modes (Kastner et al., 2019; Shobayo & van Hassel, 2019).

Heilig and Voß (2017) provided a thorough overview of literature about ITT and proposed a research agenda around gaps in ITT-related topics. It is striking though that waterborne concepts of ITT are scarce. In addition, the concept of ITT has been examined in detail in the ontology by Vries (2013), while potential applications for the port of Rotterdam were evaluated in 2014 with discrete-event simulation (Schroër et al., 2014).

The idea of using decentralized facilities as a potential solution to hub congestion has already been proposed by Slack (1999). Such a remote terminal for barges has been considered for the port of Rotterdam (Froeling et al., 2008; B.-J. Pielage et al., 2007). The use of a mobile terminal for the port of Rotterdam was first considered in 2001 (Ottjes, 1994). The idea has been reimagined multiple times in the form of floating cranes or the so-called Port Feeder Barge – there and elsewhere (Malchow, 2014; B.-J. A. Pielage et al., 2008).

5. Conclusion & Outlook

The Rhine-Alpine Corridor is the central traffic artery of continental Europe, serving the significant Blue Banana region with transport services for import, export, and continental cargo. In order to safeguard the reliability and efficiency of the Rhine-Alpine Corridor and, thereby, elevate the logistics resilience of the corridor, both the challenges of navigability restrictions in extreme low-water periods and barge congestion in seaports need to be addressed effectively. The research article presents the results of a thorough analysis of the underlying reasons and evident symptoms, and shows the technical solutions designed and developed based on the preceding analysis. Valuable feedback is received from relevant stakeholders directly involved or linked to the NOVIMOVE project or via presentations in events of the inland navigation sector.

The resulting vessel and cargo handling concepts are destined to address the identified challenges effectively and will be further examined with respect to their technical and operational verification and their economic validation. In addition, the concepts will be examined with the help of a discrete-event simulation of the (future) logistics processes with the presented innovations involved – in order to show the high resilience.

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