Chapter 16
Technological Challenges and Developments in European Inland Waterway Transport

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Abstract In many parts of the world, vast quantities of goods are transported over rivers and canals by means of ships and pushed convoys. This makes these waterways important transport corridors. Of all modes of transport, inland waterway transport has the strongest interaction between infrastructure and the vessels/vehicles that perform the transport. Locks, bridges and waterway depth limit the dimensions of vessels that are used in all directions, while the water depth, fairway cross-section and flow speed of the water have a significant impact on the speed and fuel consumption of these vessels. This in turn influences the cost of transport and thereby the economic viability of transport over water. In this chapter, the interaction between ship and waterway and its impact on the economic viability of inland shipping is highlighted, followed by a discussion of the recent and ongoing efforts to innovate the design of inland ships with the aim of minimizing transport cost and emissions. This is followed by a case study in which the dimensions of inland tank ships that are intended for operation on the river Rhine are optimized, taking into account the properties of the waterway and the boundary conditions that are imposed by the transport chain in which the ship operates. Finally, on the basis of this case study and the discussion of recent and ongoing innovations, possible approaches for optimization of inland waterway transport and inland ships are discussed.

16.1 On the Interaction Between Ship and Waterway

The interaction between a ship and the waterway on which it sails is a crucial factor in the economic viability of operating this ship and, therefore, in the viability of inland waterway transport on a given waterway. This section will elaborate on which factors influence the competitiveness of inland shipping and how these factors are affected by the interaction between ship and waterway.

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Table 16.1 Cost breakdown for a large Rhine vessel [1]

Labor	42 %
Capital cost	30 %
Fuel	14 %
Repair and maintenance	3 %
Other	11 %

In a market such as that of intra-continental transport of goods in Europe, direct transport costs are a crucial decision driver for shippers [9, 11]. Often whoever can transport goods at the lowest price will be commissioned to do so, as long as certain boundary conditions regarding service schedule, transport time and cargo carrying capacity of the vessel or vehicle are met. Furthermore, in a highly competitive market, over a longer period of time cost and price of transport will be close together [5]. Since the European inland waterway transport markets for containers, dry bulk and liquid bulk are all highly competitive, lower transport cost per unit of cargo implies a better competitive position of a shipping company. A large part of all inland shipping companies in Europe are owner-operators with a single ship, no office ashore and no administrative staff. E.g., in the Netherlands owner-operators with a single ship account for 89 % of all inland shipping companies [2]. Therefore, the cost of transport is very strongly related to the ship and its operation. As an example, Beelen [1] provides an indicative cost breakdown, as shown in Table 16.1, for a large Rhine vessel, i.e., a dry bulk vessel with a length of 110 m and a beam of 11.40 m, one of the most common vessels in western Europe:

The cost elements in Table 16.1 will be discussed below in order to create a further understanding of the influence that the properties of a waterway have on the viability of inland waterway transport.

Labor costs are strongly dependent on the crew requirement of a ship, which in western Europe is prescribed by regulations by the CCNR [3]. According to these regulations, the number of crew members and their job description are dependent on the operational profile of the ship (14, 18 or 24 h per day, represented by the codes A1, A2 and B), the length of the ship, the level of equipment on board (coded S1 or S2) and whether or not any barges are pushed. A small part of these regulations, for ships not pushing barges, is shown in Table 16.2.

Since the crew requirement is partly determined by the size of the ship, but is not linearly dependent on its cargo carrying capacity, ships of different sizes will have different labor cost per ton of cargo carrying capacity. As a rule, the larger the ship, the lower the labor cost per ton of cargo carrying capacity will be. Since the maximum size of a ship is typically determined by the length and width of the locks in its intended area of operation, the depth of the fairway and/or regulatory limits that are associated with the properties of the waterway itself, there is a strong link between these waterway properties and the labor cost of transport by inland ship. What the maximum size of ship is that is allowed to sail on various European waterways, is clarified by means of a classification system that is developed by CEMT [7]. Table 16.3 shows a part of this classification system.

Table 16.2 Crew regulations

Class	Crew	A1		A2		B	
		S1	S2	S1	S2	S1	S2
L ≤70 m	Captain	1		2		2	2
	Helmsman	–		–		–	–
	Full sailor	–		–		–	–
	Ordinary sailor	1		–		1	–
	Basic sailor	–		–		1*	2*,***
70 <L ≤86 m	Captain	1 or 1	1	2		2	2
	Helmsman	– or –	–	–		–	–
	Full sailor	1 or –	–	–		–	–
	Ordinary sailor	– or 1	1	–		2	1
	Basic sailor	– or 1	1	1*		–	1
L >86 m	Captain	1 or 1	1	2	2	2 or 2	2
	Helmsman	1 or 1	1	–	–	1 or 1**	1
	Full sailor	– or –	–	–	–	–	–
	Ordinary sailor	1 or –	–	1	–	2 or 1	1
	Basic sailor	– or 2	1	1*	2*	– or –	1

*The basic sailor or one of the basic seamen may be replaced by a deckhand
**The helmsman needs to be in possession of the patent required by the Rhine patent rules
***One of the basic sailors must be over 18 years of age

Table 16.3 CEMT classes and ship dimensions (partial)

Waterway class	Maximum length (m)	Maximum beam (m)	Maximum draught (m)
I (West of Elbe)	38.5	5.05	1.8–2.2
II (West of Elbe)	50–55	6.6	2.5
III (West of Elbe)	67–80	8.2	2.5
IV (West of Elbe)	80–85	9.5	2.5
Va (West of Elbe)	95–110	11.4	1.8–2.5–2.8
⋮			

In practice, the dimensions of the majority of ships that are built are just below these maximum dimensions or the length at which the crew complement needs to be increased, as shown in Table 16.2.

The second major cost component in Table 16.1 is capital cost. Like with labor cost, capital cost of a ship is not linearly dependent on its cargo carrying capacity. EICB [6] provide some figures: a ship with a cargo carrying capacity of 450 tons costs around 1.2 million Euro, while a 1,500 ton ship costs around 2.5 million Euro and a 3,000 ton ship costs around 3.5 million Euro. Since these figures imply lower capital cost per ton of cargo carrying capacity for larger ships, this again demonstrates that larger ships, which require larger waterways, have a definite cost advantage over smaller ships.

The third major cost component from Table 16.1 is fuel consumption, the prediction of which is still one of the main scientific challenges in inland waterway transport. The actual fuel consumption of an inland ship is strongly dependent on many factors. When water is wide and deep, for instance in oceans, the relation between the speed and fuel consumption of a ship is roughly quadratic: if a ship sails twice as fast, it will require roughly four times as much fuel to get from A to B. How much fuel that is, in turn depends on the size of the ship, its shape and the properties of its propeller(s) and drive train. It, however, also depends on other factors that are not part of the design of the ship itself such as the wind, waves and current that the ship encounters and the amount of marine growth on the hull (i.e., barnacles, algae, etc.).

When the water in which a ship sails gets shallow and/or confined, for instance on a river, there is further interaction between the waterway and the ship. Shallow water will limit the maximum speed of the ships to roughly the root of the gravity constant multiplied by the water depth: $v = (gh)^{0.5}$. When the ship's speed approaches this speed, its resistance rises rapidly. As a result of this, in practice inland cargo ships will not sail faster than 70 % of this speed, which is usually much slower than the normal speed of seagoing ships. This in turn limits the number of trips that a ship can make and thereby limits the amount of cargo that a ship can transport in a given amount of time. When a waterway is not only shallow, but also has a limited width, fuel consumption at a given speed is increased further. In this case, the ship will basically act as a blockage that is moved through the waterway. Since the remaining waterway cross-section at the position of the ship will be smaller than the cross-section in front of the ship and behind it, the flow speed of water along the ship's hull will increase. As a result of this, more power and fuel are needed to propel a ship at a given speed than when it would sail in unrestricted water.

Methods to correct a ship's speed or propulsion power for shallow water effects were developed as early as 1932 by Schlichting [13] and improved in 1963 by Lackenby [10]. Since then several more methods have been developed, but according to Raven [12] "there are doubts on their validity and accuracy", especially in the extremely shallow and confined conditions posed by inland waterways. Furthermore, there are no adequate empirical methods available to assess the impact of some of the specific features of inland ship hulls, such as the tunnels at the aftship or the bow shape, which may be very different from that of seagoing ships. This leaves only model testing or CFD calculations as acceptable ways of predicting a ship's fuel consumption, and in practice this is often considered to be too expensive for Inland ships. Furthermore, these methods also have their limitations and inaccuracies. As a result, it seems safe to conclude that there is often significant room for improvement regarding both the prediction of an inland ship's fuel consumption and the fuel consumption itself.

Apart from the difficulty of assessing the fuel consumption of a given ship in a waterway with a known cross-section and depth, as discussed above, there is the additional complication that these properties are not easily determined. Especially in free-flowing rivers, water depth as well as cross-section will change both in time and in space: The waterway slowly erodes while the current will carry sediment to different locations, thus changing the water depth locally. At the same time, rainfall and/or melting of snow will influence the amount of water that flows through the river at any given time, thereby changing both cross-section and depth. Geographically the waterway cross-section will increase as more tributaries join the river and the cross-section's shape will differ strongly from place to place due to the natural shape of the river and due to manmade obstacles such as groynes.

Summarizing the above, around 90 % of an inland ship's cost is influenced by the properties of waterway on which it sails. This makes inland waterway transport a mode that interacts much stronger with the infrastructure it uses than road and rail. There is, however, still a lot of room for improvement regarding the analysis of this interaction.

In the next section, it is elaborated what ship operators are currently doing to improve the economic and environmental performance of their ships and operations, taking into account the limitations of the waterways. Section 16.3 will discuss a case study on the optimization of ship dimensions, which will put the ongoing scale enlargement of European inland ships in perspective. Section 16.4 discusses the link between transport over water and transport of water. In Sect. 16.5, conclusions are drawn and relevant future research is discussed.

16.2 Recent Developments in Inland Ship Design

There appear to be two major drivers for innovation in inland ship design in the European inland shipping sector: innovations are either focused on reducing costs or on reducing emissions. Both will be discussed in the following sections, starting with the reduction of costs and followed by the reduction of emissions.

16.2.1 Developments with the Goal of Reducing Costs

Especially in Western Europe, the dimensions of inland ships have always been closely related to the limiting dimensions of infrastructure like locks. In practice, many ships have dimensions that are close to the maximum dimensions of the CEMT classes that are shown in Table 16.3. There is, however, a trend towards larger ships, thereby increasing economies of scale. In the last decades, only very few ships are built for class I to III waterways, while more and more ships have main dimensions that are larger than class Va, which essentially limits their operational area to the larger rivers. Figure 16.1, taken from the PhD thesis of Hekkenberg [8] shows a clear increase in the average deadweight of newbuild vessels in the period 1996–2008. This trend is also identified by TNO [14], who on the basis of trend line analysis predict an average increase in cargo carrying capacity of roughly 2 % per year between 2008 and 2020. Furthermore, in 2011, the 147 m long tank ship VT

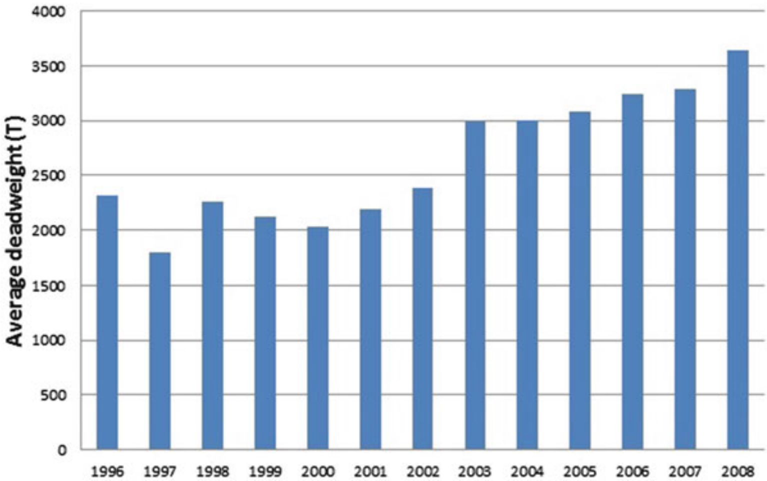

Fig. 16.1 Average deadweight of newbuild ships

Vorstenbosch entered service. This made it the first inland ship in Europe to exceed the length limit for indivisible ships of 135 m imposed by the Central Commission for Navigation of the Rhine (CCNR).

In order to maximize economies of scale for small ships, the Dutch Barge Truck and Q-barge projects looked into the development of small coupled units or push convoys with self-propelled barges, that are able to sail independently on small waterways and can be joined on larger waterways. In Belgium, a similar approach was studied by Van Hassel [16] within the INLANAV project. Thus far this has however not resulted in a significant market uptake of such concepts.

Other efforts to reduce costs through modifications to the ship are mainly found in the field of ship resistance and propulsion. There has been extensive research into the possibility of reducing drag through air lubrication of the hull, e.g., in the PELS and PELS II projects, while more efficient, bio-inspired, alternatives for the ship's propeller have been investigated in the form of the whale tail wheel in the 1990s [15] and, more recently, through a similar concept by O-foil who have built a full-scale system on a 40 m long inland ship in 2013. A different concept, the Futura Carrier, featuring distributed propulsion by means of two steerable propellers at the stern and two at the bow, was developed around 2007. Several vessels of this type were built, but there appears to have been no further market uptake of the concept.

There are also attempts to reduce costs through a more efficient drive train. Diesel-electric and hybrid alternatives to conventional diesel direct drives have been implemented on several vessels such as diesel-electric tank ship Amulet, built in 2010, and hybrid dry bulk ship Semper Fi, built in 2012. Despite claims of significant fuel savings, such vessels, however, remain exceptions and the majority of the newbuild fleet is still diesel-direct driven.

Apart from the scale enlargement discussed earlier, the main innovation that actually appears to get a foothold in the sector is the use of LNG as a fuel. The benefits that are attributed to LNG are that it is cheaper than gasoil and that it leads to lower emissions. Despite difficulties like the absence of bunker stations for this fuel and regulations that forbid its use on board inland ships, the first LNG-driven inland ship, tank ship Argonon, entered service in 2011. Since then, work is done to develop bunker points for LNG and to develop suitable regulations for its application as a fuel for inland ships. Meanwhile several more vessels that are fueled by LNG have been built, several shipyards have developed concepts for such vessels and in 2014, coupled unit Eiger-Nordwand was retrofitted with an LNG installation. However, price development of LNG as a fuel for inland ships remains highly uncertain and as a result, so does the future development of LNG-powered inland ships.

16.2.2 Developments with the Goal of Reducing Emissions

Traditionally, inland shipping is known as a very fuel-efficient and, therefore, environment friendly mode of transport. However, with the introduction of the EURO emission standards for truck engines, inland shipping's main competitor, road transport, has managed to drastically reduce its emissions of NOx and PM (particulate matter). This development, together with the fact that inland ships emitted much more SOx than trucks due to the much higher sulphur content of inland shipping fuel, led to the situation that in the first decade of the twenty-first century, inland shipping in many cases no longer outperformed road transport in terms of environmental performance. Following the development of the EURO standards for trucks, the CCNR I and II standards were developed for inland ships. At the time of writing of this chapter (i.e., 2014), however, the emission limits for these standards are much less strict than those of the latest EURO standards. Nonetheless, there have been several incentive schemes for clean ships, as a result of which a number of catalysts and particulate matter (PM) filters have been installed on board of inland ships, thereby drastically reducing their emissions of NOx and PM. Meanwhile, the emission of SOx has been virtually eliminated because in 2011, the sector switched from the "original" fuel to sulphur free diesel that is also used in trucks, called EN590. The major downside of filters and catalysts is that thus far, they are not profitable investments and there is no outlook that this will change in the future. The investment cost, maintenance cost and, in case of catalysts, price of consumed urea outweigh any potential fuel savings. Therefore, unless external incentives or more strict emission regulations are developed, it seems unlikely that there will be a large scale market uptake of these technologies. There have been a host of projects trying to reduce the emissions, including project CREATING in FP6 (the European 6th framework research programme) and project MoVe IT! in FP7, but thus far, this has not led to generic solutions that have been applied widely.

An alternative to reduction of emissions from diesel engines is the use of other sources of energy. Since solar energy requires large surfaces of solar cells to generate any significant amount of energy and using wind energy is impractical on confined waterways with many (low) bridges, these technologies have not gained a foothold in inland waterway transport. There have been several projects that investigated the potential of hydrogen as a fuel, but they have not been applied to inland ships on a larger scale than river ferries and small passenger boats. For cargo ships, there are too many obstacles like the required volume of the hydrogen tanks, the absence of bunkering facilities and the high price of fuel cells. The only alternative energy source that appears to be really breaking through is LNG, as was discussed in the previous section. It offers an outlook of reduced cost as well as reduced emissions, although the actual costs are still highly uncertain as a result of the uncertainty of the price development of LNG at bunker stations.

16.3 Transport Cost Minimization for Inland Ships: A Case Study

In the previous sections, it was discussed that there are several ways in which the European inland shipping sector has tried, and still tries, to reduce costs and/or emissions. It was also discussed that only a few of these developments are actually taken up by the market. The development that has thus far impacted the market most is scale enlargement. Therefore in this section, a case study is presented to assess how large the benefits of further scale enlargement can be for tank ships on the river Rhine. The details of this study, as well as similar studies for dry bulk and container ships and a description of the models underlying the case study may be found in previous work by the author [8].

16.3.1 Case Setting

In this case, the transport of gasoil from the oil terminals in Rotterdam that are located in close vicinity to the Dintelhaven port basin to Dordrecht (45 km), Nijmegen (136 km), Duisburg (247 km) and Koblenz (430 km) is studied, see Fig. 16.2. The route to each of these locations is free of locks, thereby allowing large ships to reach them. Furthermore, this route is located on the busiest inland waterway stretch in Europe.

To assess to which extent an increase in the dimensions of inland ships will lead to benefits in terms of cost reduction, it is assessed what the out-of-pocket cost of transport, i.e., the amount of money that the shipper will have to pay to the transport operator to transport his goods, will be as a function of the dimensions of the ship that is used. It is also assessed how a shipper's total logistical costs, which includes

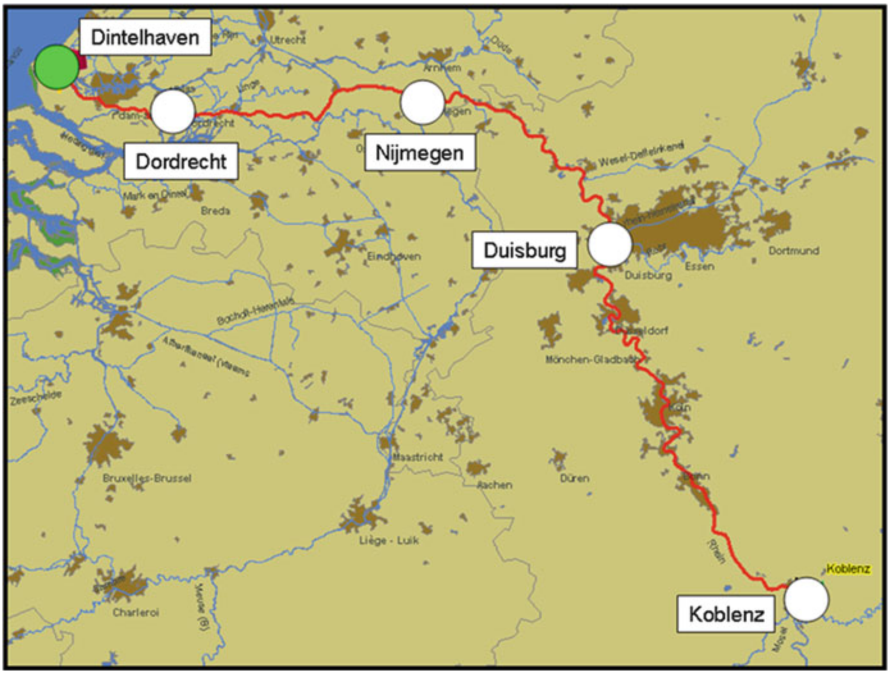

Fig. 16.2 Origin and destinations of the case study, taken from [8]

Table 16.4 Lengths and beams of ship designs

Ship lengths (m)	40	50	60	70	80	95	110	135	160	185
Ship beams (m)	5	6.5	8	9.5	11	12.5	15	17.5	20	25

holding cost of stock, is affected by the use of ships with different main dimensions. Earlier on in this chapter, it was stated that for a market like the European inland waterway transport sector, in the long run the price of transport will be very close to the transport operator's costs. Therefore, in this case the shipper's out-of-pocket costs of transport are assumed to be identical to the transport operator's costs.

For the purpose of this analysis, a series of 518 ship designs with systematically varied length, beam and draught is created. The lengths and beams of the designs are as given in Table 16.4.

Design draughts of the ship range from 1.5 to 4.5 m with 0.5 m intervals, while length to beam ratios of 4 and 20 are used as boundary conditions. This leads to the matrix of designs as shown in Fig. 16.3, in which the smallest ship has dimensions that are close to those of the smallest inland ships that are commercially operated in Europe, while the largest ship has dimensions that are very close to the largest possible dimensions on the investigated route.

To this matrix, a series of additional designs with a length of 86 m are added as well as a series of designs with a beam of 11.45 m, thus including the typical

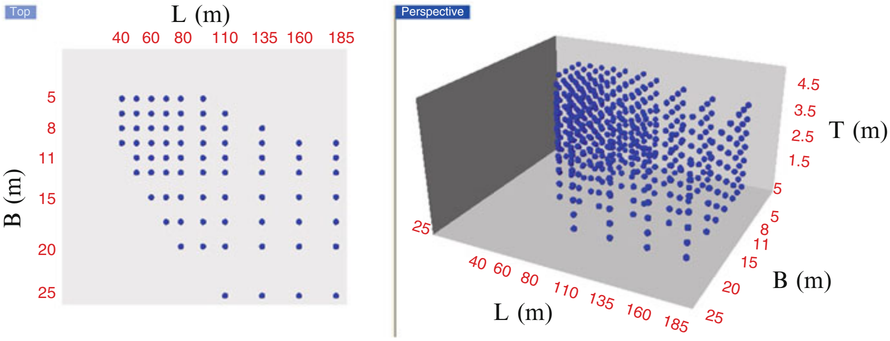

Fig. 16.3 Top down and 3D view of length, beam and draught of developed designs, taken from [8]

length and beam of common European inland ships. For each of the ships in this design set, performance on each of the routes is determined, assuming it sails upstream with as much cargo as possible and returns empty. This performance is determined by a combination of a cost model and a voyage time calculation model. For a given ship design, the voyage model determines the time that is required to make a round trip between two destinations and the amount of cargo that that ship can carry on a waterway with a given water depth. This leads to the number of tons of cargo that can be transported per year. The cost model determines the cost per ton of transported cargo by dividing the sum of annual crew cost, fuel cost, interest cost, depreciation, maintenance cost, insurance cost by the number of tons that are transported annually. These models include several assumptions and choices regarding sailing times, loading and unloading times, crew cost, fuel prices etcetera. These will not be discussed here, but may be found in [8], together with an elaborate description of the models themselves.

As was discussed earlier on in this chapter, the water depth in a river varies over time as well as geographically and is often unknown. Therefore, several water depth scenarios are included in the analysis: in the first scenario, it is assumed that the water depth is large enough to allow all ships to be loaded to their design draught. In the second scenario, the guaranteed water depth of 3.3 m between Rotterdam and Duisburg and of 3.0 m between Duisburg and Koblenz, as described in [4], are used, leading to maximum draughts (Tmax) of 2.8 and 2.5 m respectively. In practice, for a large part of the year, the actual water depth will lie somewhere between the values of these two scenarios. Finally a third scenario where ships have a maximum draught of 1.75 m, representing a period of drought, is added.

Table 16.5 Optimal ship dimensions Rotterdam–Dordrecht

Dordrecht	Tmax = 4.5 m	Tmax = 2.8 m	Tmax = 1.75 m
Optimal dimensions (m)	110 × 20 × 4.5	135 × 17.5 × 3	135 × 25 × 2
Cost percentage			
Optimal (%)	100	100	100
Standard 135 m vessel (%)	114	118	149
Standard 110 m vessel (%)	127	132	170
Standard 86 m vessel (%)	165	126	143

Table 16.6 Optimal ship dimensions Rotterdam–Koblenz

Dordrecht	Tmax = 4.5 m	Tmax = 2.8 m	Tmax = 1.75 m
Optimal dimensions (m)	135 × 25 × 4.5	135 × 25 × 2.5	135 × 25 × 2
Cost percentage			
Optimal (%)	100	100	100
Standard 135 m vessel (%)	124	132	153
Standard 110 m vessel (%)	156	167	196
Standard 86 m vessel (%)	212	152	178

16.3.2 Outcomes of the Case: Out-of-pocket Costs

The first analysis is based on the out-of-pocket costs of transport. For all above mentioned scenarios, the out of pocket costs of transport per ton of transported cargo are calculated for each of the designs using the model that is elaborately described in [8] and the design that leads to the lowest costs is identified. In Tables 16.5 and 16.6, the length, beam and draught of these optimal designs are presented for destinations Dordrecht and Koblenz. Furthermore the performance of these designs, i.e., percentage of incurred out of pocket cost per ton of transported cargo compared to the performance of common vessels with a length of 86 and 110 m, is presented.

From the second row in Table 16.5, it can be observed that in all cases the optimal length is 110 or 135 m and that the width of optimal ship, which is 20–25 m, is significantly larger than the width of common 110 meter long ships which is typically 11.45 m. It is, however, quite close to the dimensions of the largest tank ships that operate on the Rhine. Considering the fact that the largest ship designs in the matrix are 185 m long, it also becomes clear that there are limits to scale enlargement since these very long ships do not emerge as optimal solutions. What also becomes apparent is that it is beneficial to adapt the design draught of a ship to the depth of the waterway, especially if that depth frequently leads to a low maximum draught. In these cases, the cases where the maximum draught is 1.75 m, the cost difference between the optimal ship and standard 110 and 135 m with typical design draughts between 3 and 3.5 m is significantly larger than in cases where the maximum draught is closer to these draughts.

For the much longer route to Koblenz, results are presented in Table 16.6. What becomes apparent from a comparison of Tables 16.5 and 16.6 is that the optimal dimensions do not change much as a function of the distance, but that the difference in cost of the optimal solution compared to standard ships does become larger.

For the intermediate distances, in all cases, the optimal length is 135 m, the optimal beam is 20 or 25 m and the optimal design draught is equal to or slightly larger than the maximum possible draught. Altogether, this case implies that the existing length limit of 135 m for indivisible ships as prescribed by the CCNR does not impede the use of efficient and competitive tank ships. At the same time, it implies that maximizing ship length to this limit, maximizing the beam of the ship and matching design draught to the maximum possible draught can lead to significant transport cost reductions compared to the most common ships. Further analysis, not included in this chapter, shows that these conclusions are hardly sensitive to variations in crew cost, sailing schedule (14, 18 or 24 h per day) or depreciation time of the ship. Therefore the results and conclusions drawn from them are considered to be stable. It is, however, important to realize that these conclusions cannot be extrapolated to container ships and dry bulk ships, because of the different building cost and cargo carrying capacity they have at the same main dimensions. For conclusions on these ships, the reader is again referred to [8].

16.3.3 Outcomes of the Case: Total logistical Costs

For a shipper, not only the out-of-pocket costs of transport are important. He cares (or should care) about his total logistical costs, thus including among other things holding cost of stock, i.e., depreciation of goods, interest on the capital tied up in the goods, warehousing cost and insurance cost. Of all of these items, for bulk goods the interest on capital is the only one that is significantly influenced by the dimensions of the ship, since it determines the batch size in which goods are delivered. The batch size is assumed to be equal to the ship's cargo carrying capacity. Therefore, in the second part of this study, it is also assessed how the combination of out-of-pocket transport costs and interest costs change as a function of the ship's dimensions, assuming that the value of the cargo, gasoil, is 700 Euro per ton, the interest rate is 4 % and the customer's demand is 10,000, 25,000, 50,000 or 100,000 tons per year. Here, out of pocket costs are determined in the same way as in the previous case, while interest costs are determined using the above mentioned value of the goods, the interest rate and the average time that a unit of cargo will be in stock. This average time is based on the shipment size, i.e., the cargo carrying capacity of the ship, and the customer's annual demand. Again, cost calculations, the full details of the case and similar cases for the transport of coal and iron ore may be found in [8].

For the case Rotterdam–Dordrecht, the change of optimal dimensions compared to the case where only out-of-pocket cost is included is shown in Table 16.7. The original optimum mentioned in the table refers to the optimal dimensions on the basis of out-of-pocket costs alone, as described in the previous section.

Table 16.7 Optimal ship dimensions Rotterdam–Dordrecht

	Original optimum (m)	New optimum (m)	New optimum (m)
Rotterdam–Dordrecht		Annual demand 10,000 T	Annual demand 25,000 T
Tmax = 4.5 m	110 × 20 × 4.5	50 × 9.5 × 3	70 × 12.5 × 3.5
Tmax = 2.8 m	135 × 17.5 × 3	70 × 9.5 × 2	70 × 12.5 × 2.5
Tmax = 1.75 m	135 × 25 × 2	70 × 9.5 × 2	80 × 17.5 × 2
Rotterdam–Dordrecht		Annual demand 50,000 T	Annual demand 100,000 T
Tmax = 4.5 m	110 × 20 × 4.5	60 × 11.45 × 4.5	70 × 12.5 × 4.5
Tmax = 2.8 m	135 × 17.5 × 3	110 × 11 × 2.5	110 × 11 × 2.5
Tmax = 1.75 m	135 × 25 × 2	80 × 17.5 × 2	110 × 17.5 × 2

Table 16.8 Optimal ship dimensions Rotterdam–Nijmegen

	Original optimum (m)	New optimum (m)	New optimum (m)
Rotterdam–Nijmegen		Annual demand 10,000 T	Annual demand 25,000 T
Tmax = 4.5 m	110 × 20 × 4.5	60 × 9.5 × 3.5	70 × 12.5 × 3.5
Tmax = 2.8 m	135 × 25 × 3	70 × 12.5 × 2.5	110 × 11 × 2.5
Tmax = 1.75 m	135 × 25 × 2	70 × 12.5 × 2	110 × 15 × 2
Rotterdam–Nijmegen		Annual demand 50,000 T	Annual demand 100,000 T
Tmax = 4.5 m	110 × 20 × 4.5	70 × 12.5 × 4.5	80 × 20 × 4.5
Tmax = 2.8 m	135 × 25 × 3	110 × 11 × 2.5 m	110 × 11 × 2.5
Tmax = 1.75 m	135 × 25 × 2	110 × 15 × 2 m	**135** × **25** × **2**

What immediately becomes clear from Table 16.7 is that in case of a short transport distance like the 45 km from Rotterdam to Dordrecht, holding cost becomes an important factor: in order to keep stocks low, small batches (and therefore small ships) are preferred over large ships with low transport costs.

For the case Rotterdam to Nijmegen, where transport cost is significantly higher than for the trip to Dordrecht, it becomes clear from Table 16.8 that the optimal ship size increases and that it is even identical to that of the base case for the low water scenario with an annual demand of 100,000 tons. Cases where the optimal ship dimensions do not deviate from those of the original case are printed bold in tables 16.7 to 16.10.

In case of transport to Duisburg, in Table 16.9, it can be seen that this effect becomes stronger. Ship sizes increase further and are identical to original optimum more often.

When the transport distance increases further, it becomes clear from a comparison between Tables 16.9 and 16.10 that this does not lead to any major changes in ship dimensions. Apparently, the increase in transport costs for different ships is not large enough to have a significant effect on their ranking.

From the above, it becomes clear that scale enlargement to a length of 20–25 m is possible and beneficial, but that further lengthening of the ships beyond the current maximum length of 135 m does not lead to a clear improvement. These dimensions are in fact quite close to those of the largest tank ships that are currently in operation

Table 16.9 Optimal ship dimensions Rotterdam–Duisburg

	Original optimum (m)	New optimum (m)	New optimum (m)
Rotterdam–Duisburg		Annual demand 10,000 T	Annual demand 25,000 T
Tmax = 4.5 m	135 × 25 × 4.5	70 × 12.5 × 3.5	60 × 15 × 4.5
Tmax = 2.8 m	135 × 25 × 3	60 × 15 × 2.5	80 × 17.5 × 3
Tmax = 1.75 m	135 × 25 × 2	80 × 17.5 × 2	**135 × 25 × 2**
Rotterdam–Duisburg		Annual demand 50,000 T	Annual demand 100,000 T
Tmax = 4.5 m	135 × 25 × 4.5	80 × 20 × 4.5	80 × 20 × 4.5
Tmax = 2.8 m	135 × 25 × 3	135 × 17.5 × 3	**135 × 25 × 3**
Tmax = 1.75 m	135 × 25 × 2	**135 × 25 × 2**	**135 × 25 × 2**

Table 16.10 Optimal ship dimensions Rotterdam–Koblenz

	Original optimum (m)	New optimum (m)	New optimum (m)
Rotterdam–Koblenz		Annual demand 10,000 T	Annual demand 25,000 T
Tmax = 4.5 m	135 × 25 × 4.5	70 × 12.5 × 3.5	60 × 15 × 4.5
Tmax = 2.5 m	135 × 25 × 2.5	70 × 15 × 2.5	86 × 15 × 2.5
Tmax = 1.75 m	135 × 25 × 2	135 × 15 × 2	**135 × 25 × 2**
Rotterdam–Koblenz		Annual demand 50,000 T	Annual demand 100,000 T
Tmax = 4.5 m	135 × 25 × 4.5	80 × 20 × 4.5	80 × 20 × 4.5
Tmax = 2.5 m	135 × 25 × 2.5	**135 × 25 × 2.5**	**135 × 25 × 2.5**
Tmax = 1.75 m	135 × 25 × 2	**135 × 25 × 2**	**135 × 25 × 2**

on the Rhine. What also becomes apparent is that the optimal ship dimensions are not only dependent on the properties of ship and waterway, but also on the volume of goods that is required by a customer. Customers with a limited demand of relatively valuable goods have no benefit from transport by large ships, unless the batches of goods that are delivered to them can be significantly smaller than the cargo carrying capacity of this ship.

16.4 Transdisciplinary Discussion

In this chapter, the optimization of inland ships is discussed. This is part of the optimization of transport over water, but does not explicitly take the transport of water into account. The two topics are, however, closely linked since inland waterways exist only because water is transported from inland locations to the seas and/or oceans. Implicitly, the link between the two topics is incorporated in this chapter through the exploration of the effect of different water depths on the optimal dimensions of inland ships: The more water is transported through a given channel, the higher the water level will be. In practice, it can often be observed that if not enough water is transported through a channel, either permanently or seasonally, measures are taken to ensure that transport over water is still possible by building of dams and locks. This way, a sufficiently high water depth for economically viable waterborne transport of goods is guaranteed at all times.

Especially for free flowing rivers, a unified framework where transport of water and transport over water are more closely linked would be beneficial. As was discussed earlier in this chapter, the dynamics of the water flow through a river lead to ever-changing morphology of the river bed and to different water depths and waterway cross-sections in both time and space. When transport over water is assessed independently of the transport of water, the logical consequence is that water depth and cross-section are assumed static or, at best, quasi-static. In the end, this leads to an inability to properly adapt ships to the actual conditions of the waterway and, therefore, to suboptimal ships. This phenomenon can be observed in the development of inland ships in Europe in the past decade: more and more large-draught ships are built. These ships perform well when water levels are high, but perform poorly when they are low. As long as transport over water and transport of water continue to be analyzed separately, it will remain unclear what the optimal solution for the transport of goods over water is. In a unified framework, optimizing inland waterway transport from a ship-technology point-of-view does become a possibility.

In the research presented in this chapter, several steps have been taken that can be useful in such a unified framework: an approach for the calculation of transport cost for specific transport scenarios, which include water depth, was presented and, more importantly, the technical properties and building costs of inland ships with a wide range of main dimensions have been established. Without this knowledge, it is possible to establish how changes in the transport of water affect transport over water by state-of-the-art ships, but it remains impossible to re-optimize transport over water when the transport of water, i.e., water depth, changes significantly for a given waterway.

16.5 Conclusions and Future Research

In this chapter, it has been clarified that there is a strong interaction between the economic viability of operating an inland ship and the properties of the waterway on which it sails. For a case in western Europe, it was also shown that if the waterway allows it, the use of larger, wider, ships than those that are currently common in Europe can be beneficial. However, further scale enlargement beyond the dimensions of the largest tank ships that operate on the Rhine is unlikely to be beneficial. At the same time, it is concluded that it is not only the properties of waterway and ship that determine the optimum dimensions of a ship. There also needs to be a match between the amount of cargo that is delivered to a customer and that customer’s demand in order to limit the cost of stock.

Regarding innovation in the sector, there have been numerous initiatives to improve the economic and environmental performance of inland ships, but only scale enlargement has actually achieved a significant market uptake. LNG might become the next big breakthrough, but this depends heavily on the development of the price of LNG. Furthermore, many of the developments in the sector are practical in nature, while only a few are based on thorough scientific research.

Anyone who attempts to improve inland waterway transport within Europe should keep in mind that cost is a major decision driver and therefore, any proposal for a perceived improvement that leads to higher costs should include sound argumentation why the perceived benefits of this improvement outweigh the higher costs. It should also be kept in mind that the out-of-pocket costs of transport are only a part of the total logistic costs and therefore that minimization of out-of-pocket costs of transport alone may lead to a false conclusion regarding the optimal dimensions of the ship to be used. This is mainly an issue if a proposed improvement affects the cargo carrying capacity of the ship or, to a lesser extent, the transport time.

A reduction of the out-of-pocket costs of transport can be achieved in several ways, including but certainly not limited to the technological aspects discussed in this chapter. When limiting oneself, however, to these technological aspects, the most striking shortcoming in current knowledge is related to the interaction between ship and waterway: In many cases, the details of water depth and waterway cross-section are unknown, even though they have a significant impact on a ship's speed, fuel consumption at that speed and the cost of transport. Furthermore, even if these conditions are known, there is a lack of good methods to predict speed and fuel consumption for a given ship. This in turn makes it hard to optimize elements of a ship that are related to the hydrodynamics and/or drive train, while also making it hard to predict the benefits of proposed improvements.

To solve these shortcomings, several projects have recently been initiated in the Netherlands. The COVADEM project aims at mapping the waterway through cooperative depth measurements using many cargo ships, while the Top Ships project focuses on powering prediction for inland ships. These projects provide a step in the right direction, but further research on the topic is certainly required. Further ship technology-related topics include the operation of coupled units, i.e., cargo ships pushing one or more barges and the maneuverability of inland ships.

Future research topics that are not related to the technical properties of include the development of more knowledge about the decision drivers of shippers that use inland shipping, the annual volumes of goods that each shipper requires and their geographical locations. Further data on lingering times in ports is also desirable, since this influences the amount of time as ship can actually spend sailing. This in turn has a strong influence its annual transport capacity.

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