Inland Ships for Efficient Transport Chains

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Robertus Gerardus HEKKENBERG

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Dit proefschrift is goedgekeurd door de promotoren:

Prof. ir. J.J. Hopman
Prof. dr. E. Van de Voorde

Samenstelling promotiecommissie:

Rector Magnificus	voorzitter
Prof. ir. J.J. Hopman	Technische Universiteit Delft, promotor
Prof. dr. E. van de Voorde	Universiteit Antwerpen, promotor
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Prof. ir. T. Vellinga	Technische Universiteit Delft
Dr.-ing. C.H.Thill	Development Centre for Ship Technology and Transport Systems (DST)

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To my wife Marloes,
my constant source of joy and support

Preface

In this thesis, I have strived to identify the optimal dimensions of inland ships. These optimal dimensions are not only dependent on ship technology but are also strongly influenced by the economics and market-related aspects of inland waterway transport. As a result, the writing of this thesis has taken me beyond my original training as a naval architect and even beyond the confines of the academic world. I strongly believe that it is not possible to improve inland shipping by just sitting behind a desk at a university. It is crucial to gain at least a basic understanding of how the inland waterway transport sector works in practice.

Therefore, I would like to thank all those that have shared their knowledge about the practice of inland waterway transport with me. I have had the privilege of working with many of you in large and small research projects and several of you have even contributed to the education of my students. In particular, I am indebted to Robert and Robert-Jan Zimmerman of Mercurius Shipping Group. Thank you for your willingness to discuss your views on how the sector works and for your willingness to share technical and cost data of your ships. You have given me crucial knowledge and data that I could never have obtained from literature. Thanks also to Henk Blaauw. Without your ceaseless efforts to improve inland shipping, I probably would never have met so many experts on inland shipping.

For the transport economics-related part of this thesis I want to thank the staff of the Department of Transport and Regional Economics at the University of Antwerp for their hospitality, support and constructive criticism during my 3-month stay in Antwerp. Special thanks to Tom Pauwels. You are probably the most thorough reviewer I have ever met.

Combining the writing of a PhD thesis with a job as an assistant professor implies a continuous tug-of-war between the short term priorities of next week's classes and project deadlines with the long term priority of actually finishing the PhD. Since there is never a shortage of people who will pull the rope on behalf of the short term priorities, I am grateful to those who regularly stepped in to pull the rope on behalf of the PhD, especially to my promotor Eddy van de Voorde and my father in law, Gerhard Hassink. Thanks also to Hans Hopman, my other promotor and head of our department. Not only did you and Eddy van de Voorde spend a significant amount of your time on discussions with me and on reviewing my work, but my PhD also implied that our already understaffed department had even fewer manhours available for day-to-day things.

Of course, my colleagues at Delft University, who have made the past years so very enjoyable, can not remain unmentioned. This page is too short to name all of you, so I will limit myself to my partner-in-crime from the beginning, Jeroen Pruyn. I hope we will continue to work together for a long time.

Last, but certainly not least, I want to thank my wife, family, and friends for their support and for making life in general so enjoyable. In the context of this thesis, I want to name Bart Horsten explicitly. Thanks for our many nighttime discussions about the rigors of doing a PhD and thanks for reviewing this document.

Robert Hekkenberg
Delft, November 26th 2012

Summary

Inland ships for efficient transport chains

The inland waterway transport sector plays a significant role in the transport of cargo to and from several of Europe's main sea ports, annually transporting over 400 million tons of goods. This transport is carried out by roughly 14.000 ships that are mainly operated by captain-owner type companies with a single ship. These small companies have little to no power to influence the market in which they operate and have only a limited number of ways of achieving a competitive edge over other operators. In this thesis one of the promising ways to achieve such a competitive edge is researched.

Captain-owners cannot become more competitive by increasing their market share significantly unless they can set up a cooperation with a large number of other operators. Severe competition and resulting low margins in the main market imply that their profits can only be improved by lowering cost, improving their service or moving into a niche market. Accessing niche markets has, however, proven to be difficult for small operators. Furthermore, the options that are open to a single ship captain-owner to improve his services are limited. He can, however, influence his *costs* in several ways, e.g. through the way the ship is financed, the intensity of operations, the sailing speed or using the ship's design to influence capital and/or running costs.

Several other ways to improve the competitive position of inland waterway transport operators require action by policymakers, e.g. by changing crew regulations, legal waiting times in ports or taxation schemes. These measures, however, mainly alter the competitive position between different modes rather than the competitive position between different inland waterway transport operators. Furthermore, individual transport operators in general do not have enough influence to bring about such policy changes.

This thesis addresses how single ship captain-owners operating in the Rhine region, i.e. the majority of operators in the European inland waterway transport sector, can be empowered to improve their competitive position without having to rely on other parties. This implies that the approach that is followed is to reduce transport cost. While a ship's design has a major impact on the cost of transport, much is still unknown about the relationship between the design of an inland ship and the cost of transport. The research in this thesis will, therefore, focus on cost reduction that is achieved through changes in the design of inland ships.

Main research question

There are various ways to achieve a cost reduction for a transport operator through the improvement of the design of his ship. This includes but is not limited to a lighter structure, larger main dimensions and improvement in propulsion efficiency. In a preliminary evaluation, the improvement showing the largest potential for cost reduction is the increase of the ship's main dimensions. Consequently, this is the research topic of this thesis.

Although enlargement of the main dimensions of inland ships is expected to lead to cost reductions, there are a number of drawbacks associated with this solution, since larger ships lead to lower geographical flexibility and longer handling times. Moreover, when the use of larger ships leads to larger shipments for a single shipper, this will increase this shipper's stock cost. In this case, large ships will not be competitive if they offer transport at the same price as smaller ships, but need to offer lower prices. As a result, it is not only necessary to assess how a ship's dimensions affect the

cost for the transport operator, but also to assess the impact that ship dimensions have on geographical flexibility and the total logistical cost of a shipper.

The abovementioned considerations lead to the formulation of a main research question and 4 sub-research questions. The main research question is:

Which length, beam and design draught of an inland ship lead to the best competitive position for a captain-owner?

This question can only be answered when the following four sub-questions are answered:

1) *What are the practical upper limits for the dimensions of inland ships?*

Answering this question provides insight into infrastructure- and market-related boundaries for the research and prevents false optimums in the form of ships that can operate at very low cost, but may not attract enough cargo to ensure successful exploitation, e.g. because their operation is restricted to a small geographic area in which the demand for transport is limited.

2) *How do the main dimensions of an inland ship relate to its building cost and those technical properties that affect the cost of transport?*

When this question is answered, currently unavailable ship-related data that are required for a proper analysis of the cost and benefits of operating a ship with any combination of length, beam and design draught become available.

3) *How do the main dimensions of an inland ship affect the cost of operating that ship?*

In the highly competitive market of inland waterway transport along the Rhine corridor, over a longer period of time transport prices will be close to the average cost of the operator. Therefore, answering sub-question 3 will allow determination of the extent to which a transport operator can offer transport at a lower price. The answer to this question is not only dependent on the properties of the ship and its cargo, but will also be determined by the characteristics of the transport route and the time that a ship spends in port.

4) *How do the main dimensions of an inland ship affect the total logistical cost of a shipper?*

Although the price that a shipper needs to pay for transport plays an important role in his choice for a transport operator, larger ships that can offer transport at a lower price also imply larger shipments, which will affect his stock cost. As a result, a shipper will not always favor the cheapest mode of transport, but will look for the lowest total logistical cost. Therefore, sub-question 4 needs to be answered in order to be able to determine which main dimensions lead to the best competitive position of an inland waterway transport operator. Apart from the variables that are of importance for sub-question 3, the value of the transported goods and the annual demand of a shipper now become important variables in the determination of the optimal ship dimensions.

When sub-question four is answered, so is the main research question. As a result, it becomes possible to identify the optimal dimensions of an inland ship as a function of the properties of the transport route, the value of the transported cargo and the annual demand of a shipper.

Approach

The first sub-question is answered through an assessment of infrastructural restrictions on the maximum dimensions of inland ships and of the extent to which certain main dimension limit a ship's access to the market. The next steps of the research lead to the ability to determine the relevant performance characteristics of inland ships as a function of length, beam and design draught. These performance characteristics are the amount of cargo that a ship can carry in a single shipment, the building cost of the ship and its operating costs.

Through a review of existing literature, it is established that neither the required data nor the required methods to determine these characteristics for inland ships with non-standard length, beam and/or design draught are available from literature.

Because of the absence of these data and methods and because all three performance characteristics have a complex and close relationship with the design of a ship, a model is developed with which it is possible to create large series of conceptual designs of inland ships in which length, beam and design draught are varied systematically. For these designs, the building costs are established, as are the technical characteristics that are relevant in the determination of fuel consumption and the amount of cargo that can be carried. As a final step with regard to the determination of the technical characteristics of inland ships, rules of thumb for the estimation of the weight and building cost of inland ships are developed.

As a result if this, some crucial gaps in knowledge are filled. It is, however, not possible yet to determine which length, beam and design draught of an inland ship lead to the best competitive position for a captain-owner since the cargo carrying capacity of a ship is not only determined by the specifications of the ship and its cargo, but may also be affected by the depth of the water and the height of bridges. Furthermore, water depth and current speed affect the fuel consumption of a ship and thereby the running cost. At the same time, the length of the route and the time that is spent in port affect the number of trips that the ship can make in a year, which in turn affects the required ship rate per unit of cargo.

To solve these issues, a second model is developed with which the cost of transport by ship and the resulting required ship rate per unit of cargo can be determined as a function of ship dimensions and of the characteristics of the sailing route. With this model, the third sub-question can be answered. The model also allows for calculation of the effect of internalization of the relevant external costs on the required ship rate and a comparison of transport cost between waterborne, road and rail transport. Furthermore, the model allows calculation of the total logistical cost and thereby makes it possible to answer the fourth sub-research question.

In order to answer the overall research question, i.e. to asses which length, beam and design draught lead to the best competitive position for a captain-owner, a number of case studies are executed. In these case studies, the optimal main dimensions of a ship are defined for dry bulk, container and tank ships on four routes (Rotterdam to Dordrecht, Nijmegen, Duisburg or Koblenz) at three different water levels. In each of these cases, the assessment criteria are (A) required ship rate and (B) total logistical cost. To complete the analysis, it is also reviewed to which extent the internalization of external costs changes the optimal dimensions and it is analyzed in which cases inland ships can or cannot compete with road and rail transport.

Conclusions

It is concluded that the practical limits of the dimensions of inland ships that are used in the Rhine region are a length of 186.5 meters and a beam of 22.9 meters. These are the largest dimensions that allow the ship to access the sea ports of Amsterdam, Antwerp, Flushing, Gent and Terneuzen as well as the majority of inland ports along the Rhine. Despite the fact that the CCNR states that the maximum length of indivisible ships is 135 meters, the abovementioned maximum dimensions of 186.5 x 22.9 are used as the upper limits in all analyses. The reasoning behind this is that it is worthwhile to establish if there are significant benefits in using vessels that are longer than 135 meters. If this were so, it would need to be discussed with the CCNR if the length limit could be increased or a technical solution to make a longer ship divisible would need to be found.

The case studies show, however, that the optimal length of inland ships is not often much larger than the maximum allowed length, i.e. 135 meters. Their beam is, however, typically wider than that of existing ships. The optimal design draught of a ship nearly always matches the maximum draught at normal water levels on the transport route, with the exception of container ships, whose optimum design draught never exceeds 3.5 meters.

Which dimensions are optimal does, however, depend strongly on the characteristics of the route and logistics chain. Low value goods and high annual demand by a shipper favor ships with a large carrying capacity while high value goods and/or low annual demands favor smaller ships. Low water depths lead to a low draught which in turn leads to an increase in the optimal length and beam. The long waiting times that can occur in ports reduce the advantage of low round trip times that small ships can have over their larger counterparts if they are handled without delay.

Internalization of external emission costs and changes in the cost elements that make up the required ship rate (fuel cost, crew cost, depreciation time etcetera) usually do not lead to major changes in the optimal ship dimensions since they affect all ships in a similar way. They do, however, have a direct and strong impact on the absolute value of the required ship rate.

Regarding the relationship between ship dimensions, cargo carrying capacity, other technical properties and building cost of inland ships, it is concluded that existing methods were insufficient to determine this relationship with sufficient accuracy. The research that is done in this thesis, therefore, closes a crucial gap in the available knowledge while the rules of thumb for the estimation of weight and cost that are developed provide useful contributions to the accessibility of this newly developed knowledge.

With regard to cost studies on inland waterway transport and intermodal transport, the research shows that the technical characteristics, building cost and operating cost of inland ships are commonly greatly simplified. It also shows that the required ship rate of a ship is highly dependent on its specific cost structure, the route it sails on and the time it spends in ports. As a result of this, simplification of the representation of the ship and its operation may have a detrimental effect on the quality of such studies. This underlines the importance of a sufficiently detailed representation of a ship and the way it is operated when the cost of transport and/or the ship's competitiveness with other modes are analyzed.

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List of symbols

Δ	Displacement	T
Δcost	Percentage change in cost	-
ΔW_{steel}	Percentage change in steel weight	-
η_H	Hull efficiency	-
η_O	Propeller open water efficiency	-
η_R	Relative rotative efficiency	-
η_S	Efficiency of the shafting	-
η_G	Efficiency of the gearbox	-
λ_s	Stroke/bore ratio	-
A_c	Transverse cross-section of a waterway	m^2
A_s	Transverse cross-sectional area of the underwater part of the ship	m^2
AeA0	Propeller blade area ratio	-
c_{dist}	Distance cost	€/km
c_m	Mean piston speed	m/s
c_{time}	Time cost	€/h
C_b	Block coefficient	-
$C_{crew,}$	Annual crew cost	€/year
$C_{crewmember}$	Cost of an individual crew member	€/year
C_{dep}	Annual depreciation cost	€/year
C_{ext}	Annual cost of internalized external costs	€/year
C_{food}	Annual food allowance	€/year
$C_{fuel,}$	Annual fuel cost	€/year
$C_{handling}$	Cost of handling a unit of cargo	€/unit
C_{ins}	Annual insurance cost	€/year
C_{maint}	Annual maintenance cost	€/year
$C_{maint,fixed}$	Annual Fixed maintenance cost	€/m^3/year
$C_{maint,variable}$	Annual Variable maintenance cost	€/kWh/year
C_{move}	Cost for 1 move of a cargo unit	€/unit
C_{oh}	Annual Overhead cost	€/year
C_p	Prismatic coefficient	-
C_{travel}	Annual travel allowance	€/year
C_{truck}	Cost of truck transport	€/unit
C_{rail}	Cost of rail transport	€/T
Cap_{truck}	Loading capacity of a truck	cargo units
$Cont_{empl}$	Employer's contribution	%
$Cont_{coll}$	Fee for employers' organization	%
$Cont_{holl}$	Holiday allowance	%
d_g	Variance of daily demand for goods	$units^2$/day
D	Ship depth	m
D_g	Average daily demand for goods	units/day
D_{hold}	Ship depth along the cargo hold	m
D_{prop}	Propeller diameter	m
Dist	Distance	km
EBIT	Earnings Before Interest and Taxes	€
EBITDA	Earnings Before Interest, Taxes, Depreciation and Amortization	€
FC	Fuel consumption	kg
Fn	Froude number	-
g	Gravity constant	m/s^2

GM	Metacentric height	m
h	Water depth	m
hc	Holding cost	%/year
H	Maximum stacking height of cargo	m
H_{bridge}	Clearance between water surface and the underside of a bridge	m
H_{db}	Height of the double bottom	m
I_{hull}	Investment for the hull	€
I_{mach}	Investment for the entire ship minus investment for the hull	€
I	Variance of lead times	$days^2$
k_{fr}	Number of manhours required for hull construction	hours/T
K	Safety factor	-
L	Ship length over all	m
Lt	Average lead-time	days
L_{wl}	Length of the ship's waterline	m
LBD	Length x Beam x Depth	m^3
LBT	Length x Beam x Draught	m^3
M_{fuel}	Mass of fuel consumed	T
M_{subst}	Mass of substance emitted	g
P_b	Brake engine power	kW
P_{bt}	Installed power for the bow thruster	kW
P_e	Effective power	kW
P_{fuel}	Fuel price	€/Ton
P_{inst}	Installed power	kW
P_{prop}	Installed propulsion power	kW
P_{req}	Required power	kW
Q	Shipment size	units
RPM	Engine rotational speed	rev/m
rps	Engine rotational speed	rev/s
R	Resistance	kN
R_g	Annual volume of goods	units
R_{hull}	Remaining value of the hull	€
R_{mach}	Remaining value of the entire ship minus remaining value of the hull	€
RSR	Required ship rate	€/unit
Se_{subst}	Upper limit on specific emissions of a substance acc. Legislation	g/kWh
Sf	Safety factor	-
sfc	Specific fuel consumption	g/kWh
St	Yield strength in torsional shear	N/mm^2
Sumc	Specific unit maintenance cost	€/MWh
Supc	Specific unit purchase cost	k€/kW
SWBM	Still water bending moment	kNm
t	Thrust deduction	-
$t_{crew,day}$	Number of working hours per day for a crewmember	h/day
$t_{crew,year}$	Number of working hours per year for a crewmember	h/year
$t_{dep,hull}$	Depreciation time of the hull	years
$t_{dep,mach}$	Depreciation time of ship minus hull	years
$t_{driving}$	Time spent driving	h
$t_{loading,law}$	Allowed loading time according to Staatsblad [2011]	h
t_{locks}	Number of operational hours spent to pass locks	h
t_{main}	Transport time of the main transport leg	days
$t_{operational}$	Number of operational hours	h
$t_{sailing,}$	Number of operational hours spent sailing	h
t_{port}	Number of operational hours spent in port	h

$t_{pre,end}$	Transport time of pre and end haulage	days
$t_{terminal}$	Time spent at a terminal	h
t_{total}	Total number of operating hours of the ship per week	h
t_{trip}	Time needed to make a round trip	h
t_{unit}	Time required to handle 1 cargo unit	h
$t_{unloading,law}$	Allowed unloading time according to Staatsblad [2011]	h
t_{work}	Number of working hours for loading and unloading	h
T	Draught	m
T_{air}	Air draught	m
T_{loaded}	Draught at maximum cargo capacity	m
T_{design}	Ship design draught	m
T_{max}	Maximum draught	m
TC	Transport cost	€/unit
TEU_x	Number of TEU than can be placed end-to-end in the ship's hold	-
TEU_y	Number of TEU than can be placed abreast in the ship's hold	-
TLC	Total logistic costs	€/unit
upc	Unit purchase cost	k€
$Units_{annual}$	Number of units of cargo transported annually	-
$Units_{trip}$	Number of units of cargo transported per trip	-
$Util_{truck}$	Degree of utilization of a truck -	
v	Value of goods	€/unit
V	Ship speed relative to water	m/s
$V_{critical}$	Critical speed	m/s
$V_{current}$	Speed of the current	m/s
V_{power}	Speed at 85% of maximum power	m/s
w	Wake fraction	-
$W_{cargo,}$	Cargo weight	T
W_{demand}	Demand for cargo	T/year
W_{light}	Lightweight	T
W_{piping}	Weight of piping	T
W_{steel}	Steel weight	T
WACC	Weighted Average Cost of Capital	%

1 Introduction

The inland shipping sector plays a significant role in the transport of cargo to and from several of Europe's main sea ports, annually transporting over 400 million tons of goods [Eurostat 2012]. This transport is to a large extent carried out by thousands of captain-owners [CBS & AVV, 2003] that are often in direct competition with each other as well as with road and rail transport operators. These small companies have little to no power to influence the market in which they operate and have only limited means to achieve a competitive edge over other operators. The purpose of this thesis is to assess how individual captain-owners with a single ship can be empowered to strengthen their competitive position.

There are many ways in which the competitive position of captain-owners can be improved, but many of these require action by policymakers, e.g. by changing crew regulations, legal waiting times in ports or changing taxation schemes. Furthermore, these measures mainly change the competitive position of one mode compared to another mode rather than the competitive position of a single operator compared to other inland waterway transport operators. Moreover, individual captain-owners do not have enough influence to bring about such policy changes, which makes them dependent on others rather than empowering them to improve their own position independently. These measures are therefore excluded from this research.

There are still several approaches by which a captain-owner can improve his competitive position: lowering cost, maximizing profits, increasing margins through better service and increasing market share. Which approach is the most suitable one depends on the nature of the market as well as on the nature of the transport operator. Therefore, an introductory overview of the sector is provided in sub-chapter 1.1, in which the development of inland waterway transport, the commodities that are transported via inland waterways, the share of inland waterway transport in the European modal split and the characteristics of the transport operators in the sector are briefly reviewed.

On the basis of this review, in sub-chapter 1.2 the research topic is defined. Once the topic is selected, it becomes possible to specify a main research question and several sub-research questions, which is done in sub-chapter 1.3. In sub-chapter 1.4, the outline of the thesis is discussed, while the limits of the research and the research results are discussed in sub-chapters 1.5 and 1.6.

1.1 Overview of the inland shipping sector

In this sub-chapter, an introduction to the European inland shipping sector is given. Furthermore the link is made between the main aspects of the sector and the competitiveness of captain-owners. In paragraph 1.1.1 the development of the transport by inland waterways in Europe is discussed, while the most important commodities for inland waterway transport are presented in paragraph 1.1.2. In paragraph 1.1.3, the share that inland waterway transport has in the modal split of the EU-25 and several of its member countries are presented and in paragraph 1.1.4, the characteristics of the inland waterway transport operators are briefly discussed and linked to the previous paragraphs.

1.1.1 Review of the development of inland waterway transport

Since ancient times, inland waterways have played a major role in the supply of goods to and from population centers, industries and construction sites. It is known that as early as the Egyptian 12th dynasty, around 2000 B.C., a large block of quartzite with a weight of more than 100 tons was transported over the river Nile from a quarry to a pyramid because waterborne transport was the only practical way of getting it to its destination [Clarke and Engelbach, 1999, p. 34]. For a long time, waterborne transport remained the most efficient mode of transport. In the words of Filarski: *"At the* *beginning of the 19th century, waterborne transport was faster and cheaper than road transport in most countries"* [Filarski, 2004, p. 8].

However, over the years, road and rail infrastructure have improved dramatically and the market share of inland waterway transport has steadily declined, as is confirmed for the Netherlands by figures from e.g. Bureau Voorlichting Binnenvaart [2007, p. 29] and for the EU by e.g. figures by the U.S. department of transportation [2002]. This decline has been particularly significant for intra-continental non-bulk cargoes, which almost completely moved from water to road. Bulk goods on the other hand have always remained strongly water-bound: coal, ores, gravel, sand, oil and other low-value bulk goods are still mainly transported by water whenever possible.

Figure 1-1: Goods transport in the 17th century; "View of *Zwolle* from *het Zwarte Water*" by unknown artist – collection of *Stedelijk Museum Zwolle*

Especially in the second half of the 20th century, road transport development boomed, catching up to the tonnage that was transported by water even in those geographic areas that have always been most favorable for waterborne transport [Bureau Voorlichting Binnenvaart, 2007, p. 29]. Still, the absolute number of tons of goods that are transported by inland ships continues to rise, as may be concluded from Eurostat statistics [Eurostat, 2011], presented in Figure 1-2.

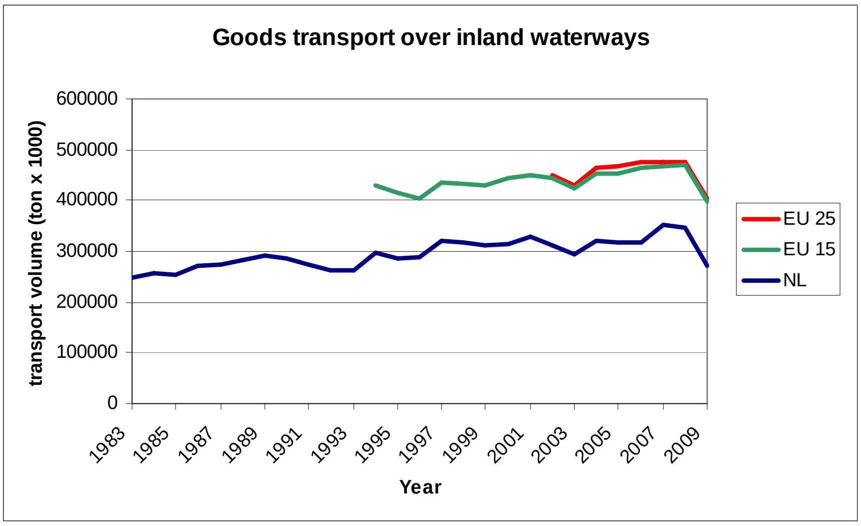


Figure 1-2: Amount of goods transported by inland waterway. Source: Eurostat [2011]

Figure 1-2 shows a small but gradual increase in the annual transport volume over inland waterways in Europe, with the exception of the clear reduction of transport volume in 2009 due to the economic crisis. There are, however, a number of developments that lead to the assumption that despite the relatively constant transport performance figures in past years and the recent drop in performance, there will be a growth in the demand for inland waterway transport in the future. This is due to the increase in demand for transport and due to a change in the modal split of that transport. These developments are discussed below.

For Europe as a whole, the Central Commission for Navigation on the Rhine [2010b] discusses results from a number of models that estimate both a total growth in transport volume of 52% in 2030 and a change in the modal split share of IWT that is between a slight decline and a doubling of the present value. This leads to a 50 to 100% increase in waterborne transport by 2030. Especially in container traffic, significant increases are expected. CE Delft et al. [2012, p. 21] arrive at a similar conclusion. They project an increase in the total number of tonkilometers of transport performance of inland waterway transport from the 2011 value of roughly 128 billion tonkilometers to between 190 and 260 billion tonkilometers in 2040.

Van Schuylenburg & Borsodi [2010] indicate that the landside container flow from and to the port of Rotterdam will roughly treble by 2040, while the share of road transport in this goods flow will drop from 50 to 35%. This implies a large increase in container traffic on the Rhine and on the port's rail links. Gussmagg and Fersterer [2010] signal a large increase in the container throughput of the port of Constanta as well and as a result expect growth for container transport on the Danube.

Furthermore, in the first decade of the 21st century the European road network starts to show strong signs of becoming overloaded in a number of places. The frequency and length of traffic jams are increasing to the point that mobility becomes a severe concern. The EU sees inland navigation as a major contributor to relieving this problem and expresses that view among others through its White paper on transport for 2010:

Short-sea shipping and inland waterway transport are the two modes which could provide a means of coping with the congestion of certain road infrastructure and the lack of railway infrastructure. Both these modes remain underused. [European Commission, 2010]

However, figures about the extent to which traffic on Europe's inland waterways can be increased in the future vary widely. Bureau Voorlichting Binnenvaart [2007] indicate that traffic can be increased by 700% for the Rhine and 100% for other Dutch waterways, while the UNECE indicate a short-term potential for a 20% to 100% increase in traffic on the major corridors in Europe [UNECE Inland Transport Committee, 2010]. Furthermore, infrastructure developments, including but not limited to major projects like the Maasvlakte II port extension at Rotterdam [Van Schuylenburg & Borsodi, 2010] and the Seine-Scheldt connection [Voies Navigables de France, 2009] are expected to create substantial further growth of waterborne transport.

The environment is also becoming an increasingly big issue and inland navigation is generally viewed as an environmentally friendly mode of transport, which sparks further interest in the mode. This is confirmed by numerous sources, including but certainly not limited to the European commission itself [Commission of the European Communities, 2006, p. 4].

As a result of this re-discovery of inland navigation as a desirable transport mode by the European Union and national governments, various national and international initiatives have arisen to stimulate inland waterway transport such as the 'Naiades' action plan [Commission of the European Communities, 2006a], various calls of the EU's 7th framework package [E.g. European Commission, 2007] & Marco Polo programs [European Parliament and Council of the European Union, 2006a] as well as e.g. Dutch national funding schemes to stimulate innovation in inland shipping in general [SenterNovem, 2010] and to revitalize the small waterways [Wirdum, 2007]. These efforts are expected to further increase the amount of waterborne freight transport.

From the above, it can be concluded that the demand for inland waterway transport has been relatively steady in the past years, but is expected to gradually increase in the coming decades, despite the current drop in freight volumes due to the economic crisis. As a result, there is a solid basis for further development of the sector. This does, however, not mean there will not be any temporary reductions in demand.

Since inland ships are operated by many small companies and have a long lifespan, the supply of transport capacity will be slow to adapt to downward changes in the demand for transport. At the same time, temporary imbalances between supply and demand that lead to high freight rates quickly also lead to an increase in the number of orders for new ships. Subsequently this leads to additional transport supply and resulting low freight rates. This has for instance happened in the 2008-2011 period. [Central Commission for Navigation on the Rhine, 2011]. As a result, it is concluded that there is a continued and potentially increasing demand for inland waterway transport but that despite of this, it is unlikely that this will lead to a structural increase in the margins for transport operators.

1.1.2 Important commodity types for IWT

Cargo is transported across mainland Europe by three principal modes: road, rail and inland waterways[1]. The choice for a mode is dominated by considerations that include but are not necessarily limited to cost, speed and/or shipment size. The importance of these considerations will vary with the type of cargo to be transported. E.g. for perishable consumer goods it is crucial that they are transported in small batches and are moved to their final destination quickly, while out of pocket cost of transport will only play a minor role in the mode choice. In stark contrast, coal or any other major bulk good will typically need to be transported in large batches at minimal out of pocket transport cost, while transit time is a much smaller issue. With this change in requirements comes a preference for a transport mode: trucks for the small batches of time sensitive goods and ships or trains for large batches of goods with less time pressure. This is reflected in the commodities that are transported by inland waterways. Table 1-1, based on data from Eurostat [2012], demonstrates the importance of the various commodity groups for inland waterway transport in the EU-25 in 2009.

Table 1-1: subdivision of goods transported by inland waterway in 2009. Source: Eurostat [2012]

type of goods	1000 Tons	%
Total transported...	**421111**	**100.0%**
GT3 Metal ores and other mining products	140186	33.3%
GT18 Unidentifiable goods (including containers)	92543	22.0%
GT7 Coke and refined petroleum products	39862	9.5%
GT1 Products of agriculture & forestry	28714	6.8%
GT2 Coal and lignite; crude oil & natural gas	26313	6.2%
GT8 Chemicals, chemical products & man-made fibers	19608	4.7%
GT4 Food products	16147	3.8%
GT10 Basic metals; fabricated metal products...	14458	3.4%
GT12 Transport equipment	12644	3.0%
GT9 Other non-metallic mineral products	11424	2.7%
GT14 Secondary raw materials; waste	9972	2.4%
GT6 Wood and products of wood & cork	4995	1.2%
Other	4248	1.0%

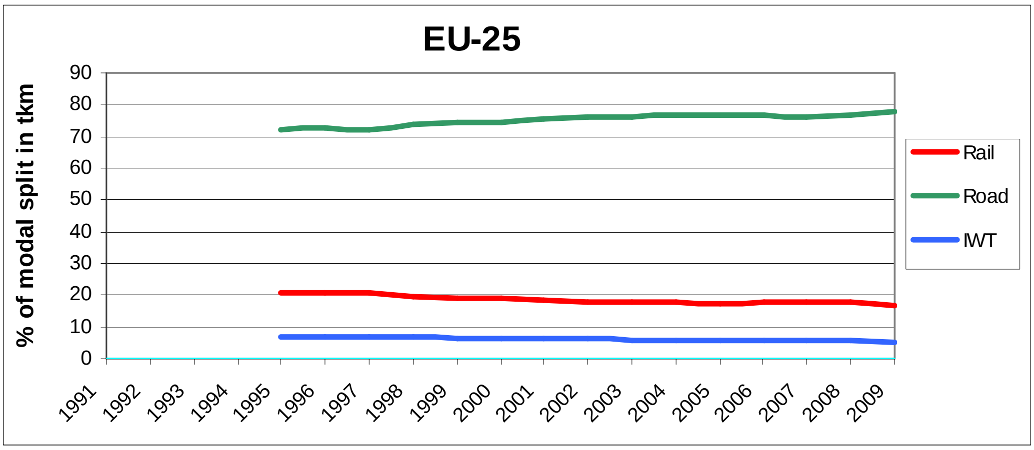
[1] Pipelines are intentionally not treated here, neither is air freight

From this table the importance of low-value commodities for inland waterway transport is again clear, despite the fact that *Unidentifiable goods* (including containers) covers 22% of the total amount of goods that are transported over European inland waterways. The large share of bulk goods and containers in the total transport of goods by inland waterways implies that inland ships are typically dry bulk, container or tank ships, i.e. basic general purpose ships that can be used for various cargoes and as a result are often in direct competition with each other. This competition is strengthened by the fact that many existing dry bulk ships have been designed in such a way that they can also transport containers effectively. This strong competition further strengthens the conclusion that was drawn in paragraph 1.1.1, i.e. that margins will stay small since in case of severe competition, transport prices will go down to marginal cost level [Blauwens et al., 2010, p. 462].

1.1.3 The share of inland waterway transport in the modal split

The role that inland waterway transport plays in the overall transport of goods does not only vary from commodity to commodity but also from country to country. Especially for goods that enter Europe through the seaports that are connected to the river Rhine and the dense waterway network in the Netherlands and Belgium, there are good possibilities to transport them to the hinterland by water. This is reflected in the modal split of these countries. A well-developed rail corridor is present in Northern Germany, where rail is the preferred mode of transport for a significant portion of goods coming from or going to the main ports [Bureau Voorlichting Binnenvaart, 2004]. Still, the relatively large amount of well-developed inland waterway infrastructure in Germany (mainly the canals in the north and west and the river Rhine) ensures that the country has a higher share of inland waterway transport than the EU-25 average, as is shown in Figure 1-3. Next to the Netherlands, Belgium and Germany, the countries that complete the top-5 of countries that use inland waterway transport are France and Austria.

When transport performance is measured in tonkilometers, thereby multiplying the number of transported tons as discussed in chapter 1.1.1 by the distance over which they are transported, in 2005 in the Netherlands around 42 billion tonkilometers of transport were executed via inland waterways, amounting to roughly 31% of the national total. In Germany, these values are 64 billion tkm and 14% while Belgium totals 8.6 billion tkm (13%), which is comparable to France (8.9 billion tkm, 3%). In absolute numbers, other European countries have a substantially lower IWT transport performance, although Austrian inland waterway transport still reaches a modal split share of 6% [Bureau Voorlichting Binnenvaart, 2007]. These values have remained more or less steady in the past years, as is shown in Figure 1-3.



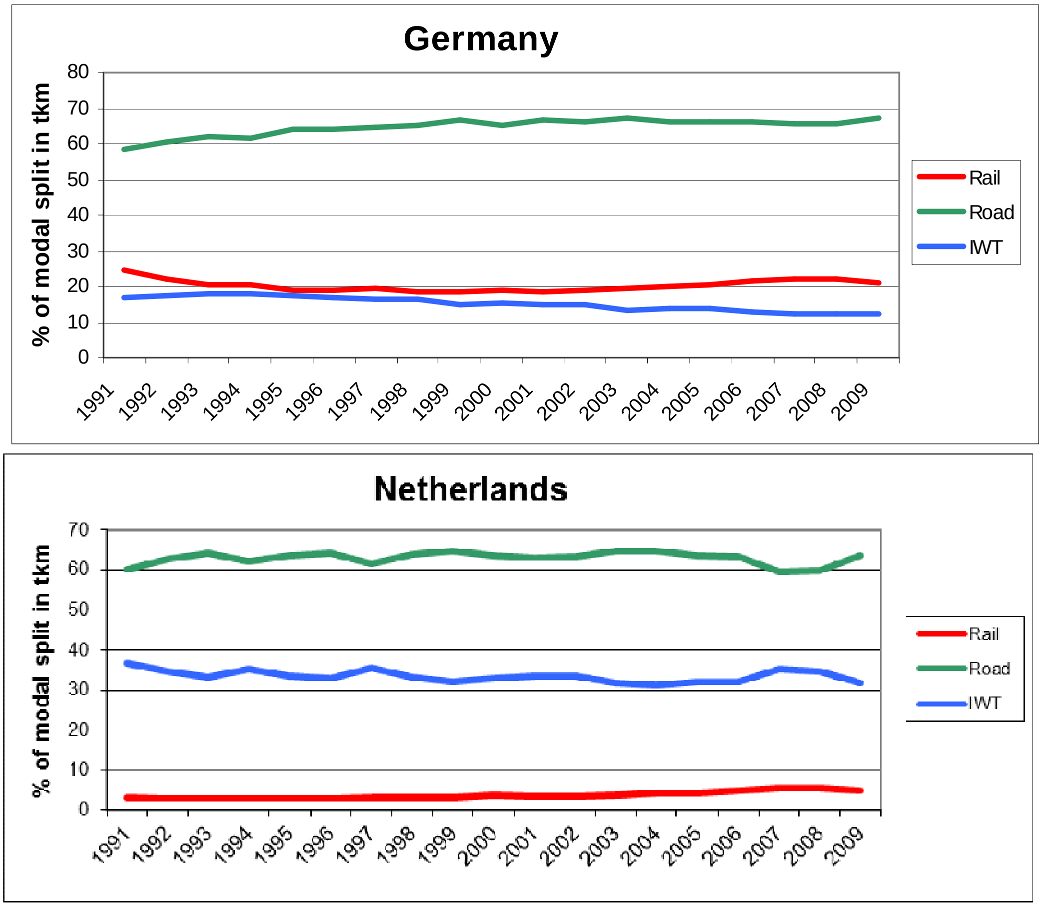


Figure 1-3: Modal split in tonkilometers for EU-25, Germany and the Netherlands. Source: Eurostat [2011]

It is important to note that the majority of the goods that are transported by inland ship either originate from or are destined for seaports. Especially in the intra-continental intermodal transport flows, waterborne transport plays only a very minor role [Platz, 2009, p. 13]. This is largely explained by the additional handling and pre- or end haulage that is required for intra-continental transport, which adds significant costs and time to the transport. Cargo to or from seaports requires only pre- or end haulage, while intra-continental transport typically requires both. Due to this effect, transport to and from seaports should be a primary focus when researching opportunities to strengthen the position of inland waterway transport.

Furthermore, the concentration of inland waterway transport activity around the Rhine and the waterways that are connected to it implies that the majority of inland waterway transport takes place in the same geographical area, which again underlines that a large percentage of the many transport operators in the inland waterway transport sector are in direct competition with each other.

1.1.4 Transport operators in the inland shipping sector

Inland shipping in Europe is carried out by roughly 14.000 cargo ships, barges and pushboats [EICB 2010b], as is shown in Table 1-2. These units are operated by a large number of companies, which mainly consist of captain-owners with a single ship (e.g. 2930 vessels in the Netherlands, equaling 87% of the total number of enterprises) [CBS & AVV, 2003]. These captain-owners typically run their business from their ship, without a land-based office and support staff. On the upper end of the company size spectrum, there are very few companies that operate more than 20 ships and have a substantial land-based support staff.

Table 1-2: Active European cargo fleet in 2010. Source: EICB [2010b]

	Rhine countries	Rest of Europe
No of Dry cargo vessels	6079	578
No of tank vessels	1370	46
No of pushboats	568	424
No of dry cargo barges	2121	2623
No of tank barges	134	15
Total	**10272**	**3686**

As was discussed in chapter 1.1.1 and 1.1.3, many of these companies operate in the same geographical area. Roughly two thirds of the transport by inland waterways in the western part of Europe is performed along the Rhine corridor [Central Commission for Navigation on the Rhine, 2007b]. This corridor is in turn directly connected to the Dutch, German and Belgian canal systems and to the Danube corridor, which are the areas where much of the remaining European inland waterway transport is performed.

In chapter 1.1.3, it was discussed that the share that inland waterway transport has in the modal split as well as the number of tonkilometers of transport that are executed by inland waterway transport differ strongly between the various European countries. This geographic distribution of the importance of inland waterway transport is reflected in the nationalities of the operators of the fleet: Dutch (51% of total tonnage), German (22% of total tonnage) and Belgian (16% of total tonnage) inland waterway transport operators represent the majority of operators in Western Europe [Bureau Voorlichting Binnenvaart, 2007, p. 45].

As was discussed in chapter 1.1.2, the vast majority of the goods that are transported by inland waterway are dry bulk, liquid bulk and containers. Since nearly all dry bulk goods as well as containers can be transported by dry bulk ships, many ship operators compete for the same cargo. To a lesser extent this is also true for tank vessels, which are slightly more diversified by type of goods into the ‘normal’, ‘chemical’ and ‘gas’ categories, each of which poses separate demands on the design of the ship [Economic Commission for Europe, 2009, Pt. 9 Ch. 9.3].

All of the aspects that are discussed above serve to illustrate that the transport operators in the inland waterway transport sector operate in a highly competitive market, where many small operators compete for the same type of cargo in the same geographical are.

1.2 Research topic

As was discussed at the beginning of this chapter, this thesis aims to empower captain-owners, which form the majority of inland waterway transport operators in Europe, to improve their competitive position independently. There are, however, still many ways to do this. In this sub chapter, it will be further specified how this general aim will be reached. In chapter 1.2.1 the most suitable strategy is selected (i.e. lowering cost, maximizing profit, increasing margins through better service or increasing market share) and in chapter 1.2.2 it is determined which options a shipowner has to implement this strategy. The most promising option for which significant scientific challenges still exist is selected as the research topic of this thesis.

1.2.1 Selection of strategy to improve the competitive position of captain-owners

As was discussed at the beginning of this chapter, captain-owners can in theory improve their competitive edge by lowering cost, maximizing profit, increasing margins through better service or increasing market share. It was demonstrated in chapter 1.1.4 that the market mainly consists of thousands of captain owners with a single ship. As a result, none of these small operators can achieve a market share that is large enough to have any significant influence over the market. This in turn implies that increasing market share is not an effective approach to improve a captain-owner's competitive position independently of others.

A second possible strategy to improve the competitive position of an operator would be to provide better service than his competitors. However, in this field captain-owners with a single ship and without a land-based office and support staff have a distinct disadvantage compared to larger operators with multiple ships and a land-based office with support staff. This strategy is therefore also ruled out.

In chapter 1.1.1, it was shown that the demand for transport by inland waterways is expected to remain steady or increase in the future. It was however also discussed that this is not expected to lead to higher margins in the sector since transport supply will quickly increase when demand increases but can hardly be reduced when demand decreases. In such a highly competitive market, transport prices will go down to marginal cost level [Blauwens et al., 2010, p. 462], thus ruling out profit maximization as an optimization approach on the main market. It is however possible to use this approach for captain-owners that operate in a commodity niche or a geographical niche where competition is less severe.

Geographical niches are mainly found on the smaller waterways up to CEMT class IV, on which ships with a tonnage of up to 1500 tons can sail. On these small waterways either the dimensions of the waterways themselves or the dimensions of locks and bridges will physically prevent access of larger ships. Presently, the ships that sail on the small waterways are mainly old vessels which have very low capital costs. As a result, it has been concluded that new vessels with high capital costs can not compete with them [Buck, 2008, p. 14]. Furthermore, due to smaller scale advantages compared to road transport there is a strong competition with this mode. As a result of this, the number of ships on these small waterways is actually declining [Buck, 2008, p. 5]. Recent efforts to revitalize these small waterways through new technical and logistical concepts, namely Q-barge [Research Small Barges, 2010], ECSWA [Hassel, 2011], Barge Truck [EICB, 2010], Watertruck [2011] and INLANAV [2010] have thus far not gone beyond the drawing board stage. Only the 'M-factor' approach of Mercurius shipping group [EICB, 2012b] has thus far had some success but this concept requires a support organization that captain-owners typically do not have. As a result, moving to a geographical niche is also not considered a promising approach to improve the competitive position of captain-owners.

Entering a commodity niche is challenging, but in recent years, there have been several initiatives by transport operators to enter a niche market that is not accessible to standard dry bulk, container and liquid bulk vessels. The cargoes for which this has been attempted include fast moving consumer goods [Groothedde and Rustenburg, 2003], cargoes requiring special treatment [Mercurius Scheepvaart Groep, 2010], and fuselages for the airbus A380 aircraft [Guns, 2004]. Furthermore, Mercurius Shipping Group has introduced a geared container vessel that is able to load containers at sites without a container crane [Amsbarge, 2010]. The abovementioned initiatives have, however, only resulted in the development of a limited number of dedicated vessels, while the projects with fast moving consumer goods and the cargo requiring special treatment have been discontinued. Vessels that were researched in 2004-2007 FP6 project CREATING [Blaauw et al. 2006], being new RoRo catamarans for the Danube, a self-unloading biomass carrier with icebreaking capability and a refrigerated pallet vessel, have not gone beyond the drawing board stage, although the biomass carrier is again under development, as is apparent from a paper by Holm [2010].

The developments that are discussed above rely strongly on the ability to create a logistics concept with multiple vessels and/or clear long term agreements with shippers, with the possible exception of the case of the geared container vessel. However, it has proven to be challenging as well as a long process to make such a concept profitable [EICB, 2012]. Since captain-owners with a single ship typically neither have the ability to set up new logistic concepts nor the financial means to endure a long startup of a concept, investigation of commodity niches is also not deemed a suitable approach for this thesis.

This leaves cost minimization as the only remaining strategy to improve the competitive position of captain-owners. Since cost and price are closely linked in a highly competitive market, lowering cost implies the opportunity to transport goods at lower prices. This is especially important since transport price is generally recognized to be a crucial factor in the decision making process of shippers, if not the most important one [Platz, 2009, p. 370] [Kreutzberger, 2008]. In times when supply exceeds demand, the ship operator with the lowest cost can ensure he will still have sufficient work by lowering his price to levels that his competitors can not sustain. In times when demand exceeds supply, his margins will be higher than those of his competitors. In both of these cases, the competitive position of the operator is improved.

Furthermore, since there is a considerable price elasticity for many types of commodities [Beuthe et al, 2001], both within inland shipping and between inland shipping and other modes, a reduction in the transport price will not only draw cargo away from other inland ships, but will also create a modal shift to water. This will effectively increase the total volume of goods to be transported by inland waterways and thereby further strengthen the position of operators that can offer transport at the lowest prices. From the above, it is concluded that cost minimization is the most suitable strategy to improve the competitive position of captain-owners.

1.2.2 Selection of the research topic

There are many ways in which the cost of transport by inland ship can be influenced and many of these have been the subject of previous research, e.g. by NEA [2001, 2003, 2004] and Beelen [2011]. The options to influence cost include but are not limited to the type of vessel that is used, ways of financing of the vessel, the type of contract, cooperation with others and intensity of operations [Beelen, 2011, p. 11].

The technical characteristics of the ship, however, are hardly ever explicit variables in cost studies on inland waterway transport, despite the fact that there is a strong and direct relationship between these technical characteristics and the cost of transporting goods by ship. Virtually all of the existing studies base their analyses on the cost and cargo carrying capacity of standardized inland ships, as a result of which the link between cost and technical characteristics of the ship is lost. Because of this and because much is still unknown about the relationship between the design of an inland ship and transport cost, the research in this thesis focuses on cost reduction through changes in the design of a ship.

Here, it is important to note that in practice, changing the design of a ship is not easily done. Apart from minor retrofits, replacement of worn-out machinery or lengthening of existing ships, changing the design of the ship implies that a ship owner sells his ship and buys a new one. The decisions that he makes when buying a new ship are hard or impossible to undo. This implies that any ship design-related efforts to improve a ship operator’s competitive position will involve long term choices which may structurally improve or worsen this position.

There are multiple ways in which the design of a ship can be altered in order to influence the cost of transport. Each of these ways either leads to an increase in the amount of cargo that a ship can carry without an increase in cost or to a decrease in the cost of transporting a given amount of cargo. Since it is not possible perform in-depth research into every possible way in which transport cost can be lowered through changes in the design of the ship, a single aspect is selected.

In order to make this selection possible, the maximum attainable effect of the main design changes is estimated on the basis of a simplified calculation. In Table 1-3, these design changes are listed together with their theoretical maximum attainable effect and potential negative aspects. An elaborate analysis of all possible design changes and the calculation of their maximum attainable effect can be found in appendix A.

Table 1-3: Overview of effects of design changes

Design change	Maximum attainable effect	(Potential) negative aspects
Increase block coefficient	≈ 11% more cargo	- Increased fuel consumption
Alter general arrangement	≈ 14 % more cargo	- Mainly effective for small vessels
Reduce hull weight	≈ 7 - 10% more cargo	- Higher building cost - Mainly applicable for small ships
Reduce weight of other items on board	≈ 2 - 5 % more cargo	- Composed of many different elements, so no single item to optimize
Lower design speed	≈ 12 - 19 % lower cost	- Increased round trip time
Optimize the drive train	≈ 4.5 - 12% lower cost	- Increased building cost
Optimize other items on board	≈ 3% lower cost	- Composed of many different elements, so no single item to optimize
Increase main dimensions	≈ 21.5 – 25.5% lower cost compared to the largest ships, larger savings compared to small ships	- Restrictions in flexibility - Increase in shipment size - Increase in roundtrip time due to longer handling

From this preliminary assessment of the benefits and drawbacks of various options to change a ship design, it can be concluded that changing the main dimensions of a ship can lead to substantially larger cost reductions per ton of transported cargo than any of the other measures that are discussed. As a result, it is considered to be a suitable topic for further research.

However, an increase in ship size may mean a decrease in geographic flexibility as well as an increase in the amount of time that is spent in port, which will increase the ship's voyage time. Furthermore, larger shipments will increase the stock cost for shippers, which may negate the positive effects of lower out-of-pocket cost of transport. This in turn leads to the conclusion that the optimal dimensions of an inland ship are not fixed values, but are dependent on the properties of the transport route, the transported goods and the shipper. These aspects should, therefore, also be included in the research.

Furthermore, the CCNR states that the maximum allowed length of indivisible ships is 135 meters [Central Commission for Navigation on the Rhine, 2010], which is significantly shorter than the maximum length of coupled units that are operated on the largest European waterways. This limit is noted, but not regarded as a hard restriction in this research. The reasoning behind this is that it is worthwhile to establish if there are significant benefits in using vessels that are longer than 135 meters. If this is the case, a technical solution to make a longer ship divisible will need to be found.

Alternatively, it will to be discussed with the CCNR if the length limit, which is not founded on a hard physical limit and has already been increased from 110 m to 135 m in the past, can be increased.

1.3 Main research question

The goal of this thesis is to assess how the design of inland ships affects the competitive position of captain-owners. In the previous sub-chapters, it was concluded that efforts to improve the competitive position of inland waterway transport operators should be aimed at a cost reduction for transport on the main waterways and for the main commodities rather than on small waterways or for niche commodities. It was also concluded that changing the main dimensions of inland ships is the design change that has the largest potential to reduce the cost of transport by inland ship.

There are, however, a number of drawbacks associated with this solution, since larger ships lead to lower geographical flexibility and longer voyage times. Moreover, when the use of larger ships leads to larger shipments for a single shipper, this will increase this shipper’s stock cost. In this case, large ships will only be competitive if they offer transport at a lower price than smaller ships.

Furthermore, the initial assessment of paragraph 1.2.2 was done on the basis of crude approximations of the properties of the ship. These approximations assume among others that the lightweight-to-deadweight ratio remains constant over the entire range of dimensions and that building cost, with the exception of the cost of the propulsion system, are linearly related to displacement. Both of these assumptions are debatable. Furthermore the approximations that are used do not give insight into the effects of changing length, beam or design draught individually. They also do not include any effects of shallow water on fuel consumption and installed power. As a result of this, the approximations that are used are suitable for a first estimate of potential cost reductions, but certainly do not provide any definitive answers.

The abovementioned considerations lead to the formulation of a main research question and 4 sub-research questions. The main research question is:

Which length, beam and design draught of an inland ship lead to the best competitive position for a captain-owner?

This question can only be answered when the following four sub-questions are answered:

1) *What are the practical upper limits of the dimensions of inland ships?*

Answering this question provides insight into infrastructure- and market-related boundaries for the research and prevents false optimums in the form of ships that can operate at very low cost, but may not attract enough cargo to ensure successful exploitation, e.g. because their operation is restricted to a small geographic area in which the demand for transport is limited.

2) *How do the main dimensions of an inland ship relate to its building cost and those technical properties that affect the cost of transport?*

When this question is answered, currently unavailable ship-related data that are required for a proper analysis of the cost and benefits of operating a ship with any combination of length, beam and design draught become available.

3) *How do changes in the main dimensions of an inland ship affect the cost of operating that ship?*

It was argued before that in the highly competitive market of inland waterway transport, over a longer period of time transport prices will be close to the average cost of the operator. Therefore, answering sub-question 3 will allow determination of the extent to which a transport operator can offer transport at a lower price. The answer to this question is not only dependent on the properties of the ship and its cargo, but will also be determined by the characteristics of the transport route and the time that a ship spends in port.

4) *How do changes in the main dimensions of an inland ship affect the total logistical cost of a shipper?*

Although the price that a shipper needs to pay for transport plays an important role in his choice for a transport operator, larger ships that can offer transport at a lower price may also imply larger shipments, which will affect his stock cost. As a result, a shipper will not always favor the cheapest mode of transport, but will look for the lowest total logistical cost. Therefore, sub-question 4 needs to be answered in order to be able to determine which main dimensions lead to the best competitive position of a captain-owner. Apart from the variables that are of importance for sub-question 3, the value of the transported goods and the annual demand of a shipper become important variables in the determination of the optimal ship dimensions.

When sub-question four is answered, so is the main research question and as a result, it becomes possible to identify the optimal dimensions of an inland ship as a function of the properties of the transport route, the value of the transported cargo and the annual demand of a shipper.

1.4 Outline of the thesis

In order to answer the research questions that were posed in the previous sub-chapter, the research that is performed follows the path that is described in Figure 1-4. In chapter 2, the first sub-research question concerning the practical limits of the main dimensions of inland ships is answered through a review of the main dimensions of the existing inland fleet, the dimension limitations that are imposed by the waterways and the amount of goods that are handled in ports along these waterways.

The answer to the second research question, i.e. the determination of how the main dimensions of an inland ship relate to its building cost and those technical properties that affect the cost of transport, is provided in chapters 3, 4 and 5. In chapter 3, it is explored where the gaps are in the knowledge about the relationship between these aspects and in chapter 4 a ship design model is created with which these gaps can be filled. Using this model, in chapter 5 a large design space is explored by the creation of several series of ship designs for which length, beam and design draught are systematically varied. This results in a number of datasets with a large number of ship designs that effectively answer the second research question. In order to make the knowledge that is developed in chapter 5 usable to the scientific community and to ship designers, rules of thumb for the estimation of the lightweight, steel weight, building cost and cargo carrying capacity of inland ships are established in sub-chapter 5.6.

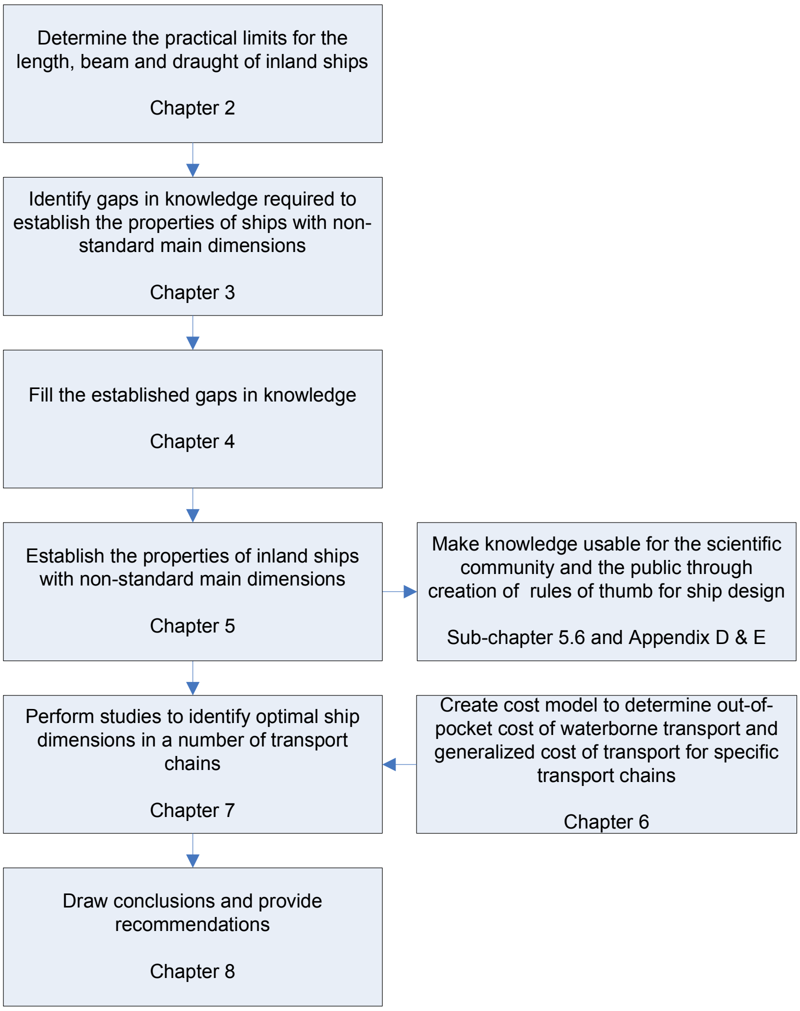


Figure 1-4: Research structure

The third and fourth sub-questions, which relate to the determination of the effect that given main dimensions have on the cost of transport by ship and the total logistical cost of a shipper are answered by placing the created ship designs in a number of transport chains in which transport distance, water depth, value of the transported goods and annual demand of a shipper are varied. In chapter 6, a cost model is developed and with this model a number of case studies are performed in chapter 7. Apart from these specific case studies a more general discussion is held about the complications and boundary conditions of use of inland ships that differ significantly from those that are in operation today. Finally, conclusions are drawn and recommendations are made in chapter 8.

1.5 Research limits

The focus of this thesis is a technical one; the emphasis will be on the impact that the technical properties of the ship have on an operator’s competitiveness. It is recognized that there are many other factors that influence the competitiveness of inland waterway transport operators, many of which have little or nothing to do with technology. Several of these options are elaborately discussed by Beelen [2011]. These options include but are not limited to the type and size of vessel that is used, ways of financing of the vessel, the type of contract, cooperation with others and intensity of operations [Beelen, 2011, p. 11]. It is, however, left to others to deal with these aspects.

Since the main goal of this thesis is to assess how the competitive position of captain-owners can be strengthened through the design of their ship, the majority of the effort that is put into this thesis goes into the determination of the characteristics of inland ships. The scope of the thesis is limited to self-propelled dry bulk, container and (coated) tank vessels, which are the main ship types in the European inland waterway fleet. The research excludes other, specialized, ship types.

Coupled units (pushtows and self-propelled cargo vessels pushing a barge) are also excluded from this research. This done because coupled units have basic disadvantages in the form of higher crew cost and higher fuel consumption when they are operated in the same way as single inland ships. When the main advantage of coupled units is utilized, i.e. the possibility to reduce the waiting times of the pusher at terminals by dropping off one set of barges and picking up another, this implies an entirely different logistic approach. Since the focus of this thesis is on the design of ships rather than on the logistics of their operation, this is considered to be beyond the scope of this thesis.

The focus of this thesis is on inland ships, i.e. on the supply side of transport. The demand for transport is, therefore, only addressed in a limited way. The amounts of goods that are handled in the main inland ports along the geographical focus area are discussed in order to gain basic insight into the market and to establish the market-related boundaries of the research. The effects of different annual volumes of cargo to be transported for a single shipper are assessed in several scenarios, but no attempt is made to determine the actual demand of individual shippers.

1.6 Research results

In order to answer the main research question, the main focus of the research lies on enabling the determination of the technical characteristics, building cost and operating cost of inland ships with a wide range of main dimensions. Furthermore, it is determined how the potential use of these ships is affected by the length and water depth of the transport route the type of goods that are transported and the annual demand of individual shippers. This will lead to:

A) Several datasets of the technical properties, cargo carrying capacity and building cost of dry bulk, container and tank ships with systematically varied main dimensions.

B) A set of rules of thumb and guidelines that enable determination of the technical characteristics and building cost of a wide range of inland ship dimensions for dry bulk, container and tank ships.

C) A number of representative case studies that demonstrate the potential for reduction of the cost of operating an inland ship and of a shipper's total logistical cost as a function of ship dimensions, physical properties of the transport route, value of the transported goods and the annual demand of a shipper. In each of these cases optimal ship dimensions are determined and their performance in terms of required ship rate and total logistical cost is compared to that of vessels with other dimensions.

D) A description of the boundary conditions and complications for the use of the 'optimal' ships that were found in the various case studies as well as the boundary conditions for use of various types of non-standard inland ships in general.

E) Decision-making flowcharts that enable the selection of the optimal ship dimensions as a function of the type of goods that are transported, the annual demand of individual shippers and the properties of the transport route.

2 The practical upper limits of inland ship dimensions

The first step in answering the main research question of this thesis, i.e. the determination of the length, beam and design draught of an inland ship that lead to the best competitive position for a captain-owner, is to establish the practical upper limit of the dimensions of inland ships. The largest waterways will accommodate push convoys of 280 m x 22.8 m (long formation) or 195 m x 33.4 m (wide formation), as is discussed in appendix A. However, this will greatly restrict the ship's flexibility in terms of the waterways and ports that the vessel can access, while also potentially introducing difficulties in turning on the river and/or in inland ports. At the same time, such convoys greatly exceed the maximum allowed length of indivisible ships, which is 135 meters [Central Commission for Navigation on the Rhine, 2010, article 11.01]. Therefore the practical limits of the dimensions of inland ships will be smaller than the maximum dimensions that can be accommodated on the largest waterways.

In this chapter, the practical limits on the dimensions of inland ships are reviewed in more detail: In chapter 2.1, it is reviewed what the current typical main dimensions of inland ships are and what the reasons behind these dimensions are. In chapter 2.2, an analysis is made of the ship dimensions that can be used on the various European waterways. In chapter 2.3 it is reviewed on which stretches of the main waterways there is a substantial market for inland waterway transport The combination of these elements will lead to a set of limits for the increase in the main dimensions of inland ships, which are important boundary conditions for the following chapters in which the effects of changing a ship's dimensions are researched in detail.

2.1 The dimensions of existing inland ships

The length, beam and draught of inland ships are strongly influenced by the properties of infrastructure and by regulations. For length and beam, these limits are very clear and strong, while for draught, the limits are much less clear. In chapter 2.1.1, the typical lengths and beams of existing inland ships and the developments therein are discussed and in chapter 2.1.2 their draught is reviewed.

2.1.1 Length and beam

The self-propelled vessels that are operated on European inland waterways come in various shapes and sizes but can roughly be subdivided in classes and dimensions that match those of the CEMT fairway classes as defined by the European Conference of Ministers of Transport [1992]. On the larger waterways (classed Vb to VII), ships up to 135 m in length are allowed [Central Commission for Navigation on the Rhine, 2010, article 11.01], but coupled vessels and pushtows may have vastly larger overall dimensions, up to 280 m in length and 34.2 m in width.

In practice, regulations and properties of a waterway's infrastructure form important design drivers for the dimensions of inland ships, as is apparent from Figure 2-1 below. From a database containing over 800 inland cargo vessels built in Europe since 1996, compiled from data presented by [Vereniging 'de Binnenvaart'], some clear insights into the usual decision making process behind a vessel's main dimensions can be obtained:

In Figure 2-1, horizontal lines 1 and 2 represent lock width restrictions at 9.6 and 11.45 m beam, while vertical lines A and C represent the length at which more crew is required according to ROS-R regulations (70 and 86 meters) [Central Commission for Navigation on the Rhine, 2007]. Line B and D present lock length limitations (85 and 110 m) and line E at 135 m represents the maximum allowed length of an 'indivisible' ship on the Rhine as stated by article 11.01 of the 'Rijnvaart Politiereglement' [Central Commission for Navigation on the Rhine, 2010].

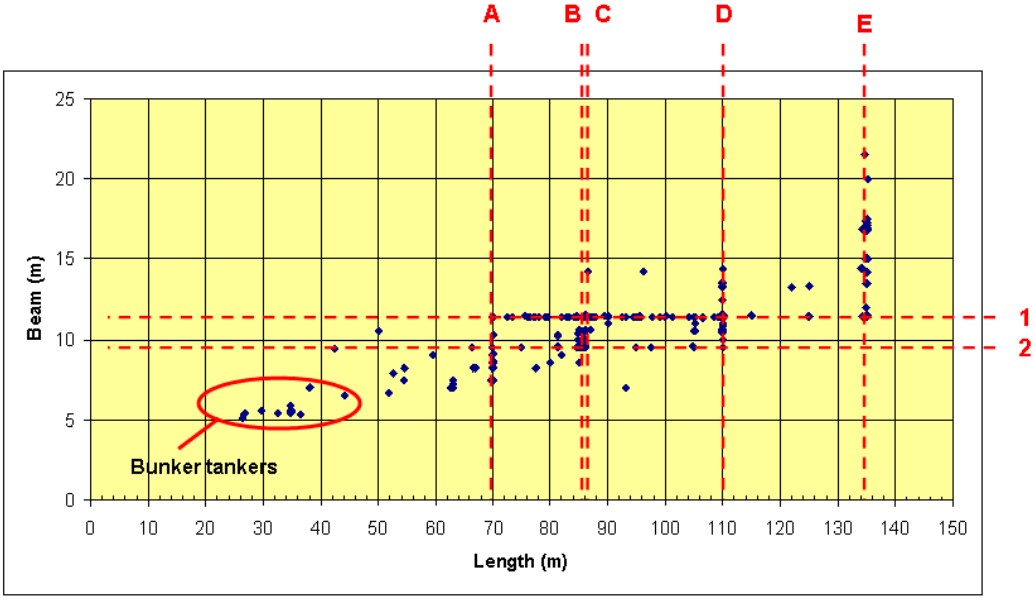


Figure 2-1: Inland vessel main dimensions: L-B Source: own representation of data from [Vereniging 'de Binnenvaart']

Of all the ships that are incorporated in Figure 2-1, 42% have main dimensions closely match the upper length and beam limits of class Va waterways, being 110x 11.45 m. These vessels have clear scale advantages over smaller vessels, but still provide the flexibility to access the class Va waterways. Another 21% percent of all vessels in Figure 2-1 exceed the dimensions of class Va waterways, which limits their area of operation to the main waterways. As such, these ships represent a more outspoken choice for economies of scale over flexibility. The previously discussed difficulty to successfully exploit new ships on small waterways is also apparent from the data underlying Figure 2-1: only 16% of all ships in the figure have a beam that is smaller than 9.6 m, i.e. the maximum beam for class IV locks.

As a result, it can be concluded that despite the obvious adaptation of vessel size to fairway dimensions and regulations shown previously in Figure 2-1, in the sector as a whole there is a strong trend towards scale enlargement, as may also be seen in Figure 2-2, which shows the general trend in the deadweight of newbuildings for each year between 1996 and 2008, based on data from [Vereniging 'de Binnenvaart'].

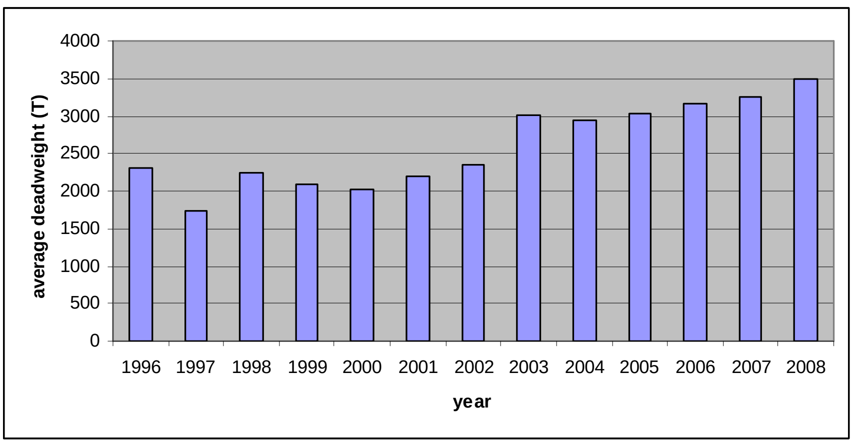


Figure 2-2: Development of the average deadweight of newbuild vessels

From this figure, it can be observed that the average deadweight tonnage of newbuild inland vessels has increased over the years and is now around 3500 tons, which is roughly equal to that of a 110 x 11.45 m large Rhine vessel.

That the average size of ships will continue to increase is also underlined by Dutch research institute TNO, 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. However, TNO also identifies a number of developments that will influence the increase in cargo capacity in an uncertain way [TNO, 2010].

This push towards ever larger vessels is further underlined by the sector's efforts to push legal boundaries: For the large waterways, research has been done into ever larger push convoys, [Hoogwout et al., 2004], while for operation in seaport areas, the first bunker tanker that exceeds the 135 meter limit has been built: Tank ship Vorstenbosch of 147 x 22.8 m [Schuttevaer, 2010], which may very well be the ship to pave the way for other vessels exceeding a length of 135 m.

From the above, it becomes apparent that the maximum length that is imposed by the CCNR may be an important limit on further scale enlargement in the European inland navigation sector. Since the maximum length that is allowed by the CCNR has already been increased from 110 meters to 135 meters in the past and is not founded on a hard physical limitation, it is considered to be worthwhile to explore how longer ships would affect the competitiveness of inland waterway transport operators. When such ships prove to be substantially more competitive than existing ships, it will need to be discussed with the CCNR if, and under which circumstances, longer ships can be allowed or a method to divide such large ships will need to be devised. In the past similar regulatory changes have e.g. been achieved in the development of the crashworthy side structure for inland ships [Ludolphy, 2001] and slackening of the conditions under which large 6-barge push convoys are allowed to sail on the lower Rhine [Brolsma, 2007].

2.1.2 Draught

When examining the relationship between draught and length in Figure 2-3, a significant scatter is seen; draughts vary significantly but limits are virtually always between 2.5 and 4.5 meters and are mainly dependent on the water depth in the intended sailing area of the vessel and the type of cargo (e.g. gas tankers have a smaller draught than dry bulk vessels due to the low density of the cargo).

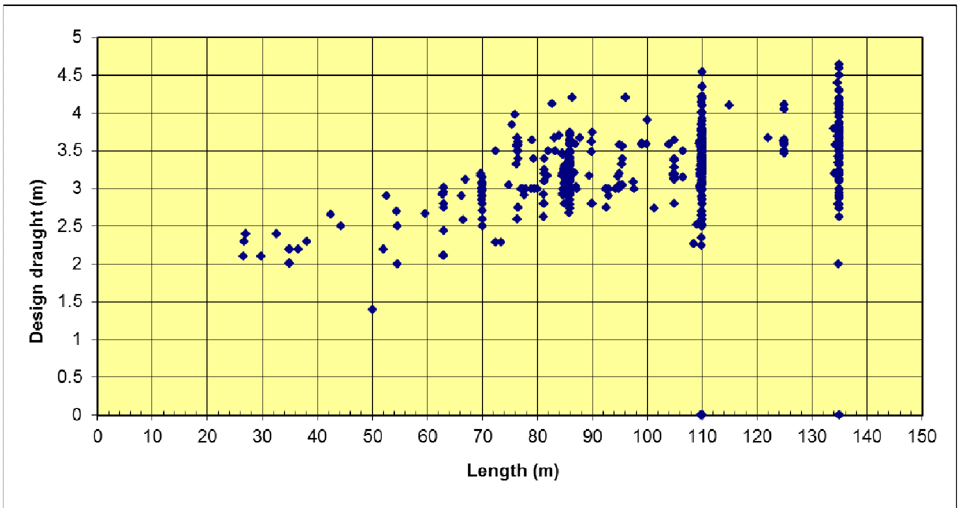


Figure 2-3: Inland vessel main dimensions: L-T_{design}. Source: own representation of data from [Vereniging 'de Binnenvaart']

Despite the considerable number of ships with a large design draught, there are signals that in some cases the draught increase for inland ships may have reached its limits: in 2011 a list of areas of concern for inland waterway transport, listed in a document by the Dutch government, includes the concern that the draught of inland ships is already too large. [Rijkswaterstaat, 2011a, p. 13].

Nearly all of the previously discussed vessels are intended for navigation on the waterways in the western part of Europe. In the Danube region, there is a very different situation. Over the last decades shipping in the Danube region has declined strongly, as a result of which hardly any vessels that are designed for that area meet modern requirements while modern vessels are not properly adapted to the waterways there (generally speaking more fast-flowing and shallower water than in the western part of Europe) [SPIN-TN, 2004, p. 10]. As will be discussed in chapter 2.3, however, the geographic focus of this research is not on the Danube.

2.2 Infrastructure-imposed limits on ship dimensions

In this sub-chapter the characteristics of the main European waterways are discussed, as are the developments therein. This provides insight into the relationship between the dimensions of inland ships and the parts of the European inland waterway system that they can access. This provides an indication of the geographic flexibility of inland ships of given dimensions.

2.2.1 Limits on the length and beam

There is some very distinct logic behind the properties of a waterway and the amount of transport that takes place on it: The waterways on which inland vessels sail often determine the maximum dimensions that a vessel can have and thereby affect the volume and/or weight of cargo it can carry. This in turn determines the economies of scale that are achievable. These dimensional limitations take the form of bridges that may limit the number of layers of containers that can be carried, lock length & width that limit vessel beam and length, water depth that limits the draught of the vessel and/or (legal restrictions resulting from) overall fairway dimensions which may impact length, beam and draught of the ship.

As an indication of the size of ship that can be used on the various waterways in Europe, the waterways have been subdivided into a number of classes by CEMT [European Conference of Ministers of Transport, 1992] as is shown in Figure 2-4, taken from that document. It describes the maximum length and beam that vessels and coupled units can have on each waterway class and provides ranges of the maximum tonnage, draught and height of bridges for these classes.

CLASSIFICATION OF EUROPEAN INLAND WATERWAYS

Type of inland waterways		Classes of navigable waterways	Motor vessels and barges: Type of vessel: General characteristics					Pushed convoys: Type of convoy: General characteristics					Minimum height under bridges 2/	Graphical symbols on maps
			Designation	Maximum length	Maximum beam	Draught 7/	Tonnage		Length	Beam	Draught 7/	Tonnage		
				L(m)	B(m)	d(m)	T(t)		L(m)	B(m)	d(m)	T(t)	H(m)	
1		2	3	4	5	6	7	8	9	10	11	12	13	14
OF REGIONAL IMPORTANCE	To West of Elbe	I	Barge	38.5	5.05	1.80-2.20	250-400						4.0	
		II	Kampine-Barge	50-55	6.6	2.50	400-650						4.0-5.0	
		III	Gustav Koenigs	67-80	8.2	2.50	650-1,000						4.0-5.0	
	To East of Elbe	I	Gross Finow	41	4.7	1.40	180						3.0	
		II	BM-500	57	7.5-9.0	1.60	500-630						3.0	
		III	6/	67-70	8.2-9.0	1.60-2.00	470-700		118-132	8.2-9.0	1.60-2.00	1,000-1,200	4.0	
OF INTERNATIONAL IMPORTANCE		IV	Johann Welker	80-85	9.5	2.50	1,000-1,500		85	9.5 5/	2.50-2.80	1,250-1,450	5.25 or 7.00 4/	
		Va	Large Rhine vessels	95-110	11.4	2.50-2.80	1,500-3,000		95-110 1/	11.4	2.50-4.50	1,600-3,000	5.25 or 7.00 or 9.10 4/	
		Vb							172-185 1/	11.4	2.50-4.50	3,200-6,000		
		VIa							95-110 1/	22.8	2.50-4.50	3,200-6,000	7.00 or 9.10 4/	
		VIb	3/	140	15.0	3.90			185-195 1/	22.8	2.50-4.50	6,400-12,000	7.00 or 9.10 4/	
		VIc							270-280 1/	22.8	2.50-4.50	9,600-18,000	9.10 4/	
									195-200 1/	33.0-34.2 1/	2.50-4.50	9,600-18,000		
		VII						8/	285	33.0-34.2 1/	2.50-4.50	14,500-27,000	9.10 4/	

Figure 2-4: Classification of inland waterways. Source: ***European Conference of Ministers of Transport [1992]***

Of these waterway classes, only waterways of class IV and higher are considered to be of international importance [United Nations, 1996, p. 341], while the most common modern inland ships are adjusted to class Va limits, as was discussed in chapter 2.1. The waterway systems of class VIb and higher, which is where significant increases in main dimensions are possible, are mainly the Rhine, the Danube, some of their tributaries and a number of canals that connect important ports like Amsterdam and Antwerp to the main waterway systems.

The largest units that currently sail on the inland waterways of Europe are the 6-barge pushtows that transport ore and coal from Rotterdam to the German Ruhr area which are either 269.5 m long and 22.8 m wide (long formation) or 190 m long and 34.2 m wide (wide formation). The number of waterways that such vessels can enter is, however, limited: from Rotterdam 6-barge pushtows can only sail along the Rhine up to Koblenz. Vessels with dimensions of 186.5 x 22.9 meters can sail further up the Rhine up to Mannheim, while the Rhine between Mannheim and Strasbourg can accommodate vessels of 135 x 22.9 meters (see Figure 2-6).

The Amsterdam – Rhine canal as well as the Rhine –Scheldt connection, which connect the ports of Amsterdam and Antwerp to the Rhine are class VIb waterways, allow convoys of up to 195 x 22.8 m to pass. The waterways that connect the smaller ports of Gent, Terneuzen and Flushing (Vlissingen) to the Rhine can be navigated by vessels of similar dimensions.

The German port of Hamburg is connected to the main waterways by much smaller canals: Although vessels of up to 190 x 24 m can sail on a part of the river Elbe that stretches from the sea to 170 km east of Hamburg, the main waterways that connect the port to the European inland waterway system are of class IV. On these canals, the maximum ship beam is 9.6 m, while a maximum length of 147 m is possible [Noordersoft]. The same is valid for the ports of Bremen and Bremerhaven, where large vessels can only sail between Bremen and the North Sea. Therefore, for the German ports, scale enlargement is only possible to a limited extent, by using long and narrow vessels or coupled units.

From Constanta, the Danube has locks with chambers of 310 x 34 m or 280 x 34 m all the way up to Vienna (Freudenau, km 1921) and 230 x 24 m up to Geisling (km 2354) [Via Donau, 2007, p. A.27]. Additionally, researchers in the SPIN-NT project state that for the river Danube that: "***Vessel length*** *is restricted by the size of locks and by waterway bends. These restrictions are well above the values implied by the technical logic, so the length (of self-propelled vessel) should not be considered restricted by the waterway."* [SPIN-TN, 2004, p. 12]

From the above, it can be concluded that there is potential to use very large units, but that that potential is mainly limited to the river Rhine, some of its tributaries, the canals that connect the Rhine to several seaports and the river Danube. It can also be concluded that the use of vessels with dimensions that exceed 186.5 x 22.9 meters will greatly restrict an operator's flexibility, especially in the Rhine region, while vessels that do not exceed these dimensions can serve nearly the same geographical area as existing large inland ships of 135 x 17.5 meters. Furthermore, the largest units that can be operated on European waterways will have turning on rivers or in ports unless they are uncoupled. Vessels with a length of 186.5 m will have far less difficulties, since their length is roughly equal to that of existing coupled units, which can operate without needing to be uncoupled in many cases.

2.2.2 Limits on draught

Although the length and beam of inland ships that can be used on certain inland waterways can be determined with relative ease, determination of their maximum draught is more difficult. Especially on the natural free flowing waterways, fluctuations in water depth will occur. The water depth may change dramatically throughout the year and as a result the draught and resulting cargo carrying capacity of vessels will also fluctuate throughout the year. For the lower Rhine, the water depth typically fluctuates between 1.9 and 5 meters, as is demonstrated by Hetzer [2005, p. 47], who uses a data set of least measured depths from 1993 to 2003. The low water depth for the lower Rhine that is used in the Dutch national Traffic and Transportation plan is 2.8 meters, while for more upstream parts of the Rhine it is even lower [Wasser- und Schifffahrtsverwaltung des Bundes, 2009]. A direct consequence of this is that the vessels with the highest draughts, i.e. the largest vessels and push convoys, which have design draughts of 3.5 meters and over, can not always be loaded to their maximum capacity. This in turn negates scale advantages of these larger vessels when water levels are low.

For the Danube (at Wildungsmauer), information from Via Donau [2007] reveals similar fluctuations but with a water depth of only two meters during a large part of the year. This both stresses the need for shallow draught vessels there and demonstrates that vessels that are very effective on a waterway like the Rhine may be ineffective on another, such as the Danube. Furthermore, Bosschieter [2005] indicates that due to climate change, there will be more high water periods in winter and more low water periods in summer on the river Rhine. The Central European University [2008, p. 15] predicts a similar situation for the Danube. The results of the KLIWAS project [Holtmann et al., 2012] show that especially in the more distant future, average water levels on the Rhine will be lower than today.

As a result of this, current deep-draught inland ships may eventually be replaced by ships that are better adapted to shallow water. This expectancy also exists in the ship design community, as is underlined by the presentation by Thill, head of the hydrodynamics department at DST, the German Development Centre for Ship Technology and Transport Systems. Thill predicts lighter and wider shallow draught vessels to cope with low water levels in the Rhine [Thill, 2009]. The idea that the current design draught of vessels has reached an upper limit or has even exceeded it is also voiced by a document from the Dutch government, where an identified area of concern for inland waterway transport is that the draught of vessels is too large [Rijkswaterstaat, 2011a, p. 13].

2.2.3 Future development of infrastructure-imposed limits on ship dimensions

For an assessment of the upper limits of the dimensions of inland ships, it is also necessary to analyze how the waterways on which these ships will sail are likely to develop in the future. Although the development of new waterways pales in comparison with that of road and rail, significant changes to the waterway network have occurred and will occur in the future. The most notable development in the recent past is the Rhine-Main-Danube canal, which was completed in 1992. This 171 km long canal forms a connection between the rivers Main and Danube, thereby connecting the waterway systems of the western and eastern parts of Europe. It has locks of approximately 190 m long and 12 m wide [Encyclopaedia Brittanica, 2010].

In 1996, the *European Agreement on Main Inland Waterways of International Importance (AGN)* [United Nations, 1996] was drafted. It states that only waterways of class IV and up can be considered as waterways of international importance, so called E-waterways [United Nations, 1996, p. 341]. Furthermore it recommends that when waterways of class IV are modernized, they should at least comply with the parameters of class Va waterways. It also states that new E-waterways should meet the requirements of class Vb (which allows ships of 172 x 11.4 m to pass) as a minimum, that a draught of 2.80 meters should be ensured and that vessels and that convoys of greater dimensions should always be taken into account when modernizing existing waterways and/or building new ones. However, the initiatives to act on this are very limited.

In a report by Platina [2010], the main missing links and bottlenecks in the European E-waterway system are discussed. The bottlenecks relate to fairway depth, but also to the class of important fairways, waterway maintenance, locks and bridge heights.

The document identifies the following missing links:

Table 2-1: Missing links in the European waterway system

Country	Missing link	Planning horizon	Cost
Austria	Danube-Oder-Elbe Connection (E 20).	Unknown, no priority	Unknown
Belgium	Meuse-Rhine link	Unknown, no priority	Unknown
	Maldegem - Zeebrugge (E 07).	After 2025	>=200 Million Euro
Croatia	Danube - Sava Canal (E 80-10) from Vucovar to Samac.	Start before 2016, finish before 2025	825 million Euro
Czech Republic	Danube - Oder - Elbe Connection (E 20 and E 30).	Unknown, no priority	Unknown
France	Rhône - Rhine Canal (E 10)	Unknown, no priority	Unknown
	Seine - Moselle Link (E 80)	After 2025	Unknown
	Seine - Scheldt Link (E 05)	Before 2025, started	4 billion euro
	Saône - Moselle Link (E 10-02)	Finish before 2025	10 billion euro
Poland	Danube - Oder - Elbe Connection (E 30).	Unknown	Unknown
Romania	Danube - Bucuresti Canal (E 80-05)	Finish before 2025	900 million Euro
	Olt (E 80-03)	Unknown	Unknown
Slovakia	Danube - Oder - Elbe Connection (E 20)	Unknown	Unknown
	Vah - Oder Link (E 81)	Unknown	Unknown

From the above, it is clear that there are no concrete plans to develop the majority of these missing links in the near future with the exception of the Seine - Scheldt link, for which development has started. However, there is at least a latent intention to allow ships of up to 172x11.4x2.8 m to sail on a larger number of waterways than today.

2.3 Market-imposed limits on ship dimensions

The upper limits of the dimensions of inland ships are not only determined by the physical properties of waterways, but also by the market for transport along these waterways, since a very cost-effective ship will not be successful if it does not have access to the ports where the majority of goods are handled. In this chapter, these market-imposed restrictions are discussed.

In the previous paragraphs, it was established that the use of vessels with main dimensions that are larger than those of common inland ships is mainly restricted to the Danube and the Rhine with its connections to the ports of Amsterdam, Antwerp, Gent Terneuzen and Flushing. However, the amount of transport that takes place on the Rhine, i.e. roughly two-thirds of all inland waterway transport in the western part of Europe [CCNR 2007b], is significantly larger than on the Danube. On the Danube, roughly 55 million tons of goods are transported annually, of which nearly half is transported within Romania. [Gussmagg and Fersterer, 2010]. The main German ports on the Rhine annually handle about 120 million tons [Winter, 2009] and several tens of millions of tons are handled on the main inland ports along large waterways in the Netherlands. [Bureau Voorlichting Binnenvaart, 2011].

The primary focus of this thesis is, therefore, on the Rhine and its connection to the abovementioned Dutch and Belgian sea ports. Since nearly all intermodal inland waterway transport takes place between a seaport and an inland port rather than between two inland ports [Platz, 2009, p14] and many of the bulk goods like coal, ore and petroleum products also enter Europe through a sea port, the amount of goods that are handled in the Dutch and German inland ports give a good impression of the transport flows between these inland ports and the Dutch and Belgian sea ports. Figure 2-5 shows the amount of cargo that is handled in the main inland ports in the Netherlands, while Figure 2-6 shows the annual handled volume of cargo in the main German inland ports along the Rhine.

Figure 2-5: Overview of the main inland ports in the Netherlands
Source: Bureau Voorlichting Binnenvaart [2011]

As was discussed in chapter 2.2, Rotterdam can be reached by a class VII waterway, on which 6-barge push convoys can operate. Antwerp and Amsterdam are connected to this class VII waterway by means of canals of class VIb, on which pushing units of 195 x 22.9 m can sail. All traffic from Amsterdam Rotterdam and Antwerp into Germany takes place via the Rhine, which becomes progressively smaller in Germany and as such can facilitate smaller ships. In Figure 2-6, the Rhine is subdivided into a number of stretches on which inland ships with certain dimensions can sail. The maximum dimensions per stretch are taken from the software package PC Navigo [Noordersoft] and stated in Table 2-2. Figure 2-6 also shows the annual throughput, in millions of tons, of the main ports along the river.

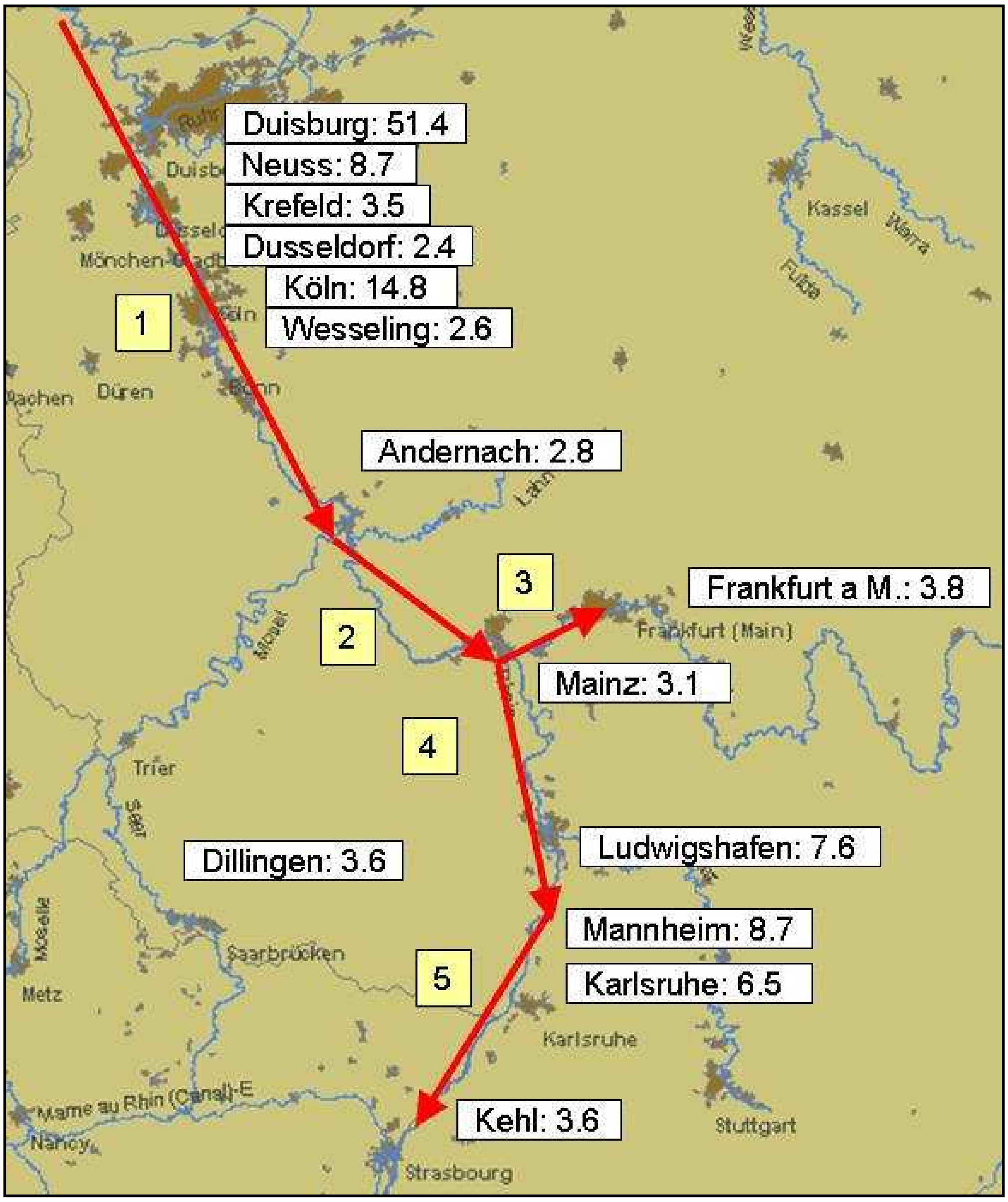


Figure 2-6: Overview of main German ports along the Rhine (throughput in mill. Tons)

Table 2-2: Maximum vessel dimensions on various parts of the Rhine

Stretch ID	Stretch	Maximum dimensions (L x B)
1	Rotterdam - Koblenz	285 m x 22.8 m /200 m x 34.2 m
2	Koblenz – Mainz	186.5 m x 22.9 m
3	Mainz – Frankfurt am Main	186.5 m x 14.0 m
4	Mainz – Mannheim	186.5 m x 22.9 m
5	Mannheim - Strasbourg	135.0 m x 22.9 m

From Figure 2-6 and Table 2-2, it can be concluded that most of the German ports along the Rhine can be served by very large vessels, but that there are also a considerable number of ports that can be served by smaller ships. The Rhine can facilitate vessels of 186.5 x 22.9 m up to Mannheim and vessels of 135 x 22.9 m up to Strasbourg. The Main, from Mainz to Frankfurt am Main can be navigated by vessels of 186.5 x 22.9 m.

From this paragraph, it can be concluded that large inland ships can only operate well on the Rhine and the Danube, but that the Danube constitutes a much smaller market than the Rhine. Due to this large difference in market size, the geographic focus of the research will be on the Rhine. Vessels that exceed a length of 186.5 meters or a beam of 22.9 meters cannot access the ports of Amsterdam and Antwerp, nor can they sail inland beyond Koblenz. Vessels that do not exceed these dimensions can reach the majority of inland ports on the Rhine as well as the seaports of Rotterdam, Amsterdam and Antwerp as well as the secondary ports of Flushing, Gent and Terneuzen. As a result, from a market perspective a length of 186.5 and a beam of 22.9 m are considered the practical upper size limit for inland ships that need to be flexible in the geographic area in which they can operate.

2.4 Synthesis

In this chapter, it was assessed what the practical upper limits for the dimensions of European inland ships are. From the review of the dimensions of existing inland ships, it can be concluded that both physical and regulatory size limits are strong drivers in the choice of the main dimensions of inland ships, but also that there is already a push towards larger ships: the average size of newbuild ships has increased and only 16% of newbuild ships in the period 1996-2008 was suitable for waterways of class IV or smaller, while 22% exceeded the dimensions of class Va waterways. There is a regulatory limit on the length of inland ships, which is set at 135 m, but at the same time, the first inland ship that exceeds these limits is already built.

Since the maximum length that is allowed by the CCNR has however already been increased from 110 meters to 135 meters in the past and is not founded on a hard physical limitation, it is considered to be worthwhile to explore how longer ships would affect the competitiveness of inland waterway transport operators. When such ships prove to be substantially more competitive than existing ships, it will need to be discussed with the CCNR if, and under which circumstances, longer ships can be allowed or a method to divide such large ships when it is required will need to be devised.

From an infrastructural point of view, it was concluded that there is a potential to use very large (coupled) units. From Constanta, the Danube has locks with chambers of 310 x 34 m or 280 x 34 m all the way up to Vienna (Freudenau, km 1921) and 230 x 24 m up to Geisling (km 2354). On the Rhine, the port of Rotterdam is the only sea port that is connected to the Rhine to which vessels that exceed a length of 195 meters or a beam of 22.9 meters have access. Such ships also can not sail beyond Koblenz as a result of which a significant number of inland ports on the Rhine can not be reached. Vessels that do not exceed dimensions of 186.5 x 22.9 m can reach the majority of ports on the Rhine as well as the seaports of Rotterdam, Amsterdam, Antwerp, Flushing, Gent and Terneuzen.

Furthermore, the largest units that can be operated on European waterways will have turning on rivers or in ports unless they are uncoupled. Vessels with a length of 186.5 meters will have far less difficulties, since their length is roughly equal to that of existing coupled units, which can operate without needing to be uncoupled in many cases.

Moreover, it was concluded that the European inland waterway infrastructure will largely remain unaltered in the near future, despite the identification of missing links and a latent intention to allow ships of up to 172 x 11.4 x 2.8 m to sail on a larger number of waterways than today.

Since the market in the Rhine is much bigger than in the Danube region, the geographic focus of the research is placed on the Rhine region. As a result, a length of 186.5 and a beam of 22.9 m are considered the practical upper size limits for inland ships that do not have long term contracts and, therefore, need to be flexible in the geographic area in which they can operate. Such vessels can serve nearly the same geographical area as existing large inland ships. With regard to the draught of inland ships, it is concluded that the upper limit of the existing draughts, i.e. around 4.5 m, will not increase further in the future and that due to longer periods of low water levels and lower mean water levels, vessels with a smaller draught may be more beneficial.

As a result of the above, the practical upper limits on the length, beam and draught are set at 186.5, 22.9 and 4.5 meters respectively. These dimension limits are used in the remainder of this thesis.

3 Literature review on transport cost, technology and building cost of inland ships

In the previous chapter, the practical upper limits of the length, beam and draught of inland ships that operate in the Rhine region were established to be 186.5 x 22.9 x 4.5 m. This has answered the first of the four sub-research questions of this thesis and provided important boundary conditions for the remaining effort to deal with the main research topic, i.e. the determination of which length, beam and design draught of an inland ship lead to the best competitive position for a captain-owner. The second sub-research question that needs to be answered is how the main dimensions of an inland ship relate to its building cost and those technical properties that affect the cost of transport. These data are in turn crucial inputs when answering the last two sub-research questions, in which the relationship between the main dimensions of an inland ship, its operating cost and the total logistical cost of a shipper are analyzed.

In this chapter, it is reviewed to which extent the data and methodologies that are available from literature are sufficient to allow determination of the performance of an inland ship as a function of its main dimensions. The gaps in knowledge that are identified in this chapter are filled through the development of a model in chapter 4 and this model is subsequently used in chapter 5 to create large series of ship designs with systematically varied lengths, beams and draughts. This effectively answers the second sub-research question. The assessment of the performance of various inland ships within the context of a given transport chain will be done in chapter 7, thus answering the third and fourth sub-questions. This is done by means of a cost model that is developed in chapter 6 and the series of ship designs that are developed in chapter 5.

In order to be able to assess the impact of a change in a ship's dimensions on its performance, it is necessary to establish how main dimensions and performance are related. On one hand, main dimensions have an impact on the amount of cargo that a ship can carry and on the other hand they influence the building and operating cost of the ship.

Numerous studies have been performed about the performance of inland ships in transport chains. In paragraph 3.1, it is reviewed to which extent these studies provide data and/or methodologies that can be used to determine the cost, cargo carrying capacity and/or performance of any inland ship as a function of its length, beam and design draught.

Whenever the data and/or methodologies that can be obtained from the cost studies are insufficient, the building cost and cargo carrying capacity of inland ships need to be deduced directly from the technical properties of a ship. Therefore, in paragraph 3.2, it is reviewed which methodologies that may assist in the determination of the technical characteristics of inland ships are available from literature.

In paragraph 3.3 the results from the literature review are synthesized and conclusions are drawn with regard to the way in which the missing data that is necessary for a comparison of inland ships with various main dimensions can be obtained.

3.1 Literature review on transport cost of inland ships

The main dimensions of a ship influence both its cargo carrying capacity and its cost. In this paragraph, it will be established to which extent the data and methods that are available in literature can provide a sufficiently clear image of transport cost and cargo carrying capacity as a function of the main dimensions of a ship. Furthermore it will be determined where there is insufficient knowledge to find the optimal main dimensions of an inland ship.

In the *comparison framework modalities* [NEA, 2001], NEA describe the cost of using ships of a number of types and size ranges as shown in Table 3-1. For these ships, average speed, average cargo carrying capacity, average installed power, utilization by volume, fraction of loaded trips, number of travelled kilometers per year, handling times and awaiting times are stated. All data are based on statistics and assumptions based on existing ships.

Table 3-1: Ship cargo capacity ranges as used by NEA [2001]

Cargo capacity class	Dry bulk & unitized cargo	Wet bulk	Container
< 650 ton	X	X	
650-1000 ton	X	X	X
1000-1500 ton	X	X	X
1500-3000 ton	X	X	X
> 3000 ton	X (pushers)		X

Since NEA specify a size range rather than a specific size, there is no direct relationship between a vessel's main dimensions and its performance and as such no distinction can be made between e.g. a 1501 ton vessel and a 2999 ton vessel. As a result, the data presented by NEA is suitable for the comparison of the performance of different classes of ships, but is insufficiently detailed to compare the performance of vessels with a similar cargo carrying capacity but a different combination of length, beam and design draught. Furthermore, since length, beam and design draught are not explicit variables in the approach by NEA [2001] and the statistical approach that was used relies on data from existing ships, the method can not be used for the detailed determination of the cost transporting goods with ships with non-standard main dimensions.

In a report in which the cost per hour are estimated for inland ships, NEA [2003] provide a breakdown of capital cost, crew cost, maintenance and fuel cost as a function of cargo carrying capacity and number of operational hours for dry cargo ships, tankers, coupled units and pushing units, based on the existing European inland fleet. The direct link that is made between cost and cargo carrying capacity does provide more insight into the relationship between ship size and cost than the previous approach by NEA [2001], but it still does not allow comparison between the cost of a wide shallow draught ship and a narrow deep draught ship of the same cargo carrying capacity, since length, beam and draught are not considered as independent or even explicit variables.

VBD [2004] Provide an extensive yet mainly qualitative overview of the relationship between vessel dimensions and cargo carrying capacity as well as between vessel dimensions, water depth, speed and required power, while providing a number of numerical examples for existing ship types. Furthermore, the report describes a number of innovations and provides recommendations for future vessels. It also provides an elaborate breakdown of building cost, operating cost and capabilities for a number of existing ship types and concludes with a number of case studies of transport cost for various vessels and transport routes. As such, VBD [2004] provides some valuable qualitative insight into the effects of changing main dimensions as well as good benchmarking data, but it does not provide any means for a systematic quantitative analysis of the technical properties or cost of ships with main dimensions that deviate from those of common ships.

Groothedde [2005], in his thesis on hub network design, only briefly describes the specification and cost of a single existing barge for the assessment of the performance of an intermodal chain. No data or methodology is provided to determine the cost of ships that differ from the ship that was used.

Hofman [2006] performs an analysis that is aimed at finding the optimal dimensions for a container vessel on a specified waterway. In that analysis, he reviews combinations of length, beam and draught that do not necessarily follow those of conventional designs. One of the conclusions of Hofman [2006] is that he lacks a weight estimation method that can properly predict the weight of the vessels that he reviews. With regard to the economic analysis in his paper, Hofman only includes fuel cost. As such, Hofman performs an analysis that is useful for container ships, but does not provide all required data for this thesis. He also indicates that there is an important gap in the existing knowledge about inland ships, namely with regard to the determination of the weight of the ship.

Via Donau [2007] provides cost breakdowns and example transport cost calculation schemes for an existing 1350 ton vessel, a 2000 ton vessel, coupled units and pushing units, all operated on the Danube. As a result, Via Donau [2007] provides useful data on existing vessels, but does not explore other designs. As a result, Via Donau [2007] provides neither data nor method for an accurate determination of the cost of operating non-standard inland ships.

Planco [2007] provides an extensive comparison of transport costs for various transport modes. This comparison includes cost per tonkm as a function of utilization, sailing distance and vessel draught for a number of common vessel types. Furthermore, it provides an elaboration of the relationship between fuel consumption, speed and water depth for three common vessel types. Like a number of previous studies that were discussed above, this again provides insight in the performance of existing vessels, but does not include information on non-conventional designs, nor does it include a method to get that information.

Beelen, [2011] provides an extensive overview of the cost models of inland shipping that have been developed in the last decades. These models are all aimed at estimating the cost for existing vessels. Beelen's own cost model includes eight common ship types/sizes, as is shown in Table 3-2.

Table 3-2: Ship cargo capacities as used by Beelen. Source: Beelen, [2011]

Type	tonnage
Spits	350
Kempenaar	500
Enlarged Kempenaar	600
Canal du Nord	750
Dortmunder	1000
Rhein-Herne	1500
Large Rhine Vessel	2500
Large container vessel	4000

As a result, Beelen has provided another method of determining cost for existing ships, but does not provide the information that allows extrapolation of this data to non-standard ships.

Van Hassel [2011] researches the use of small barge convoys in order to revitalize inland waterway transport on small waterways. Van Hassel investigates the technical details of pushboats and container barges with various dimensions in detail, relying on Germanischer Lloyd's rules to determine the weight of the structure and using the ship resistance model by Holtrop, Mennen and van Terwisga [Holtrop et al., 1990] for powering predictions. The upper displacement limit of the designs that are investigated by Van Hassel lies at approximately 800 tons, while the barges have a maximum length of 55.2 meters. For the determination of the building cost of the barges and pushboats, a cost breakdown based on their technical properties is used. As such the approach by Van Hassel provides useful data on small barges, but does not allow extrapolation of these data to larger barges, self-propelled vessels or other ship types like tank ships.

Grosso, [2011] in her thesis on improving the competitiveness of intermodal transport assesses a single container ship with a cargo carrying capacity of 1900 tons, thereby again providing useful data on an existing ship, but not filling the gap in the knowledge that is required for this thesis.

From the above it can be concluded that in virtually all studies in which the cost of transport by inland ship plays an important role, only data on ships of common types and sizes are provided. In the two exceptions where a broader range of dimensions is explored i.e. Hofman [2006] and Van Hassel [2011], neither provides a means of estimating the costs and capabilities for the large range of main dimensions and different ship types that are under investigation in this thesis.

As a result, it is concluded that existing literature on the cost of transport by inland ships does not provide the data or tools that are required to determine the optimal main dimensions of inland ships. The methods that are applied by Hofman [2006] and Van Hassel [2011], however, are considered suitable approaches, since they determine the cost and capability of ships and barges on the basis of detailed technical data.

As a result, it is concluded that modeling the technical characteristics of inland ships and deriving the cost and capabilities of the ships from those characteristics is the only suitable approach. Without the use of a model that can do this, it remains impossible to determine the relationship between the main dimensions of the ship and its performance in a transport chain.

In the next paragraph, it is determined to which extent the methods are available to determine the relevant technical characteristics and cost of inland ships.

3.2 Literature review on technology and building cost of inland ships

In the previous paragraph it was concluded that it is necessary to derive the cost and capabilities of non-standard inland ships from their technical properties since the discussed cost studies do not provide the data or methodologies to extrapolate the cost of transporting goods using standard ships to ships that have different main dimensions.

Before reviewing to which extent the methods to determine these technical properties and the cost associated with them are available from literature, it is shown in Figure 3-1 how the various technical properties of a ship affect its carrying capacity and total cost[2]. It shows that a vessel's dimensions and block coefficient determine its displacement and thereby affect the weight of cargo that can be carried. Cargo weight is also influenced by hull weight and weight of the items that are on board, since the cargo weight is by definition equal to displacement minus all other weights of the ship. Furthermore, the general arrangement affects the space that is available for storage of cargo, while stability my limit the height to which cargo can be stacked.

[2] The representation in Figure 3-1is a simplified one. For readability, it does not show the interrelation between the various technical aspects. Furthermore, it excludes the internalization of any external cost, which, like fuel consumption is influenced by the resistance and propulsion of the ship.

Figure 3-1 also shows that the building cost of an inland ship is determined by three main aspects: main dimensions, propulsion & resistance and other items. The main dimensions determine the price of the hull and together with the design speed also strongly influence the amount of power that is required to propel the ship. The specification of the drive train affects the building cost of the ship, the fuel consumption and the cost of maintenance.

The other items that are on board (navigation equipment, accommodation, steering gear….) affect the maintenance cost, building cost and to a smaller extent also the fuel consumption of the ship. Finally, the crew cost is affected by the length of the ship, since ROS-R regulations prescribe the number of crew members as a function of the length of the ship [Central Commission for Navigation on the Rhine, 2007].

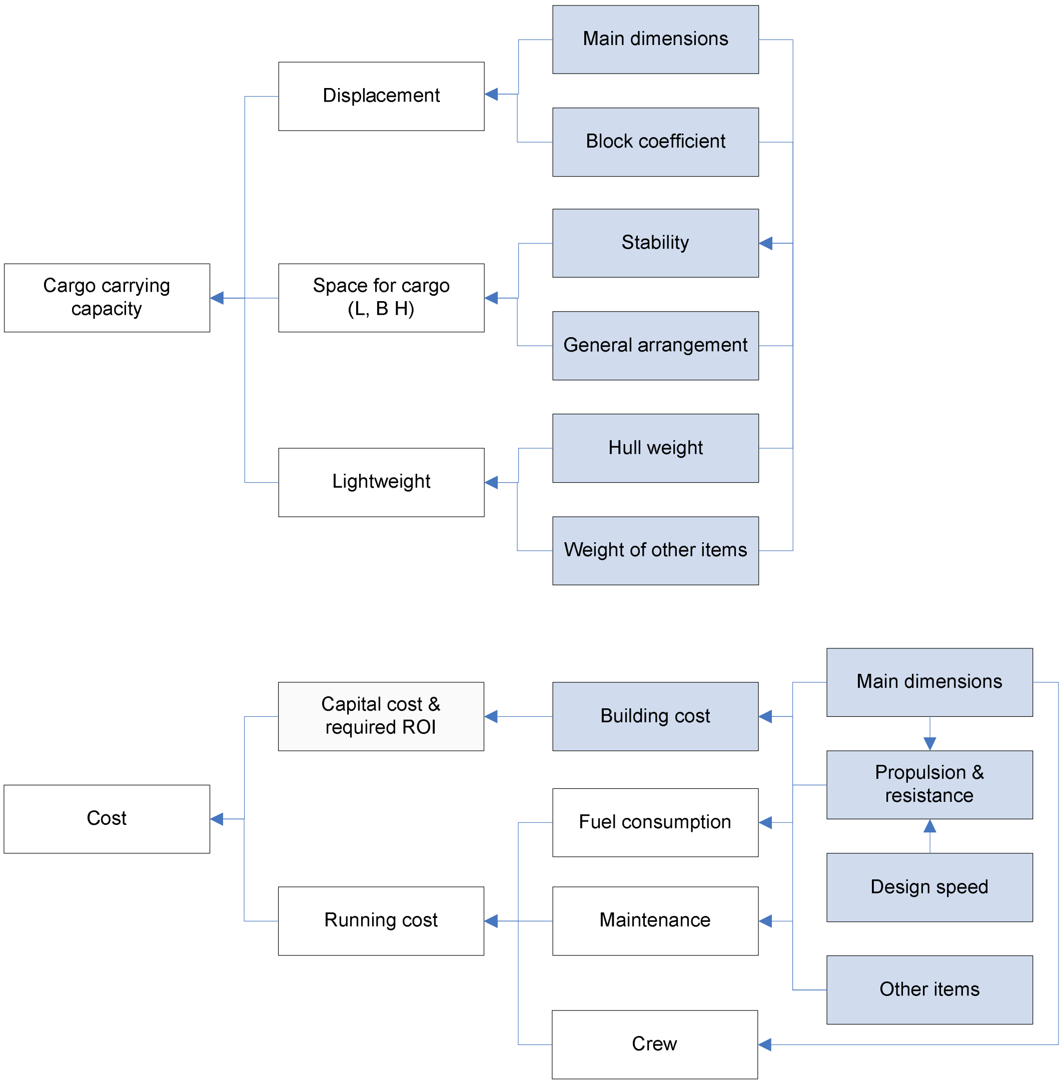


Figure 3-1: Relationship between ship design, cost and cargo carrying capacity

In the remainder of this paragraph, a literature overview is provided for each of the technical aspects in Figure 3-1. This will result in a gap analysis of the knowledge that is required to determine cost and cargo carrying capacity of an inland ship.

Main dimensions
There are typical vessel dimensions that are associated with the various waterway classes as described by CEMT [European Conference of Ministers of Transport, 1992] and there is ample data on the main dimensions of existing vessels from numerous sources. Furthermore, there are limits on the maximum length of inland ships [Central Commission for Navigation on the Rhine, 2010] and regulations concerning the ship length at which the crew requirement of a ship changes [Central Commission for Navigation on the Rhine, 2007]. However, these limits on main dimensions are regulatory or infrastructure-related; there is no technological reason why it is not possible to deviate from these dimensions. Still, exceeding regulatory limits can only be done after gaining approval from the relevant authorities is acquired, which may be challenging or impossible.

Block coefficient
The hullform and block coefficient of a ship are elements of the design that are determined on a case-by-case basis. As a result, there is hardly any literature on the boundary conditions that a hullform needs to meet. However, Heuser [1987] does present 'typical' length and local block coefficients in the bow and stern of inland ships. Furthermore, resistance prediction methods like those by Holtrop & Mennen [Holtrop, 1984, Holtrop and Mennen, 1978] and Holtrop, Mennen and Van Terwisga [1990] use the shape characteristics of the hull to determine a ship's resistance. As a result, there is still design freedom for the hullform, but there is also basic guidance on the selection of the form of a hull and the resulting block coefficient.

Stability
The principles behind the stability of inland ships are no different from those of seagoing ships and, therefore, the methods that can be used to determine the stability of a ship are considered common knowledge. There are, however, regulations that are related to the stability of inland ships which need to be adhered to [European Parliament and Council of the European Union, 2006a]. These regulations affect the freeboard of the ship and may limit the amount of cargo that can be carried.

General arrangement
The general arrangement of the ship determines the dimensions of the cargo hold(s) and thereby the amount of cargo that fits in the hold. The general arrangement of an inland ship is the result of a large number of design choices, as a result of which there are no rules of thumb or similar design methods available that will allow quick determination of the dimensions of the cargo hold of a ship with given main dimensions. However, there are rules from various classification societies that determine certain dimensions of the ships arrangement such as the height of the double bottom and the length of the fore peak [Lloyds register, 2008]. Furthermore, ADN regulations [Economic Commission for Europe, 2009] set requirements for the minimum height of the double bottom, width of the double sides and maximum volume of individual tanks of ships that carry dangerous goods. It is concluded that despite of some regulatory guidance there is no readily available method to determine the dimensions of the hold of an inland ship. As a result, it is necessary to make a rough general arrangement of the ship in order to determine the dimensions of its cargo hold.

Hull weight
The hull weight or steel weight of inland ships constitutes one of the main gaps in required knowledge on the technical characteristics on inland ships, as will be demonstrated.

Hengst [1995, p. 119], who provides a broad overview of the inland shipping sector, directly refers to the detailed calculations of classification societies for the determination of the vessel's structure and provides no estimation methods for the weight of inland ships. The classification societies provide detailed calculations for the various structural elements of the ship, while for use as quick reference formulas, Germanischer Lloyd and Bureau Veritas [Germanischer Lloyd, 2006, Pt B, Ch 4, Sec 2, par 5.2] only state a steel weight of 0.15 * LBD for vessels with a depth of 3.7 m or less and 0.1 * LBD for vessels with a larger depth. Apart from the obvious weight discontinuity resulting from this approach and the fact that no differentiation by vessel type is provided, it is considered to be too inaccurate for the calculation of the cargo carrying capacity of non-standard vessels since length, beam and draught are not independent variables in this formula.

Rules by Lloyds Register [2008], the main classification society for inland ships, do not provide quick weight estimates like those by Germanischer Lloyd [2006] but only provide detailed requirements for steel structures of inland ships As a result, these rules require a detailed and time-consuming analysis of the steel structure before a weight estimate can be made.

This lack of available quick weight estimation methods is further underlined by Hofman [2006], who describes a method to determine the optimal characteristics for an inland container vessel for a specified waterway. In this paper, Hofman concludes that he lacks a proper way to determine the lightweight for those inland ships since direct calculations of scantlings, based on rules alone, leads to an underestimation of lightweight. Hofman also states that previous methods by Heuser [1986] and Michalski are inadequate for his purposes since the work by Heuser stems from 1986 and is a rough one, based on LBD rather than individual ship dimensions while the work by Michalski only covers a small range of vessel sizes.

Heuser [1986] does provide one of the few weight estimations that are valid for inland ships, but only uses LBD (length x beam x depth) as a variable and does not subdivide lightweight into steel weight and other weight elements. As a result of this, the method is too crude for the weight estimation in this thesis since it does not include length, beam and design draught as independent variables.

The only known paper in which the effects of length, beam and draught on the weight and building cost of inland ships are systematically explored stems from 1978 [Schellenberger]. The paper provides data on the steel weight and cost of hull construction of dry cargo vessels and dry cargo push barges with lengths between 75 and 125 meters, beams between 8 and 15 meters and depths of 3 to 4.5 meters. The calculations are made according to rules that are now over 30 years old and are based on the calculated scantlings of the midship according to the Germanischer Lloyd rules of the time, rather than the weight of the entire hull. Furthermore the weight of container ships and tankers is not covered and the range of dimensions that is explored by Schellenberger [1978] is smaller than the range of main dimensions that is under review in this thesis. Therefore, this data too is considered insufficient.

This lack of up-to-date inland navigation-specific calculation methods would not be a particular problem if there were a large degree of similarity between seagoing and inland ships; one could use methods for small seagoing ships as a basis and derive values for inland ships from those. Unfortunately, this large degree of similarity between the steel structures of seagoing and inland ships does not exist; Due to the vastly different environmental conditions (i.e. mainly no significant waves), near absence of freeboard and different L/B, B/T and D/T ratios, steel weight estimates for seagoing ships can not be used for inland ships.

Figure 3-2: Koppelverband Evanti, note the virtual absence of freeboard. Source: own photograph

In Table 3-3, it is demonstrated how the differences between seagoing ships and inland ships affect the validity of weight estimation methods that are intended for seagoing ships when they are applied to inland ships. In the table the results of the steel weight estimation method by Watson and Gilfillan for coasters, bulk carriers, container ships and tankers [Watson, 1998, p. 82] are compared to known steel weights of the bare hulls of three existing inland ships:

Ship A) A 86 x 9.6 x 3.5 m (L x B x D) dry cargo vessel
Ship B) A 135 x 11.45 x 4.25 m (L x B x D) dry cargo vessel
Ship C) A 110 x 11.4 x 5 m (L x B x D) tank vessel

Table 3-3: Comparison of inland ship steel weight with estimation method of Watson & Gilfillan

Ship	W&G coaster	W&G bulk	W&G container	W&G tanker	Actual
A	463 T	478 T	556 T		375 T
B	1091 T	1128 T	1309 T		845 T
C				953 T	700 T

From Table 3-3, it is clear that for each of the ships, the structural weight is always overestimated and as a result, the method is not applicable for inland ships.

From this review of weight estimation methods, it is concluded that the estimation of the steel weight of inland ships represents an important gap in knowledge that needs to be addressed, especially since steel weight has a direct influence on both the cargo carrying capacity of the ship and on the building cost of the hull.

<u>Other items</u>
For the determination of the weight of the main machinery, equipment items, outfitting and accommodation, few estimation methods exist. This is at least partly due to the high degree of freedom that a designer has to choose the most suitable equipment for his design. For inland navigation, no quick estimation methods have been published, while machinery weight estimations for seagoing ships such as that by Watson [1998] are not applicable due to the fact that the type of engine that is used in inland ships is substantially different from the types of engines that are used in seagoing ships: inland ships use light, high speed engines rather than the heavier slow or medium speed engines common on seagoing ships and there is virtually no auxiliary equipment.

There are only a few other sources on the weight of items on board of inland ships. Gerr [2001] provides weight estimates for propellers and propeller shafts and the European Parliament and

Council of the European Union [2006a] provide requirements for the weight of anchors and anchor chains.

From this, it can be concluded that there is a very limited set of estimation methods available for the determination of the weight of the items on board of a ship, while for many items like electrical components, bow thrusters, cargo gear, accommodation, wheelhouse, etc. such methods are lacking. As a result, this too forms a gap in knowledge that needs to be addressed.

Building cost

From literature, only a partial picture of the relationship between the technical properties of an inland ship and its building cost can be obtained. Several sources list the commercial prices for a number of standard ship types [Vries, 2000], [Schuttevaer, 2011], [EICB 2011]. VBD [2004] provides a rough breakdown of the building cost into various components. A more detailed estimate of the cost of specific elements of the ship is provided by a number of other sources, as will be discussed below.

The building cost of a ship can be subdivided into the cost of all activities by the yard and the cost of all activities by subcontractors. The yard typically manages the project, designs and engineers the ship and erects the hull, while subcontractors supply and install all equipment. The yard-related cost can be estimated by combining the estimates of Kerlen [1981] and Coenen 2008, p15]. Kerlen [1981] provides a building cost estimate for the hull as a function of LBD, steel price and labor cost, while Coenen [2008] provides an estimate of the cost of engineering, including procurement and ship management.

For some of the systems that are supplied and installed by subcontractors, cost data are available from various sources, while for other systems, no reference data is available from literature. For the drive train, Hunt and Butman [Hunt & Butman, 1995, 9-2] arrive at a cost estimate as a function of installed power expressed as cost = c x P_{inst}^{n}, while Aalbers [unknown year, 200X] arrives at a similar estimate for the relationship between power and cost of the drive train. However, due to the fact that Aalbers, Hunt and Butman look at seagoing ships with medium and slow speed engines, running on marine diesel oil and heavy fuel oil, the coefficient of cost that is used is not believed to be representative for high speed inland ship engines that run on gasoil. The power of 0.79-0.82 that Aalbers, Hunt and Butman arrive at, however, is believed to provide an acceptable indication for scale effects.

Stapersma, [2001] provides a more detailed approximation of specific unit purchase cost (supc) of an engine based on the detailed characteristics of the engine. For propellers, shafting and attached hydraulics (if any), lecture material from Delft University of technology [Delft University of Technology, 2009] quotes values for fixed and variable pitch propellers operating at various speeds.

Schneekluth and Bertram [1998, p. 95] provide a trend for the cost of hatch covers: They state that hatch cover price depends linearly on length and to the power 1.6 on width.

Outfitting, which is generally recognized as one of the most difficult and design-specific cost elements to calculate, is determined as a function of outfitting weight to the 2/3 power both by Watson [1998, p. 478] and Hunt & Butman [1995].

From this, it can be concluded that there are several handholds to determine the cost of inland ships, but also that up-to-date cost data are very scarce due to the age of several literature sources. Furthermore, import cost elements such as the cost of the accommodation, wheelhouse, navigation equipment, electrical installation, rudders, bow thrusters, cranes and piping of tankers are still lacking. Therefore, the data from literature will need to be supplemented with recent cost data from actual ships before a proper cost model for inland ships can be assembled.

Propulsion & resistance

To determine the power that is required to propel a ship of given dimensions over a given waterway at a given speed it is necessary to determine the following aspects:

- Ship resistance
- Propeller open water efficiency
- Wake fraction & trust deduction
- Losses in the drive train

For each of these aspects, the sources for available calculation methods are briefly discussed.

Through the years, various methods have been developed to assess the resistance and propulsion of especially seagoing ships[3]. One of the most important methods in use today for the estimation of the resistance of seagoing vessels is the work of Holtrop and Mennen [Holtrop, 1984; Holtrop and Mennen, 1978].

However, since inland ships typically have a higher block coefficient, larger L/B ratios and larger B/T ratios than seagoing ships, the method by Holtrop and Mennen [1978] is not by definition suitable for inland ships. Several resistance calculation models that are dedicated to inland ships have been developed over the years, as is aptly described by Van Terwisga [1989]. Since then, no major new methods or references to such methods have been found apart from the method by Holtrop, Mennen and Van Terwisga [1990].

All of the methods discussed above determine the resistance of ships sailing in deep water. If a ship sails in shallow water or restricted water, like inland ships do almost continuously, this increases their resistance, which needs to be compensated for. Lap [1957] provides an elaborate overview of the available methods to account for these effects, including the work of Schlichting (1934), which is still counted among the most important methods to correct for shallow water effects. Van Terwisga [1989] discusses an alternative method by Karpov[4] which, like Schlichting (1934), corrects for shallow water, but not for the cross-section of the channel. Jiang [2001] provides a more recent method to correct for shallow water effects and Raven [2012] discusses several newer correction methods which provide a correction for the form factor of a ship due to shallow water effects.

Two other methods do correct for the channel cross-section but in turn do not correct for the shallow water effects: Schijf, as discussed elaborately in e.g. Verheij et al. [2008, Ch 3] relies heavily on As/Ac, the ratio between the ship's underwater cross section and the cross section of the waterway, as does the method of Kreitner, discussed by Lap [1957].

In order to get from the resistance of the ship to the power that needs to be transmitted to the propeller by the engine, it is necessary to determine the efficiency of the propeller. For this, several systematic series of propellers have been researched. The best known of these series are the Wageningen B-series of propellers as discussed by Oosterveld and Van Oossanen [1975] and a series of Kaplan type propellers in type 19A nozzles as presented by Oosterveld [1970]. These propeller series are widely applied for seagoing ships, but due to their high propeller loading, inland ships often use custom propellers that differ from the specifications of the propellers from these series. The only series of propellers that have been developed especially for inland ships is the Meyne-VBD

[3] The major empirical methods for the estimation of ship resistance have been developed before 1990, so all literature discussed in this paragraph is relatively old, but still considered to be the state-of-the-art.

[4] The original paper by Karpov, (Karpov, A.B., "Calculation of Ship resistance in restricted waters", TRUDY GII T. IV, Vol. 2.,1946) is written in Russian and is no longer publicly available.

series from VBD [2002], which is, however, also not commonly applied on inland cargo ships due to the higher cost, complexity and vulnerability of the propellers[5].

The wake fraction and thrust deduction for inland ships may be estimated by Papmel's formulas as presented amongst others in Van Terwisga [1989], while a method for the prediction of thrust deduction is presented in that same source. Finally, for the losses in the drive train, Klein Woud and Stapersma [2002] provide the relevant values.

From the above, it can be concluded that there are usually several methods to choose from when determining the required power to propel an inland ship of given dimensions over a given waterway at a given speed. Despite the fact that many of these methods are relatively old and as such it is likely that their accuracy may be improved upon by newer methods, they do provide the means to make an acceptable first estimate of the resistance and propulsion characteristics of inland ships.

Design speed

The design speed is the result of the previously discussed resistance and propulsion of the ship and has a strong influence on the amount of power that needs to be installed in a ship. The design speed of an inland ship is not fixed, but does need to meet the constraint that is has a minimum value of 13 km/h [European Parliament and Council of the European Union 2006a]. Usually, the chosen design speed exceeds this value for economic reasons.

3.3 Synthesis

In chapter 1.2.2, it was established that it is worthwhile to research if inland ships with main dimensions that deviate from the main dimensions that are common on the European waterways can improve the competitive edge of captain-owners. In order to determine which length, beam and design draught of an inland ship lead to the best competitive position for a captain-owner, it is necessary to establish how a change in length, beam and/or design draught affects the cargo carrying capacity, building cost and operating cost of a ship.

In this chapter, it was investigated to which extent the required data and/or methods to do this can be obtained from literature. It has been shown that the cost studies for inland shipping that have been executed over the last decade only present data for ships with common main dimensions. These methods do not provide methods that allow extrapolation of this data to ships with other main dimensions since length, beam and design draught are not explicit variables in any of the studies. In a limited number of cost studies, the relationship between the technical properties of a ship and its cost is investigated. However, these studies either focus exclusively on small barges and pushers [Hassel, 2011] or conclude that some of the necessary data and methods to determine the required technical characteristics of vessels are missing [Hofman, 2006].

From this, it is concluded that the executed cost studies provide insufficient data and/or methods to be able to answer the main research question of this thesis. As a result, it is necessary to make a more in-depth analysis of the technical characteristics and cost of inland ships and to derive the relevant values for an analysis of the transport cost from this analysis. In the second part of this chapter, it was assessed to which extent technology-oriented literature is available with which such an analysis can be made.

From this overview, it was concluded that usable estimation methods are available for a number of relevant aspects of the ship. However, some crucial elements are also missing: there are no proper

[5] Information obtained through a private conversation.

estimation methods available for the weight of the hull, the weight of all items on board of the ship, the dimensions of the hold(s) and the building cost of the ship. These gaps in knowledge need to be addressed before the main research question of this thesis can be answered.

Furthermore, from the methods and tools that are available, the most suitable ones need to be selected and all of the selected and newly developed methods need to be integrated into a consistent design model with which the relevant technical characteristics and the building cost of an inland ship with given main dimensions can be determined.

The way in which the gaps in knowledge are filled and all methods are integrated into a single design model is discussed in chapter 4. In chapter 5 this design model is used to generate designs and cost estimates of several large series of inland ships with systematically varied main dimensions and in chapter 5.6 the newly developed knowledge on the weight and cost of inland ships is captured in a number of rules of thumb, thereby making the knowledge available to the scientific community and general public in a practical and easily digestible way.

How the designs that are developed in chapter 5 perform in a certain transport chain is investigated in chapter 7, which also provides the answer to the main research question of this thesis. In order to make these analyses possible, in chapter 6 a transport cost model is developed with which the performance of a given ship design in a specific transport chain can be assessed.

4 A design model for inland ships

In the previous chapter, it was concluded that there are gaps in the knowledge that is required for the determination of the technical properties and building cost of inland ships as a function of length, beam and design draught. These gaps in knowledge need to be filled before the main research goal of this thesis, i.e. the determination of the length, beam and design draught of an inland ship that lead to the best competitive position for a captain-owner, can be answered.

In chapter 3.1, it was established that the existing literature on the cost of transporting goods with inland ships does not provide the data or methods that are required to determine the cost of transporting goods with ships that have main dimensions that deviate from common main dimensions. As a result of this, it was concluded that it is necessary to determine the operating cost, building cost and cargo carrying capacity of an inland ship with given main dimensions on the basis of its technical properties. From the literature review on the methods that are available to determine the technical properties of inland ships in chapter 3.2, it was established that there are a large number of methods available, but that there are also some important gaps in the available knowledge. These gaps mainly concern the determination of weight, hold dimensions and building cost.

In this chapter, for those cases where knowledge or methods were lacking, the right methods are created. Where multiple methods to calculate certain characteristics are available, the most suitable one is selected. Furthermore, all developed and selected methods are joined into an overall design model which is validated and for which a sensitivity analysis is performed. This model is used in chapter 5 to develop several large series of ship designs with systematically varied main dimensions. In chapter 7 it is assessed which of these designs results in the lowest cost when it is used on a specific route in a specific transport chain. This is done using a cost model that is developed in chapter 6.

4.1 Specification of the design model

Before elaborating the details of the design model that is developed in this chapter, the functional requirements of this model need to be discussed. Since it was determined in the previous chapters that the building cost and cargo carrying capacity of inland ships with main dimensions that deviate from common main dimensions can only be determined on the basis of the technical properties of the ships, the model needs to be able to determine all technical properties that influence these two aspects. For completeness, Figure 3-1 from chapter 3, which shows how the various technical aspects and cost of the ship relate to the cargo carrying capacity and total cost of using the ship, is iterated below in Figure 4-1.

Since the model will be used to determine the building cost and cargo carrying capacity of inland ships with main dimensions that deviate from those of common inland ships, it is important that the model allows for free variation of length, beam and design draught as independent variables. Furthermore, since the vessel types that are under investigation in this thesis are dry bulk, container and tank vessels (see chapter 1.5) the model needs to be able to deal with these three ship types.

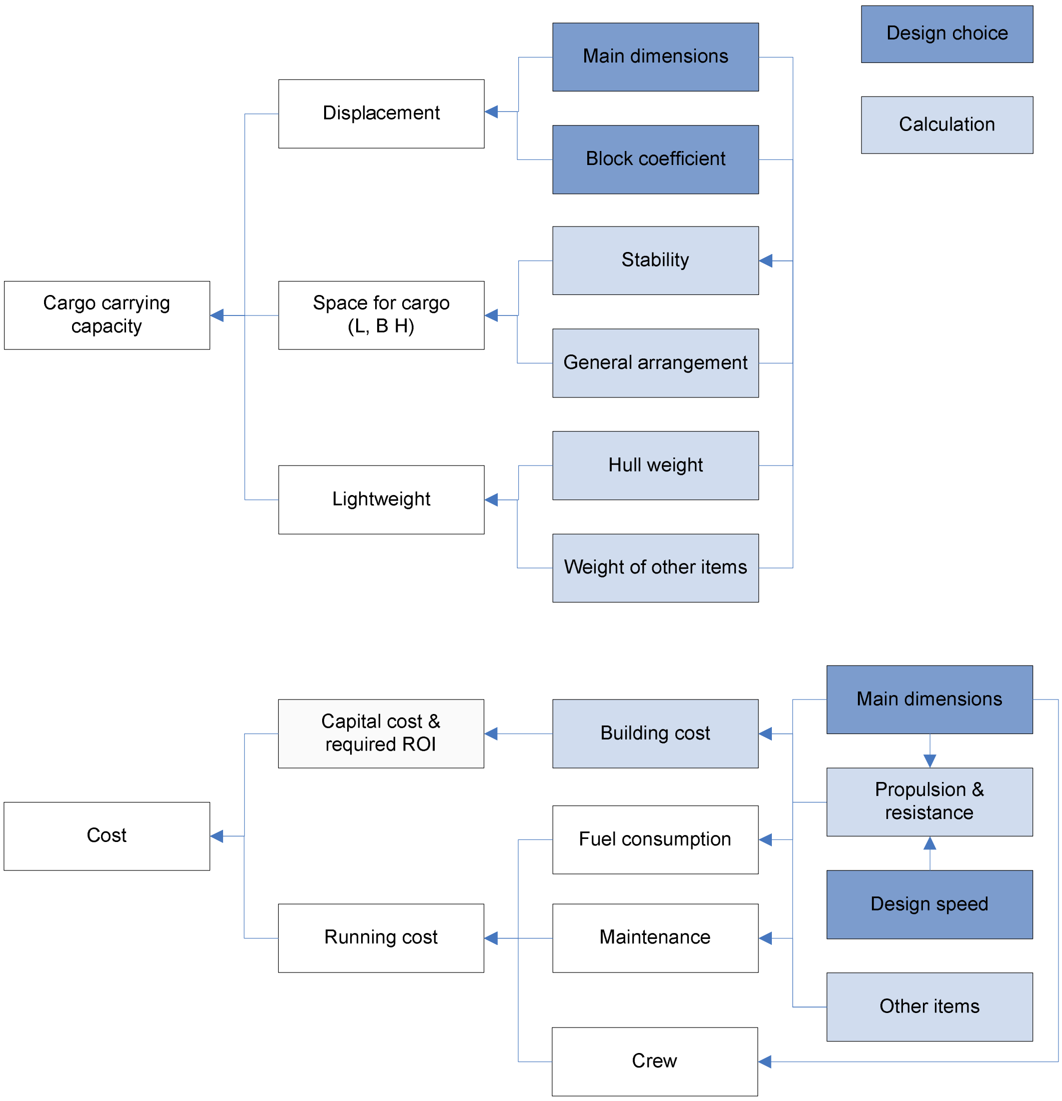


Figure 4-1: Relationship between ship design, cost and cargo carrying capacity

Not all of the calculations that are shown in Figure 4-1 (i.e. the light blue blocks) can be performed within a ship design model since they require knowledge about the transport chain in which the ship operates.

Stability requires knowledge about the properties and amount of cargo that is on board of the ship, which may be limited by water depth or bridge height limitations. Therefore, the design model will not include a final stability calculation, but will need to be able to determine the center of gravity of the hull and all items on board. This way, a stability calculation can be made once the limitations that are posed by infrastructure are known.

The propulsion & resistance calculation also depends on the loading condition of the ship and the properties of the waterway on which it sails. However, it is necessary to make a propulsion & resistance calculation as part of the design of the ship as well in order to determine the amount of power that will be installed.

As a result, the design model includes all calculations except for the stability calculation which, together with a separate propulsion & resistance calculation to determine fuel consumption, is included in the cost model that is developed in chapter 6.

The structure of the model is as shown in Figure 4-2. In this figure, light blue blocks represent calculations which are elaborated in this chapter, dark blue blocks represent design choices and yellow blocks represent model outputs.

The dark blue blocks show that the user of the model should select the ship type, main dimensions and hull form parameters as well as the desired size of the accommodation, type of wheelhouse and non-propulsion related equipment. On the basis of the main dimensions and hull form, a propulsion & resistance calculation is made, leading to the specification of the drive train. The drive train and all other items on board are fitted into the hull to arrive at a general arrangement, which in turn forms the basis for the calculation of the ship's structure. Based on the specifications of all items on board, their weight and cost are calculated while the cost of the hull is based on its weight and several secondary parameters which will be discussed in detail at a later stage.

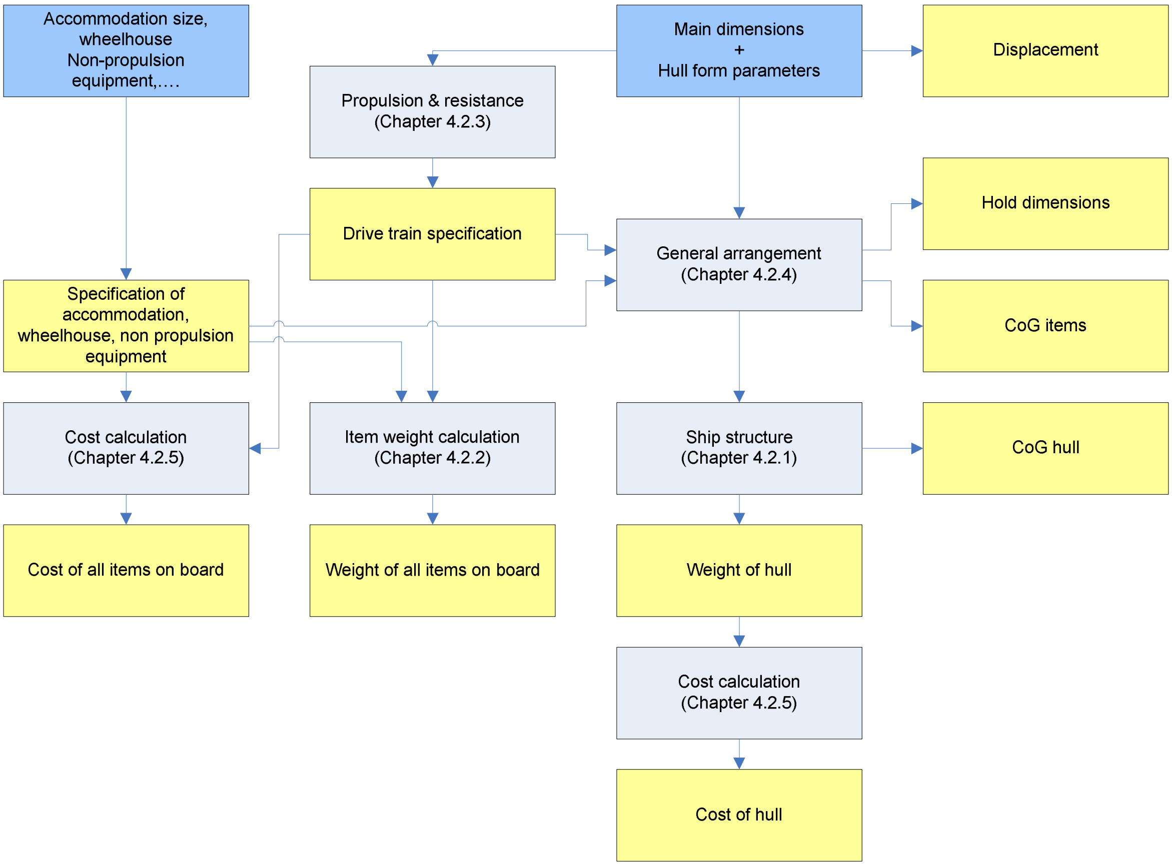


Figure 4-2: Design model structure

From Figure 4-2 above, it can be observed that the model produces all relevant values that are stated in Figure 4-1: The hullform determines displacement, while the weight of hull and weight of all items on board equals lightweight. The general arrangement provides the dimensions of the holds and the combined information of the weight and center of gravity of the hull and all items on board allows for a stability calculation at a later stage. Furthermore, the cost of all items and the cost of the hull allow for determination of the building cost of the entire ship and the specification of the drive train together with the main dimensions and hull form allow for case-specific propulsion & resistance calculations to determine fuel consumption.

4.2 Discussion of model calculations

In the following sub-paragraphs, the five calculations that are included in the model (see Figure 4-2) are discussed:

- Steel weight is discussed in paragraph 4.2.1.
- The weight of machinery, equipment & outfitting is discussed in paragraph 4.2.2.
- Propulsion & resistance are discussed in paragraph 4.2.3.
- The general arrangement is discussed in paragraph 4.2.4.
- The building cost is discussed in paragraph 4.2.5.

The validation of the most important calculations is discussed in chapter 4.3 and a sensitivity analysis is performed in chapter 4.4.

4.2.1 Steel weight

The first of the five abovementioned aspects to be discussed in this chapter is the determination of steel weight. As was concluded in chapter 3.2, there are no suitable quick methods available for the estimation of the steel weight of inland ships. Therefore, a detailed analysis is made of the scantlings of all main structural elements of the ship as required by class, i.e. according to the rules by Lloyds Register [2008]. Based on these scantlings and a rough 3D general arrangement (which will be elaborated in paragraph 4.2.4), all of the main structural elements for the ship are designed, leading to a 3D steel plan such as the one that is shown in Figure 4-3.

Since the size, weight and position of all structural elements are determined on the basis of a 3D-general arrangement, this approach results in a weight estimate as well as an estimate of the center of gravity of the structure.

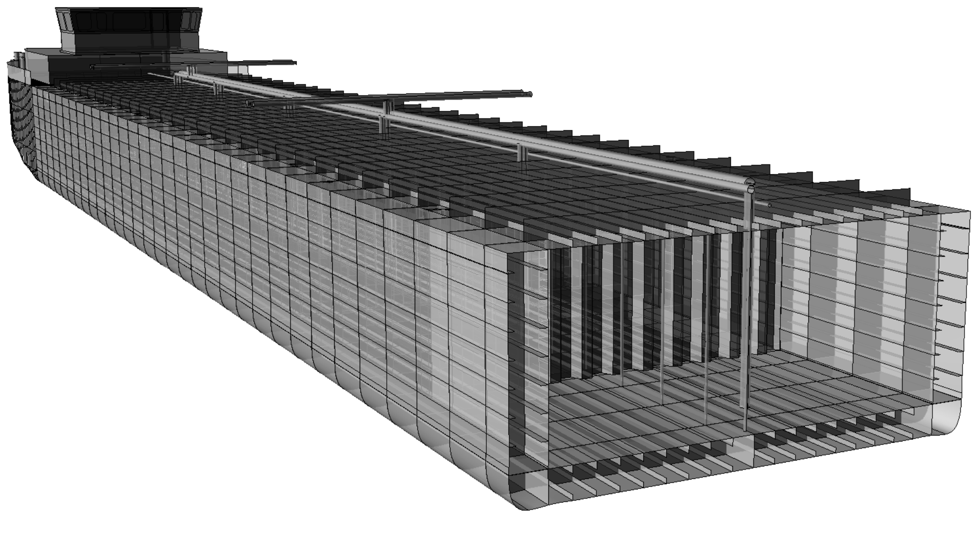


Figure 4-3: Example ship design created by the design model

Still, even with an accurate calculation of the scantlings of the main structure, the weight of the vessel will be underestimated due to the absence of structural details and additional weight due to e.g. welds and paint. Furthermore, uncertainty in the actual weight of structural members occurs due to the fact that lightening holes in webframes, floors, plate stringers and non-watertight girders are not modeled and that local reinforcements to support machinery other than the main engine and generator sets are also not modeled. Finally, simplification of the hullform, especially in the aftship may also lead to errors in structural weight.

This has been compensated for by applying the following weight additions and subtractions to the calculated weight of all structural items:

- All structural elements in the midship and foreship have been allocated a 10% weight addition.
- All structural elements in the aftship have been allocated a 15% weight addition.
- A 25% weight reduction is applied to the weight of webframes, floors, plate stringers and non-watertight girders in order to account for lightening holes.
- A 30% weight reduction is applied to plate frames in tanks.

Such values are common values within naval architecture and it will be shown later on in chapter 4.3.1 that these assumptions result in realistic steel weights.

4.2.2 Weight of machinery, equipment and outfitting

The second of the five elements of the design model that are discussed in this chapter is the weight of the machinery, equipment and outfitting, which is discussed in this paragraph.

For the determination of the weight of the main equipment items, similar issues occur as for the determination of steel weight: for inland navigation no quick estimation methods have been published, while machinery weight estimations for seagoing ships such as that by Watson [1998] are not applicable due to the fact that the type of engine that is used in inland ships is substantially different from the types of engines that are used in seagoing ships: inland ships use light, high speed engines rather than the heavier slow or medium speed engines that are common on seagoing ships and there is virtually no auxiliary equipment. To remedy this absence of estimation methods for equipment weight, formulas are derived for the weight of the ship's main components based on actual product lines of manufacturers and/or reference data from actual inland ships. For items for which data from literature is available, that literature is used. The weight of machinery, equipment and outfitting is subdivided into the following elements, which represent the main weight groups of inland ships:

1. Propulsion & maneuvering
    a. Engines
    b. Gearboxes
    c. Shafts
    d. Propellers
    e. Rudders
    f. Steering machines
    g. Bow thrusters/pumpjets
2. Electrical power system
    a. Generator sets
    b. Switchboards
    c. Frequency converters
    d. Electrical motors
3. Miscellaneous engine room weights
4. Accommodation
5. Piping
6. Miscellaneous items
    a. Masts
    b. Wheelhouse
    c. Wheelhouse raising column
    d. Winches
    e. Anchors & chains
    f. Small ironwork

The way in which the weights of the various equipment items determined is elaborated in detail in appendix B.

4.2.3 Propulsion & resistance

The third of the five design elements that are discussed in this chapter (i.e. steel weight, weight of machinery, equipment & outfitting, propulsion & resistance, general arrangement and cost) is the propulsion & resistance of the ship, which is discussed in this paragraph.

An important aspect of the building cost, running cost and, to a lesser extent, weight of a ship is the amount of power that is installed. For all ship types, various energy consumers can be named but especially for cargo carrying vessels, the main consumer is always the propulsion system. Therefore, it is imperative to have a relatively accurate estimate of the required power for the propulsion of a ship. How this is achieved for this thesis is elaborated in the following sub-paragraphs.

The required power for propulsion is the result of both the vessel's resistance and its propulsion characteristics. Here, for clarity the typical way of calculating required power for ships as can be found in many textbooks is briefly iterated without attempting to iterate the full textbook explanation behind the calculation.

First, the power that needs to be delivered by the ship's propellers (P_e) can be calculated by:

$$P_e = V \cdot R \qquad \text{Eq. 4-1}$$

Where:
P_e = effective power (kW)
V = ship speed relative to water (m/s)
R = ship's resistance (kN)

R, the ship's resistance can be calculated on the basis of a resistance model, as will be discussed below. However, due to the interaction between hull and propeller, the output power that needs to be produced by the propeller(s), P_t, is not equal to P_e, as a result of the wake fraction (w) and thrust deduction factor (t). The ratio between P_t and P_e is called the hull efficiency, η_H.

$$\eta_H = \frac{1-t}{1-w} \qquad \text{Eq. 4-2}$$

Where:
η_H = hull efficiency (-)
t = thrust deduction (-)
w =wake fraction (-)

Next, to get to the input power for the propeller from the drive train, it is necessary to account for the open water efficiency of the propeller (η_O) and the relative rotative efficiency (η_R), which accounts for the effects of non-uniformity of the flow field in front of the actual propeller.

Finally before the required output power of the engine can be determined, losses in the shafting, expressed by efficiency η_S, need to be accounted for as well as losses in the gearbox, expressed by efficiency η_G
As a result, the power that is required from the engine can be expressed as:

$$P_D = \frac{R \cdot V}{\eta_H \cdot \eta_O \cdot \eta_R \cdot \eta_S \cdot \eta_G} \qquad \text{Eq. 4-3}$$

Below, it is discussed how all abovementioned variables are treated in this thesis. First, the resistance of the ship (R) is discussed and then the various efficiencies in the powering calculation are elaborated.

Resistance

As was discussed in chapter 3.2, through the years various methods have been developed to assess the resistance of especially seagoing ships[6]. One of the most important methods in use today is the work of Holtrop and Mennen. Tracing back the method to its roots through their various development stages [Holtrop, 1984] [Holtrop and Mennen, 1978], the method is found to be built around a large set of experimental data for various types of ships [Holtrop, 1977], including but not limited to ships with a high prismatic-coefficient like tankers and bulk carriers (Cp between 0.73 and 0.85, L/B between 5.1 and 7.1) and more slender vessels like container vessels (Cp between 0.55 and 0.67, L/B between 6.0 and 9.5). All in all, the primary dataset that the method is built on covers Cp values between 0.55 and 0.85 and L/B ratios of 3.9 to 9.5. The inland vessels that are reviewed in this thesis, with typical prismatic coefficients of 0.85 and higher and L/B between 4 and 20, partly fall outside of this reference data.

Still, the method is believed to provide a reasonable approximation of inland vessel resistance for lack of a better alternative, since virtually no seagoing vessels exist that have L/B ratios as large as those that are reviewed here (L/B up to 20) and as a result no other estimation method has the required data to fill the gap that is left by Holtrop & Mennen. However, the method relies heavily on relatively detailed knowledge of the hullform and propulsion, which makes a proper prediction of the expected resistance of inland ships using the method of Holtrop and Mennen less than ideal, especially considering the fact that no significant amount of hullform optimization is attempted here.

As a result, a different method that is tuned for inland ships is desirable. Several such models have been developed over the years, as is aptly described by Van Terwisga [1989]. No newer methods or references to such methods have been found apart from the method by Holtrop, Mennen & Van Terwisga [1990]. In the methods discussed by Van Terwisga, mainly vessels with L/B between 1 and 6.9 were researched, except for a very old method from the 1940’s, which used a larger range. As a result these methods are deemed less suitable than the method described by Holtrop, Mennen & Van Terwisga [1990], which is the most recent method that covers Lwl/B ratios up to 7.25 and B/T ratios up to 10.

A weakness of this method is that it does not cover the entire dimension range relevant for this thesis. However, this is a weakness for all existing empirical methods. The main strong points of the method are that it is based on inland vessels and requires a relatively low level of detail. Furthermore, it is believed to be appropriate for the ship type under investigation and that it is suitable for conceptual designs such as those that are developed in this thesis. It is, therefore, considered to be the most appropriate method available.

That the low level of detail is not a major problem is underlined by Hofman and Kozarski [2000, p. 65] who state that especially for ships sailing in shallow water at speeds in the critical region (i.e. the upper end of the speed range of inland ships), the ratio between ship length and water depth is far more important for the increase in resistance compared to deep water resistance than details of the hullform. They also state that common measures applied to reduce the resistance of ships in deep water are less effective in shallow water. Their statements are supplemented by e.g. Latorre and Ashcroft [1981, p. 14], who state that the bow shape has little influence on the resistance

6 The major empirical methods for the estimation of ship resistance have been developed before 1990, so all literature discussed in this paragraph is relatively old, but still considered to be the state-of-the-art.

characteristics of barges in smooth water. This statement is further supported by the wide range of bow shapes on inland ships that sail around today, see Figure 4-4 below.

Figure 4-4: Various bow shapes. Source: own photographs

However, there is a complicating factor in the determination of a ship's resistance on inland waterways: The resistance of a ship at a given speed may be influenced significantly by the presence of channel walls and the low water depths that are typical for inland waterways. As a result of the limited cross-section of the waterway, a back flow is created around the moving ship, increasing the speed of water along the hull and with it, its frictional resistance. At the same time, due to the limited water depth, the speed of waves is restricted (wave retardation), resulting in high wave making resistance at a given ship speed. As a result, the need arises to compensate for these factors.

Lap [1957] provides an elaborate overview of the methods that are available to account for these effects, including the work of Schlichting (1934), which is still counted among the important methods to correct for shallow water effects. Van Terwisga [1989] discusses an alternative method by Karpov[7], which like Schlichting (1934), corrects for shallow water, but not for the cross-section of the channel. Two other methods do correct for the channel cross-section but in turn do not correct for the shallow water effects: Schijf, as discussed elaborately in e.g. Verheij et al. [2008, Ch 3] relies heavily on As/Ac, the ratio between the ship's underwater cross section and the cross section of the canal. So does the method of Kreitner, discussed by Lap, [1957]. Jiang [2001] provides a more recent method to correct for shallow water effects but according to Raven [2012] *"Some examples are given in the original papers, but little further validation is known and the method does not seem to be used often."*

As a result of the above, the choice remains to be made as to whether to use a method that corrects for water depth or to correct for channel cross section. Here it should be noted that in both cases, the correction will be made on the basis of an approximation of the actual waterway conditions that the ship is sailing on: especially for free flowing rivers, the cross-section will be different from location to location and will also vary with time. The same is true for the water depth. However, since inland ships will typically sail with a very small under keel clearance and draught is a major design variable in this thesis, the correction for shallow water is deemed more crucial than that for waterway cross-section. Since the method of Karpov provides separate corrections for wave retardation and back flow, is quoted in several publications and is substantially newer than the method of Schlichting, Karpov's method is used for this thesis.

<u>Propulsion</u>
The second part of the analysis of the power that is required to propel a ship at a certain speed is an analysis of the drive train. To determine the power that is required to propel a ship, the previously

[7] The original paper by Karpov, (Karpov, A.B., "Calculation of Ship resistance in restricted waters", TRUDY GII T. IV, Vol. 2., 1946) is written in Russian and is no longer publicly available.

discussed resistance estimation method put forward by Holtrop, Mennen and van Terwisga is used, together with the shallow water correction method by Karpov, as was also discussed before. For estimation of propulsion characteristics, Papmel's estimates for the wake fraction as presented amongst others in Van Terwisga [1989] is used, together with a thrust deduction method presented in that same source. Finally, the propeller's efficiency is determined by calculating the most favorable propeller from a range of large-blade-area-ratio 4-bladed Wageningen B-series propellers (B4-70, B4-85 and B4-100) with pitch ratios ranging from 0.5 to 1.4, as discussed by Oosterveld and Van Oossanen [1975] and from a number of ducted propellers in a 19A duct (Ka 3-65, Ka 4-70 and Ka 5-75) with pitch ratios ranging from 0.6 to 1.4 as presented by Oosterveld [1970]. For the selected propeller, open water efficiency is calculated for the vessel under review at design speed.

As a final factor of influence on the hydrodynamics of the ship, the relative rotative efficiency, η_R, is not accounted for due to the lack of a proper early-design-stage estimation method. However, Klein Woud and Stapersma [2002, p. 58] indicate its effect is small, with η_R ranging from 0.98 to 1.02. As a result, this omission is believed to be acceptable.

In order to arrive at the total installed power, the required output power of the propeller is taken and assumed to be of 85% of installed power after addition of 1% of shaft losses and 2% of gearbox losses, which is at the high-efficiency-end of the range presented by Klein Woud and Stapersma [2002, p. 62-63].

4.2.4 General arrangement

The fourth of the five design elements discussed in this chapter (i.e. steel weight, weight of machinery, equipment & outfitting, propulsion & resistance, general arrangement and cost) is the arrangement of the ship, which is discussed in this paragraph.

The amount of cargo that a vessel can carry may be limited in three ways: the volume that is available in the holds/tanks (in case of light cargoes like low density solid bulk or liquid bulk), the maximum weight of the cargo (in case of e.g. oil, sand, coal etc.) and the stability of the ship (in case of containers or other stackable low-density cargoes). These limitations lead to the need to determine the displacement, stability and weight of a ship as well as the internal volume of its holds or tanks. This last aspect requires a basic definition of the layout of the ship for, which no quick estimates are available; it is mainly a matter of fitting the various items that need to go on board.

Assuming a given length, beam and design draught for a vessel, the space that is available for the holds is determined by subtracting the space that is occupied by the fulfillers of functions other than the carriage of cargo (propulsion, maneuvering, accommodation, fuel storage, ballast storage, compliance with double hull requirements, ….) from the available space. This implies the need to establish the required length of the fore and aft part of the ship in order to determine how much space is available for the carriage of cargo.

In practice, not all of the functions on a ship represent crucial elements in the determination of the lengths of fore and aftship. Fuel and ballast tanks, freshwater tanks, small pumps, switchboards and so on can usually be fitted in the void space around the main equipment. As a result, only the main equipment will be considered in the dimensioning of the fore and aft end of a ship. This consists of the drive train, generator sets, accommodation and bow thruster.

Arrangement of the aft section

The length of the aft ship is governed by either the length that is required by the accommodation or by the length that is required for the engine room, whichever is larger. The length of the engine room is largely determined by how far aft the main engines can be placed (distance 'A' in Figure 4-5).

Forward of the engines, at least one generator set will be placed, leading to a required length ‘B’. If the wheelhouse is raisable, its column will also have a foundation in the engine room. In case no space is available alongside the engine or generator set(s), it will be placed in front of them, thereby increasing length ‘B’. Finally, a minimum clearance between the most forward-placed item and the engine room bulkhead (length ‘C’) completes the overall engine room length. The position of the aft end of the accommodation is determined by the required space aft of the accommodation (length ‘E’) while the length of the accommodation itself is determined by the required floor space, number of tiers and required room for walkways alongside the accommodation.

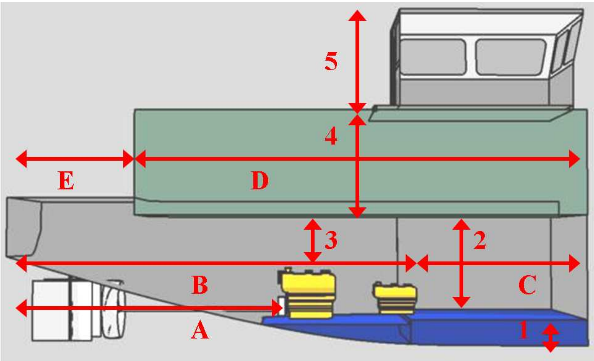


Figure 4-5: Arrangement of the aft section

The height of the engine room is determined by the vertical position of the bottom of the engines (height ‘1’) plus either the minimum height for people to work after all piping, ducting & cabling is in place (height ‘2’) or the engine height plus sufficient clearing over the engine (height ‘3’). The height of the accommodation and wheelhouse (height ‘4’ and ‘5‘) are fixed at 2.5 meters per tier.

Arrangement of the fore section

In the fore section of the ship, similar issues are at play: accommodation may be present, as may some major equipment. For the arrangement of the fore ship, the starting point is the length of the forepeak (length ‘A’ in Figure 4-6), which is prescribed by rules.

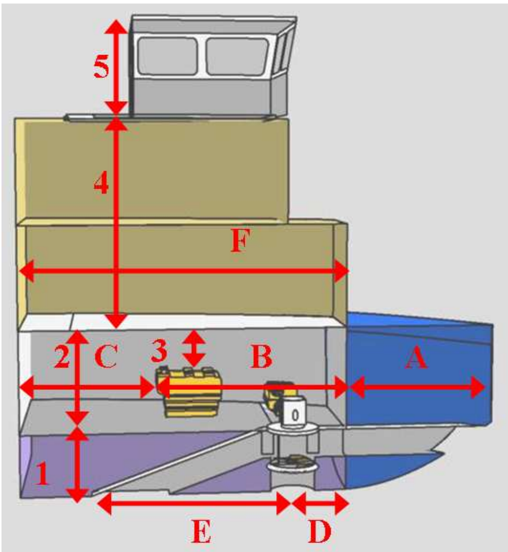


Figure 4-6: Arrangement of the fore section

The approach to fitting equipment in the fore section is similar to that of the aft section: The bow thruster is placed as close to the collision bulkhead as possible while adhering to a user-defined space between the unit and the bulkhead (length ‘D’). Generator sets, if any, are placed aft of the bow thruster, resulting in a length 'B'. Length 'C' represents the required clearance between equipment and the aft bulkhead. If an accommodation that is placed on the fore part of the ship requires more length than this, the total length of the bow thruster room is increased to length 'F'. The length of the accommodation of the fore part (length 'F') is determined in a similar way as for the accommodation aft: it is determined by the required floor space, number of tiers and required room for walkways alongside the accommodation.

The minimum deck height of the bow thruster room (height '1') is determined by the height of the bow thruster tunnels, while the height of the bow thruster room is determined in the same way as that of the engine room: either the minimum height for people to work after all piping, ducting & cabling is in place (height '2') or the engine height plus sufficient clearing over the engine (height '3'). The height of the accommodation and wheelhouse (height '4' and '5') are fixed at 2.5 meters per tier.

Arrangement of the cargo section
Once the bow and stern section have been arranged, whatever space is left in between may be used for holds, ballast tanks and a double hull. The definition of the cargo space requires determination of the minimum height of the double bottom and the width of the double sides, which may be chosen freely as long as rule-prescribed minimum values are adhered to [Lloyds register, 2008]. Furthermore, the cross-section of the holds as well as the subdivision of the cargo section into separate holds, double bottom tanks and/or side tanks should be defined. In some cases, e.g. in case of cargo tanks for ADN cargoes, the size of the tanks are limited by regulations [Economic Commission for Europe, 2009, paragraph 9.3.2.11], while in many other cases, the cargo section may consist of a single hold.

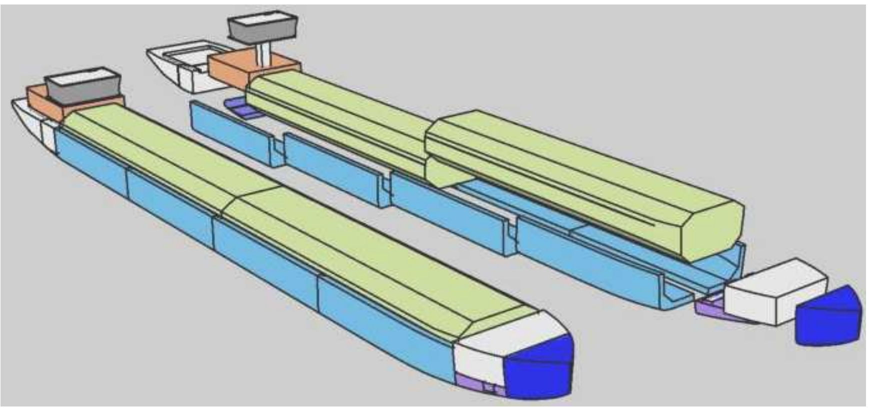


Figure 4-7: Volume subdivision of a typical design

Once this is done, cargo hold dimensions are known and the general arrangement is defined in sufficient detail.

4.2.5 Building cost

The fifth of the five design elements discussed in this chapter is the cost of building the ship, which is discussed in this paragraph.

Once the technical properties of the ship are available, it is possible to make a reasonable estimate of the building cost of the ship on the basis of rules of thumb and extrapolation from actual quotations. Since the cost of purchasing a ship is a crucial element in the overall cost breakdown of the operation of a ship, it needs to be estimated with some accuracy.

A complicating factor is that the newbuilding price of an individual ship is highly volatile and depends strongly on market conditions. However, the relative prices of inland ships of a different type and/or size at a specific point in time may be determined on the basis of their respective building cost, since market conditions (and as a result, profit margins) may be considered to be similar for the builders of all sizes of inland ships. This general conception is supported by [Stonehouse, 2006], who reveals highly similar cost of between 2200 and 2400 US dollars (2006 values) per Compensated Gross Ton[8] of vessel, for the Netherlands as well as for China and Romania, i.e. for high-wage countries as well as for low wage countries. Although these figures require careful interpretation, and some notably different (but explainable) values are quoted for a number of countries, they do serve to support the claim that the conception of a more-or-less location independent vessel cost price is possible.

For the purpose of this thesis, the cost of the ship is broken down into 12 different categories:

1) General object cost
2) Hull
3) Propulsion & maneuvering
4) Electrical system
5) Bilge & ballast systems
6) Cargo pumps & piping for tankers
7) Accommodation
8) Mooring gear
9) Hatch covers
10) Outfitting
11) Miscellaneous equipment
12) Profit margin

In appendix C, the way in which costs for each category are determined is explained. In chapter 4.3.3, it will be validated that this way of calculating costs results in prices that are close to those quoted in literature for a number of common ship sizes.

Still, even with most of the cost pinned down with reasonable accuracy, it remains important to recognize that vessel cost may be heavily influenced by specific desires of the owners, especially when these are related to the level of finishing on the vessel. One operator quoted a difference in price of roughly 5% due to different levels of finishing and quality of the accommodation on two otherwise identical vessels, while another quoted a difference of € 100.000,- (2010 value) for engines from different manufacturers but the same rated power. Also, changes in market conditions are have a large impact on the price of a newbuild vessel. For inland ships little data exists, but values of peak sales prices that are 50% higher than the price in normal times have been quoted. E.g. Schuttevaer [2011] quoted "… *In 2008 prices for a new ship were much higher than today. Then a 110 m ship cost 4.5 million Euros, now only 3.3 million Euros*".

[8] Compensated gross tonnage is used for consistent measurement of shipbuilding output. It compensates for the difference in workload per ton of vessel gross tonnage as a result of different sizes and types of ships: The amount of work that goes into building 1 gross tonne of vessel space should be equal independent of the type and size of vessel. For an elaborate overview of the system, refer to [OECD, 2007]

4.3 Verification and validation

After the discussion of the main elements of the model in chapter 4.2, confirmation of the correctness of the developed model is provided in this paragraph. This is done in a number of ways. It is checked if the structures of ships that are created in the model match those of actual ships, both in terms of scantlings and steel weight, a check is made that the calculated power matches that of actual ships and a building cost comparison is made.

4.3.1 Structure

Validation of the structure module of the model is done in three ways:

1) Verification of the design bending moment model
2) Validation of scantlings through comparison with reference main frame drawings
3) Validation of overall weight through comparison with the weight of reference vessels

Since the weight of equipment, as discussed before in chapter 4.2.2, is already for the largest part deduced from reference vessels, this will not be validated further.

Bending moments

When designing the structure of a ship, it is crucial to get a proper estimate of the design bending moments it will encounter, since this directly determines the stresses on longitudinal structural elements and thereby on the required plate thickness at the extreme fibers of the ship (deck, coaming and bottom). Both Lloyds register [Lloyds register, 2008, Pt 3 Ch 4, section 5, 5.2] and Germanischer Lloyd [Germanischer Lloyd, 2006] provide guidelines for this, but both only consider themselves to be reliable within the standard dimensions of inland ships that are in operation today. Outside that range, a direct calculation is required. Since this direct calculation is developed within the design model, it should be verified if it results in similar bending moments as the methods that are provided by classification societies within the validity range of these methods.

The bending moment model takes length of hold, cofferdams (if any), fore section and aft section from the vessel design, as well as the length of the shaped bow and stern sections. In order to facilitate calculations in MS Excel, the vessel is subdivided into discrete 1 m long steps and the shape of the ship is simplified to a box shape to which weights that are equal to the loss of buoyancy at bow, stern and bilges are added, in four steps for the stern and two steps for the bow, as shown in Figure 4-8. Since inland ships may have a draught of up to 4.5 m while propeller diameter is limited to roughly 1.8 m, a standard transom of 0.2 T or T-2.3 m, whichever is greater, is used.

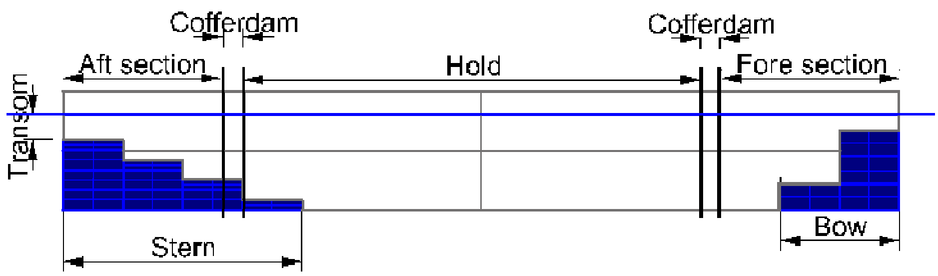


Figure 4-8: Visualization of bending moment model

The model is considered to be verified if it results in bending moments for conventional inland ships that are comparable to those that are determined by the rules by Germanischer Lloyd and Lloyds Register. The figure below shows results for a series of dry cargo ships with a beam of 11.45 m, a design draught of 3.75 m and a depth of 4.25 m. The loading conditions for which bending moments are reviewed are empty, fully loaded and with the aft 10, 15, 20 and 25% of the hold loaded.

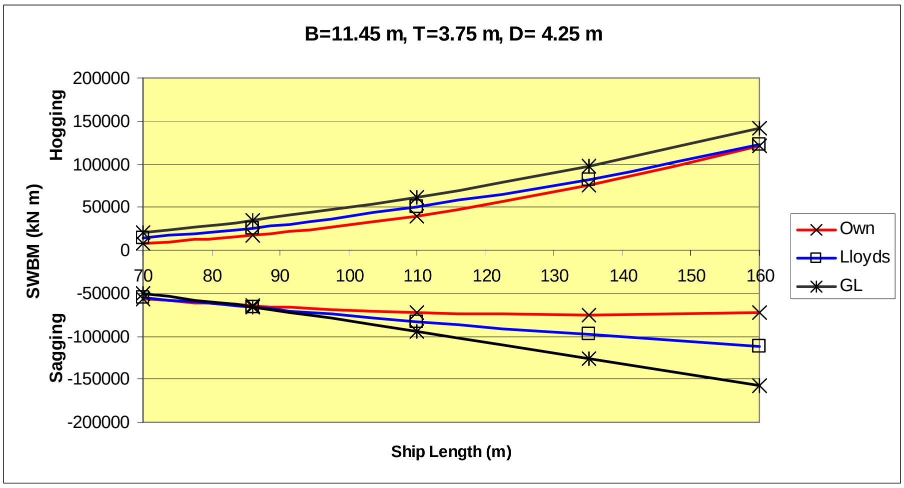


Figure 4-9: Verification of bending moment model

From the above, it is clear that the model follows the general trend of the rules of the class societies, although the calculated bending moments in hogging condition are slightly lower. The tendency of own results to become more hogging/less sagging for longer ships can be explained by the fact that in the calculations on which the graph above is based, block coefficient is kept constant for all ships while dimensions of the fore and aft sections of the ship are not altered. As a result of this, the loss of buoyancy due to the shape of the hull reaches into the cargo zone, resulting in a tendency towards a hogging moment.

The correctness of the model is further underlined through verbal confirmation from a Lloyds staff member that Lloyds Register's standard bending moments are indeed higher than those that typically arise from direct calculations for inland ships and that their validity is doubtful beyond 110 m in length, as is also stated in the rules themselves, where validity beyond 65 m is considered to be in need of verification. [Lloyds register, 2008, Pt 3 Ch 4, section 5, 5.2].

One of the main simplifications in the bending moment model is the use of the lightweight estimate as proposed by Germanischer Lloyd [Germanischer Lloyd, 2006] instead of the use of an iterative method which estimates bending moments on the basis of the lightweight distribution of the actual designs that are made. This is believed to be acceptable since the main weight element that will deviate from estimates by GL is the steel weight. Since changes in steel weight will directly reduce or increase the amount of evenly loaded cargo at full load, its impact on the sagging moment is limited. At the same time, the most severe hogging moment is caused by only loading the aft part of the ship, as a result of which cargo weight has a much stronger impact than steel weight.

To demonstrate this limited effect, in Table 4-1 the bending moments of a 110 x 11.45 m vessel are shown with varying fractions of steel weight. It shows that increasing steel weight results in a lower sagging moment and a slightly increasing hogging moment. Hogging moments will have a larger effect on increases in plate thickness, both due to the larger distance between the neutral axis and the deck than to the bottom and due to the smaller width of the deck. Therefore, it is considered justifiable to not to recalculate bending moments as a result of the outcome of the design and then re-designing the steel structure, but to base the bending moment calculation on the steel weight estimate that is provided by Germanischer Lloyd.

Table 4-1: Change of bending moments as a function of changes in steel weight

W_{steel}/LBD	0.06	0.08	0.1	0.2	0.3	0.4
Msag (Tm)	-47789	-45289	-42790	-30303	-17823	-5397
Mhog (Tm)	41379	41598	41818	42942	44067	44800

Mainframe scantlings

Validation of the scantlings that are created by the design model is done through a comparison with the main frames of three actual vessels:

1) An 86 x 9.6 m dry cargo/container ship with a transversely framed double bottom and sides.
2) A 104.5 x 11.44 dry cargo/container ship with transversely framed double bottom and sides.
3) A 110 x 11.4 m tank vessel with longitudinally framed double bottom, sides and deck.

Ship 1: dry cargo, L = 86 m, B =9.6 m, T = 2.85, D = 3.0 m

The vessel is a dry cargo ship, transversely framed, with a frame spacing of 500 mm and a webframe placed every 6 frames. It has a double bottom height of 485 mm and sides that are 635 mm wide. A comparison of the actual scantlings and the scantlings that are calculated by the model are shown in Table 4-2 below.

Table 4-2: Validation of modeled scantlings - ship 1

	real		Model	
Bottom plating	10	mm	7.5	mm
Inner bottom plating	12	mm	12	mm
Bilge	12	mm	9.5	mm
DB floors	8	mm	8	mm
DB girders	8	mm	8	mm
Inner side plating	9	mm	7	mm
Side plating	9	mm	7	mm
Sheer strake	25	mm	19	mm
Side frames	HP140x8	Profile	HP120x8	Profile
Inner side frames	HP140x8	Profile	HP120x8	Profile
Deck plating	18	mm	19	mm
Coaming	20	mm	21	mm
Web frames	8	mm	8	mm

When reviewing this comparison between actual and modeled scantlings, several issues are important to note:

A) Deck plating, coaming and sheer strake have similar thicknesses in model and reality. In both cases these are the elements of which thickness is increased to withstand the longitudinal bending moment. That they have similar thickness implies that the model responds correctly to the need to increase scantlings in order to withstand these moments.

B) Plating thickness in the side and bottom is thicker in reality than in the model. This is, however, a designer’s choice: for robustness, plating is never thinner than 9 or 10 mm, despite the fact that the rules allow the use of thinner material. To eliminate such unwanted differences, the model has the option for use of a user-defined minimum thickness of side and bottom plating, which is used in the designs of chapter 5.

C) There is probably a similar reason for the difference in scantlings of the stiffeners in the side: according to the rules, they can be made lighter than they are in practice. This is not compensated for.

Ship 2: Dry cargo, L = 104.5 m, B =11.44 m, T = 3.1 m, D = 3.5 m

The vessel is a dry cargo ship, transversely framed with a frame spacing of 620 mm and a web frame placed every 5 frame spaces. The double bottom is 500 mm high and the sides are 635 mm wide. Figure 4-10 shows the main frame of the vessel, while Table 4-3 shows a comparison of the actual scantlings and the modeled values.

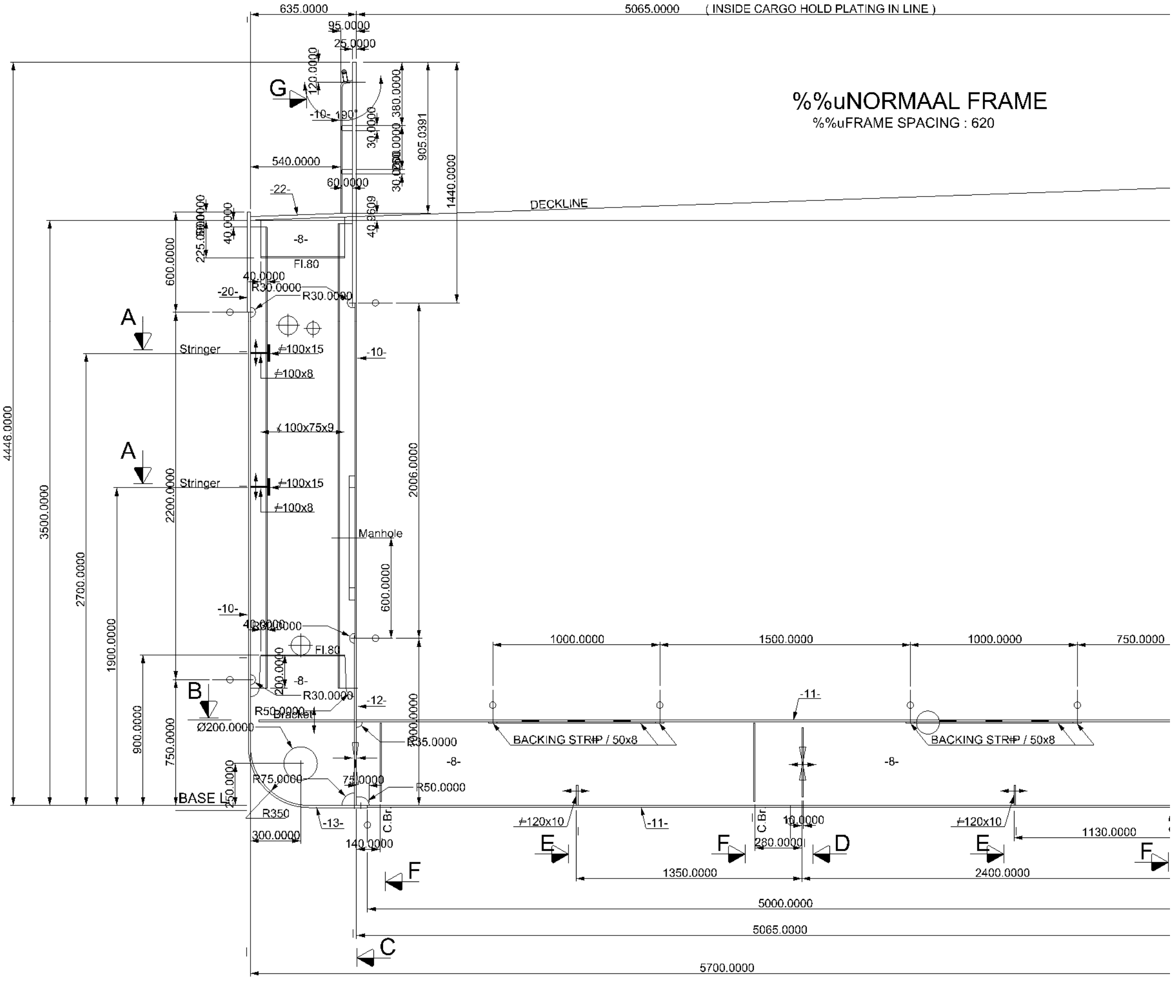


Figure 4-10: Main frame of a dry cargo ship. Drawing courtesy of Mercurius Shipping Group

Table 4-3: Validation of modeled scantlings - ship 2

Element	Real value		Model value	
Bottom plating	11	mm	11.5	mm
Inner bottom plating	11	mm	12	mm
Bilge	13	mm	13.5	mm
DB floors	8	mm	8	mm
DB girders	10	mm	8	mm
Inner side plating	10	mm	8.5	mm
Side plating	10	mm	8.5	mm
Sheer strake	20	mm	21.5	mm
Side frames	100x75x9	profile	130x65x8	profile
Inner side frames	100x75x9	profile	HP160x7	profile
ADN stringers	100x8 with 100x15 face plate		100x10 with 100x15 face plate	
Deck plating	22	mm	21.5	mm
Coaming	25	mm	23.5	mm
Web frames	8	mm	7.5	mm

When reviewing the comparison between actual and modeled scantlings in Table 4-3, several issues are again important to note:

A) Deck plating, coaming and sheer strake have similar thicknesses in model and reality. In both cases these are the elements of which thickness is increased to withstand longitudinal bending moment. The fact that they have a similar thickness implies that the model responds correctly to the need to increase scantlings in order to withstand these moments.

B) There is a slight discrepancy between modeled and real bottom plating thickness as well as DB girder thickness. The latter is the result of a design choice rather than a strict requirement and the first is likely to be caused by minor differences in calculated bending moments.

C) Inner bottom plating thickness differs. This thickness is on occasion considered negotiable with class and subject to a number of designer choices. Note that in this case the designer opted for a thinner inner bottom than a different designer did for the inner bottom of ship 1, which has a smaller beam, depth and draught.

D) Scantlings of frames in side and inner side differ slightly. The difference in stiffener type in the side is caused by a required section modulus that is marginally higher than that of the stiffener that is used in the real ship. The difference in stiffener type in the inner side is caused by the designer's choice to use identical frames in side and inner side, while the inner side frames selected by the model are lighter frames with a similar section modulus. The reason that this frame type was not also used on the side shell is a requirement for stringers on the shell, posed by ADN regulations.

E) Plating thickness in the side is thicker in reality than in the model. However, this is again a designer's choice.

All in all, the result from the model for this ship and ship 1 are very similar: general results match those of actual ships and discrepancies can mainly be explained by deliberate deviations from rule requirements. What is important, however, is to realize that these design choices exist, making ships in practice heavier than they need to be if they are built strictly according to the rules.

Ship 3: Stainless steel tanker, L = 110 m, B =11.4 m, T = 3.35 m, D = 5.05 m

The vessel is a stainless steel (duplex) chemical tanker, with web frames every 1785 mm. The double bottom is sloped with a height between 730 and 830 mm while the double hull is 820 mm wide. Design pressure of the tank is 50 kPa and design density of the cargo is 1.6 T/m^3.

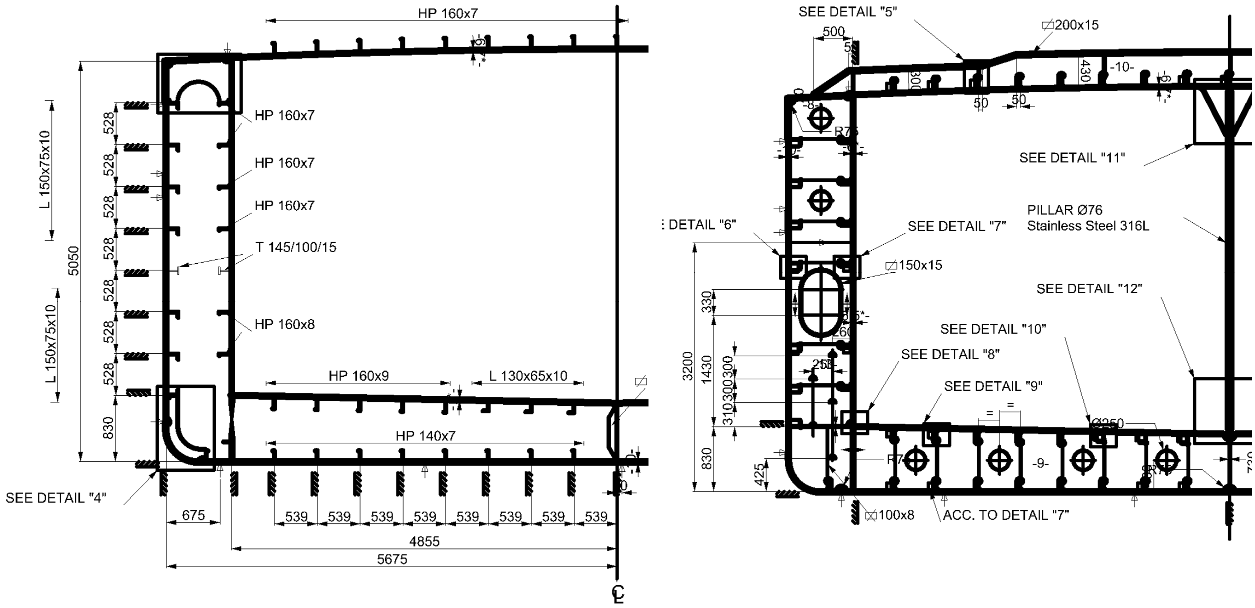


Figure 4-11: Structural drawings of a stainless steel tanker. Drawings courtesy of Mercurius Shipping Group

Table 4-4: Validation of modeled scantlings – ship 3

	Real value		Model value	
Bottom plating	10	mm	8.5	mm
Inner bottom plating	7	mm	7	mm
Bilge	13	mm	10.5	mm
DB floors	9	mm	8.5	mm
DB girders	?	mm	8.5	mm
Inner side plating	6.5	mm	6.5	mm
Corrugated bulkheads	6.5	mm	6.5	mm
Side plating	10	mm	9.5	mm
Deck plating	6.7	mm	7	mm
Inner bottom longitudinals	HP160x9 / 130x65x10		HP 180x8	
Bottom longitudinals	HP120x7		HP120x7	
Inner side longitudinals	HP160x8 / HP160x7		HP160x9	
Side longitudinals	150x75x10		150x75x10	
Deck longitudinals	HP160x7		HP160x7	
Deck beams	430x10,200x15 face plate		440x200x14	
Pillars/tension rods	76	mm	75	mm

From the comparison in Table 4-4, a close match between actual and modeled scantlings can again be observed. The main deviation in this case is a heavier/stronger bottom structure for the real ship. This may also explain the lighter inner bottom longitudinals, since the rules state that they may be made smaller than normally allowed if "*there is an appreciable excess in the midship section modulus*" [Lloyds Register, 2008, Pt. 4 Ch. 6, table 6.5.1], which is the case for this ship. The difference in the deck beams is explained by the fact that the model contains a limited number of large modulus beams and has selected the most appropriate one, which is indeed a close match.

Overall steel weight

Validating the weight of the overall steel structure is difficult due to the impact of the many possible design choices in terms of frame spacing, double hull width, double bottom height, choice of framing system, vessel layout etcetera. However, based on a number of reference vessels and estimates from Germanischer Lloyd [Germanischer Lloyd, 2006] a reasonable validation can be done.

Germanischer Lloyd [2006, Pt B, Ch 4, Sec 2, par 5.2] states a steel weight of 0.15 * LBD for vessels with a depth of 3.7 m or less and 0.1 * LBD for vessels with a larger depth. When these values are compared to the steel weight of existing vessels, they prove to be a good match. Comparisons are made on the basis of data from existing reference vessels that are shown in Table 4-5.

Table 4-5: Steel weight of various reference vessels

Vessel number	1	2	3
Vessel type	Dry cargo	Dry cargo	Dry cargo
LBD	135x11.45x4.25	86x9.6x3.5	86x9.6x3.75
Weight aftship	150 T	57 T	76 T
Weight midship	620 T	270 T	271 T
Weight foreship	75 T	48 T	53 T
Weight total	845 T	375 T	400 T
Weight/LBD	0.129	0.130	0.129

Vessel number	4	5	6
Vessel type	Tanker	Tanker	Tanker
LBD	86x9.6x3.75	85.9x11.4x5.05	110x11.40x5.4
Weight aftship	76 T	74 T	-
Weight midship	338 T	392 T	-
Weight foreship	53 T	45 T	-
Weight total	467 T	511 T	700 T
Weight/LBD	0.151	0.103	0.103

When modeling the vessel 3 from Table 4-5 with a double bottom height of 0.6 m, a double hull width of 0.635 m, a transverse framing system, a frame space in the midship of 0.62 m and a frame space at the fore and aft end of 0.5 m, results match reality closely, as is shown in Table 4-6, although both fore and aft sections are relatively light. In both cases this may be because accommodation weight is modeled separately from steel weight in the model. Weights of the front and aft section are, however, very similar to those of another existing 86x9.6x3.5 m dry cargo vessel: vessel 2 in Table 4-5.

Table 4-6: Comparison of actual and modeled steel weight of a dry bulk vessel

	Dry cargo (real)	Dry cargo (model)
LBD	86x9.6x3.75	86x9.6x3.75
Weight aftship	76 T	58 T
Weight midship	271 T	271 T
Weight foreship	53 T	41 T
Weight total	400 T	370 T
Weight/LBD	0.129	0.120

In case of (stainless steel) tank vessels for which the weight is known, but the details of the structure are not, validation becomes harder, since these ships no longer are transversely framed by default. Also, the length of the fore section becomes more uncertain due to the fact that there is more equipment there, which may require more space. Finally, the depth of the fore and aft sections will be lower than that of the midship section, but it is unknown how high it is for this specific ship.

Therefore, a number of design alternatives are calculated in Table 4-7. The first case is a transversely framed ship with a depth of 5.05 m along the entire length of the vessel. This ship is clearly heavier than the reference vessel, see Table 4-7. By longitudinally framing this same ship (case 2), weight comes down considerably. Finally by lowering the spacing of the girders in the double bottom (thereby also decreasing the spacing between the tension rods supporting the deck and thereby the span of stiffeners), and lowering the depth of the fore and aftship to a more realistic value of 3.5 m, weight comes down to a value that is close to that of the reference vessel. If this means that the modeled vessel is a close copy of the reference vessel remains debatable, but this case does show that results from the model are believable. It also shows that the model can produce results that have a sufficient level of detail to distinguish between the effects various design choices. As a by-product, this validation also shows the wide range of steel weights that may occur for ships with identical main dimensions.

Table 4-7: Comparison of actual and modeled steel weight of a tank vessel

Case	Reference	1	2	3
Vessel	Tank vessel (real)	Tank vessel (model, transv. framing)	Tank vessel (model, longit. framing)	Tank vessel, alt. long. framing
LBD	85.9x11.4x5.05	85.9x11.4x5.05	85.9x11.4x5.05	85.9x11.4x5.05
Weight aftship	74 T	73 T	73 T	61 T
Weight midship	392 T	465 T	422 T	403 T
Weight foreship	45 T	63 T	63 T	52 T
Weight total	511 T	601 T	558 T	517 T
Weight/LBD	0.1033	0.1215	0.1128	0.1045

4.3.2 Powering

When validating the powering calculations, there are two checks to be made: the verification of the underlying models and the validation of the outcome. In this paragraph, the models that were used are verified, and the similarity between calculated and real installed power for vessels of various main dimensions is checked. However, some critical notes are also made about the outcome of calculations.

The quality of the resistance prediction that is used can be established by comparing the results that it provides to those of the method of Holtrop & Mennen, which has proven its validity for seagoing vessels. In his master thesis, Gort [2009, p. 48] demonstrates that for a conventionally shaped barge , both methods follow the same general trend, although at higher speeds, above 13 km/h, the method of Holtrop & van Terwisga results in a resistance that is lower than that of Holtrop & Mennen. This difference increases to about 25% at 18 km/h. In another analysis, students of Delft University, supervised by staff members at MARIN [Consuegra et al., 2011, p. 17] arrive at a close match between the two methods. Differences between the two methods may be explained by the level of detail in the methods and the type of ships they are based on: for instance the results from the Holtrop & Mennen calculation show a strong effect of the entrance angle of the bow, while the method used for this thesis simply assumes a blunt bow. For pontoon-shaped blunt bows, the method of Holtrop & Mennen is likely to result in a wrong resistance estimate, since its underlying dataset does not include vessels with such a bow. This may explain the difference between the two methods.

A second verification is done in Figure 4-12 through comparison of results with CFD calculations by DST [Zigic, 2007] for a 135 x 11.45 x 2.75 m ship that was designed in the context of the EU funded FP6 project CREATING.

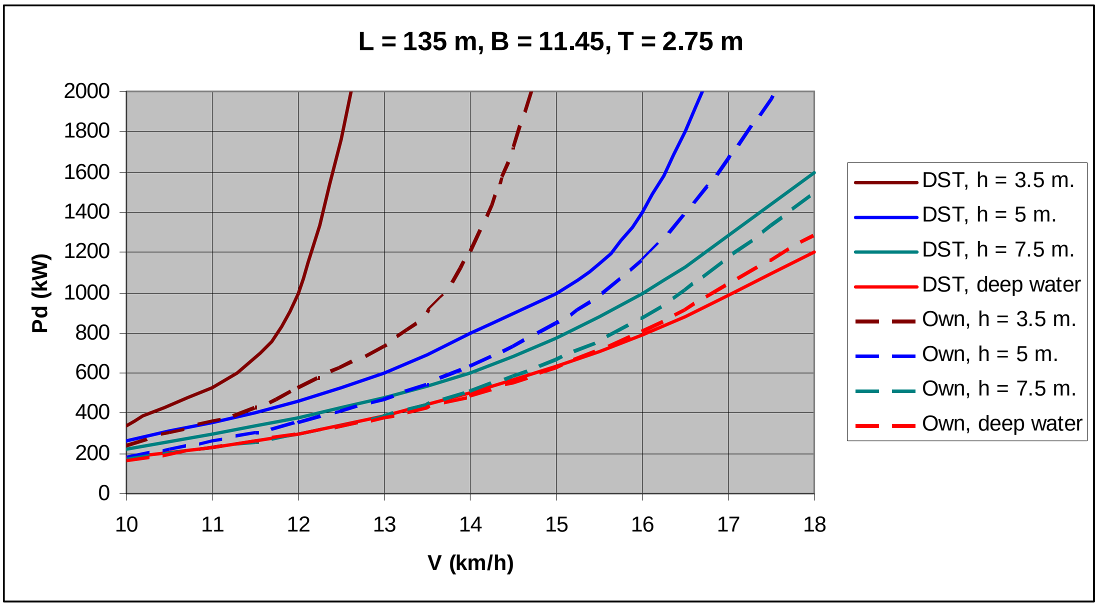


Figure 4-12: Validation of powering calculations

Results for this ship, equipped with two 1.7 m Ka 5-75 propellers with pitch ratio of 1.2, show two important things: In deep water results match very well, but in shallow water, where restricted water effects determine the vast majority of the ship's resistance, the model starts to deviate significantly from the calculations by DST, since the limits of the shallow water correction model are reached. However, it should also be noted that the reference calculations are indeed also calculations, not measured values.

Since shallow water effects will have a large effect on required propulsion power, the designs that are made with the model for the systematic variation of vessel dimensions, which will be discussed in detail in chapter 5, all rely on powering predictions for deep, unrestricted water. It can be validated that this leads to acceptable results with regard to the amount of propulsion power that is installed in the designs. In Figure 4-13 below, results from these systematic variations, with draught ranging from 1.5 to 4.5 m, beam ranging from 5 to 25 m. and length ranging from 40 to 185 m, are shown, as are a large number of actual dry cargo vessels as obtained from Vereniging 'de Binnenvaart' [Vereniging 'de Binnenvaart'].

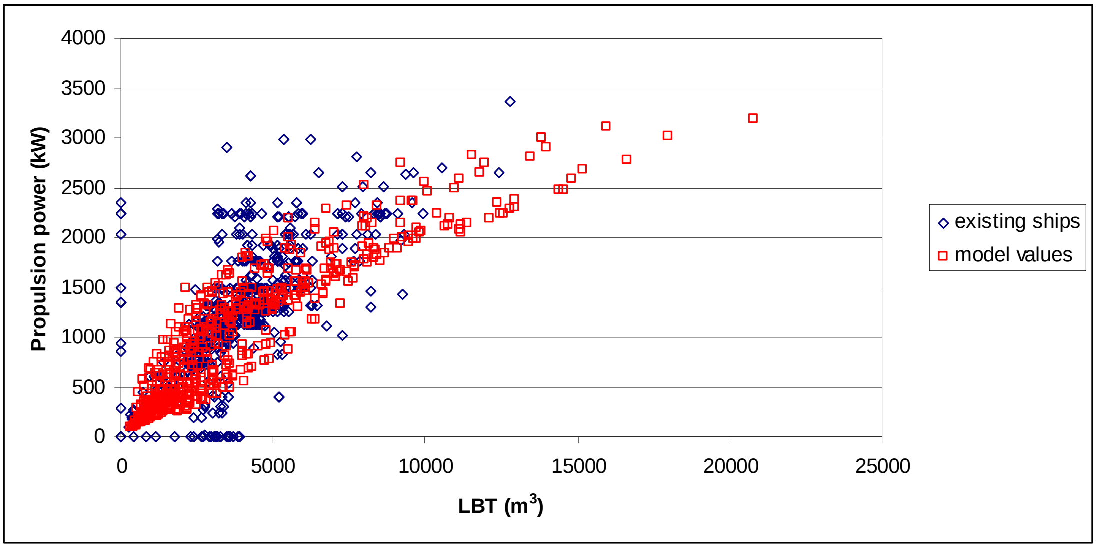


Figure 4-13: Validation of installed power

What become clear from Figure 4-13 is that the amounts of installed power of actual vessels and generated vessel designs are in the same range, but also that there are differences. Most notably, the model results in some small ships with relatively high power, which can be attributed to a number of very wide shallow draught designs as well as a design speed that may in some cases be somewhat higher than that of existing small ships. At the same time, it is interesting to note the large scatter in propulsion power of existing ships especially in the 3000 to 4500 m^3 range. This can be attributed to differences in design speed, hull form and propulsion efficiency, but probably also to the fact that a number of the high-powered ships will be used to push a barge in a coupled unit (koppelverband) formation.

Some critical notes concerning power calculations

In the previous paragraph, it has been shown that calculated values for required propulsion power match reality relatively well for an example ship. However, it needs to be mentioned that there are a number of uncertainties and simplifications in the model which may have a negative effect on the estimates of installed power, cost of the drive train of a ship and fuel consumption that are used in the remainder of this thesis:

- Many inland ships have a propeller with a blade area ratio in the range of 1 to 1.3 or custom designed propellers[9]. Furthermore they may apply more advanced propellers like those discussed by Guesnet [1995] or VBD [2002], which have a higher efficiency than Wageningen B and Ka series propellers. Due to the fact that the available propellers have a smaller blade area ratio than those that are placed under actual inland ships, the ships in the model tend use two propellers instead of one long before a second propeller is added to real vessels. As a result, smaller vessels in the model will have a more elaborate drive train than real vessels. The choice not to incorporate the Meyne-VBD series propeller from VBD [2002] is their higher cost and vulnerability as a result of which they are not commonly applied on cargo ships.[10]
- The large tunnels that are present at the stern of many inland ships were not modeled due to lack of an available empirical model.
- Both wake fraction and thrust deduction can only be estimated with limited certainty, while they have a large impact on performance, especially at low water depths.
- The restricted water correction method appears to underestimate the impact of low water depth, as was shown in Figure 4-12. Furthermore, since the actual profile of a waterway is hardly ever known in detail, using such a method to correct for the actual water depths that a vessel encounters on its journey is very difficult, if not impossible.
- Especially for low draught vessels, the actual achievable propeller diameter should be assessed on a case-by-case basis in order to find the right balance between a propeller that is small enough to remain submerged at ballast draught and one that is large enough to provide sufficient power at full draught. As an example: the old Peniche-type vessels with a draught of about 2 m have propellers of around 1.1 m, while large pushers have propellers of 2.05 m in diameter [Guesnet, 2011]. The propeller diameter of pushers is in fact larger than their draught. Since the impact of propeller diameter on performance is significant, this has a strong positive impact on the propulsive efficiency of such ships.

Concluding, the fact that relatively simple models and propeller data from literature were used for this thesis leads to considerable uncertainty about the actual amount of power that is needed to propel a vessel of given dimensions at a given speed over a waterway with a given depth. However, the method that is used here has resulted in believable amounts of installed power for the vessels under investigation.

[9] Information obtained through a private conversation.
[10] Information obtained through a private conversation.

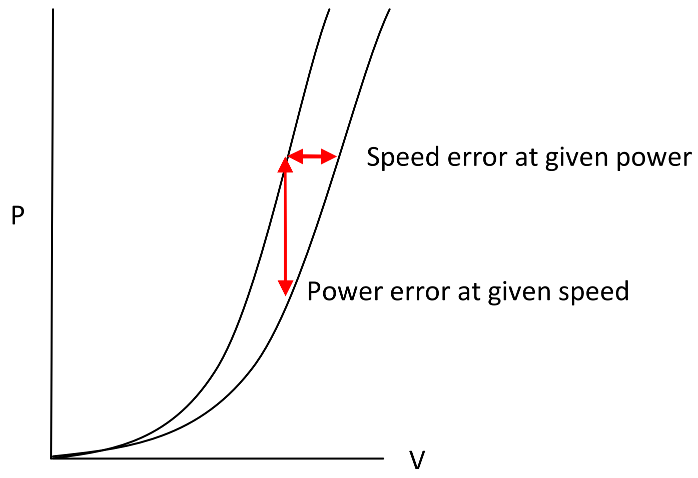


Figure 4-14: Visualization of speed and power errors

In the transport cost calculations of this thesis, the effects of the abovementioned uncertainties will be limited by using available power as an input to calculate the sailing speed of the vessel rather than to use the speed as an input to calculate the amount of power that is needed. Since power is roughly related to speed by the third power, a considerable error in calculated power will result in only a limited change in speed, as is shown in Figure 4-14 above. As a result the impact of errors in the powering prediction is greatly reduced.

4.3.3 Building Cost

To validate the building cost of the ship, several options exist. In Chapter 4.2.5, the origins of the values that are used in the determination of the cost of individual parts of the ship were already discussed: for some elements, data from reference vessels, combined with trend lines and formulas from literature were used. In this paragraph, the cost estimate for entire ships is validated.

Apart from sales price data that comes directly from shipbuilders, very little detailed data is available to validate calculated cost values. However, some data ís available. The Duisburg-based German research institute VBD [2004], currently known as DST, provides cost data for a number of conventional ship types. Indexing the values by VBD [2004] to 2011 values by means of the OECD producers' price index for the EU 27 [OECD, 2012] leads to the following values for the cost of ships:

Table 4-8: Building cost of various vessel types. Source: adapted from VBD [2004]

type	Gustav Koenigs	Johann Welker	GMS	Elbeleichter (small)	Elbeleichter (large)	pusher	
L	80	85	110	32.5	65	20	m
B	8.2	9.5	11.4	8.2	8.2	8	m
T	2.5	2.7	3.5	2.32	2.32	1.4	m
P_{inst}	750	900	1100	0	0	800	kW
Hull cost	1.30	1.36	2.00	0.17	0.40	0.69	M €
Propulsion cost	0.58	0.62	0.92	0.00	0.00	0.62	M €
Other equipment cost	0.24	0.25	0.36	0.00	0.00	0.27	M €
Elec., navigation, accomm. cost	0.24	0.25	0.36	0.02	0.02	0.27	M €
Total cost (2011 values)	**2.36**	**2.48**	**3.63**	**0.20**	**0.42**	**1.86**	**M €**

De Vries [2000, p. 148], in a very rough estimate, arrives at a cost of approximately 3.9 million euro for a 110x 11.45 m ship and 2.2 million euro for a 63 x7 m ship (2011 values), as a result of which, his indications are somewhat higher than those of VBD.

As a rough but illustrative example, Schuttevaer, [2011] quoted "… *In 2008 prices for a new ship were much higher than today. Then a 110 m ship cost 4.5 million Euro, now only 3.3 million Euro*". This provides further confirmation of the values by VBD, but also reveals large fluctuations in commercial prices due to changes in market situation. In the same article, Schuttevaer [2011] also quotes *"…a small hull costs between 1 and 1.5 million Euro."* (2011 values). This is comparable with the hull cost as stated by VBD [2004] for the Johann Welker and Gustav Koenigs type ships.

EICB [2011] also quotes a number of prices for various inland ships, as is shown in Table 4-9:

Table 4-9: Building cost for various ship types. Source: adapted from EICB [2011]

Ship type	Newbuild cost (2011 values)
Peniche (350-400 T, 40 x 5 m)	€1.2 million
Kempenaar (650 T 55 x 6.6 m)	€1.6 million
Europa ship (1200-1500 T, 86 x 9.5 m)	€2.5 million
Large ship (3000 T, 110 x 11.45 m)	€3.5 million

To validate the model, several cost results that are generated by the design model are compared to the cost as stated by VBD and EICB. According to the cost breakdown as discussed in chapter 4.2.5, results from the model are as follows: The Gustav Koenigs class vessel costs 2.02 million Euros, the Johann Welker/Europa ship class costs 2.30 million Euro and the GMS costs 3.28 million Euros. The cost breakdown for these vessels is as shown below, in Figure 4-15.

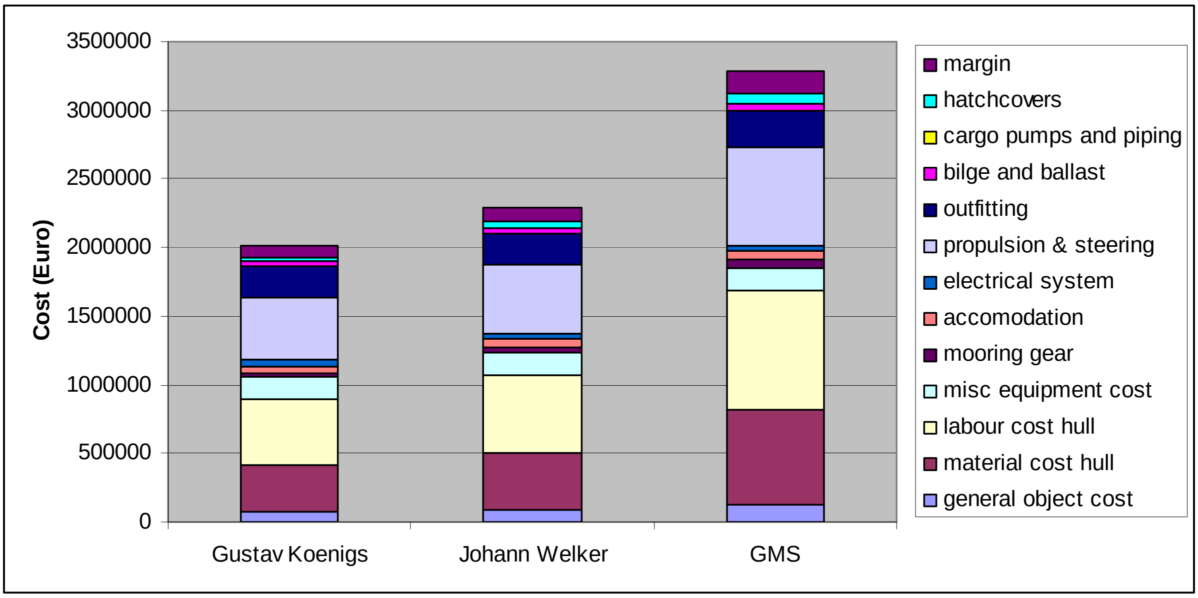


Figure 4-15: Modeled building cost for various ship types

The values presented in Figure 4-15 are slightly lower than those calculated by VBD and EICB. For the GMS (i.e. a 110 m ship) the calculated cost exactly match those quoted by Schuttevaer and the prices of the hulls for the smaller ships are also in the range mentioned by that magazine for 2011. Differences may be explained by difference in specifications such as accommodation size, installed power level of finishing and so on, but probably also by the effects of economic factors like inflation, wages, material prices and margins.

4.4 Sensitivity analysis

In the previous paragraphs, the model with which the technical characteristics and building cost of inland ships can be determined has been elaborated and validated. At the beginning of this chapter, it was explained that the purpose of developing the model is to allow a proper determination of the cargo carrying capacity and building cost of an ship of a given length, beam and draught. Therefore, a sensitivity study is carried out for those model elements that influence these aspects most. In chapter 4.4.1, it is established how a 1% change in the cost of the various cost groups of the ship as defined in chapter 4.2.5 affects the total cost of the ship. Furthermore, it is established which percentage of change may be expected for the most influential cost elements and how much this affects the total cost of the ship. For the sensitivity analysis of cargo carrying capacity, a similar approach is followed: in chapter 4.4.2, it is analyzed how large the impact of a 1% weight change of the main weight components is on the cargo carrying capacity of the ship and it is researched which percentage of change can occur for real ships. This establishes the total sensitivity of the cargo carrying capacity to changes in weight of the ship itself.

4.4.1 Cost

In Figure 4-15, it was shown that the cost breakdown is roughly the same for all of the vessels that were used for the validation. Therefore, the sensitivity study will be performed for one of these vessels, a 110x11.45x3.5 meter container ship. In Table 4-10 below, the effect of a 1% change of each of the cost components on the total cost of the ship is shown.

Table 4-10: Sensitivity analysis of building cost

Cost element	Cost	Effect of a 1% change of the variable on total cost
general object cost	€ 141029	0.04%
material cost hull	€ 739002	0.21%
labor cost hull	€ 940197	0.27%
mooring gear	€ 59870	0.02%
accommodation	€ 60000	0.02%
electrical system	€ 41000	0.01%
propulsion & steering	€ 740036	0.21%
outfitting	€ 270411	0.08%
bilge & ballast system	€ 49500	0.01%
hatch covers	€ 83037	0.02%
miscellaneous equipment cost	€ 165000	0.05%

From Table 4-10, it becomes apparent that the material and labor cost of the hull are the most influential cost factors. The third major cost component is the cost of propulsion and steering. Since they have such a major impact on cost, the effect of realistic changes in the values of these three components on the total cost of the ship is investigated in more detail.

The price of steel is highly volatile. CESA [2009] shows that the price of shipbuilding steel more than trebled between 2003 and the market peak in 2008. As an example, a 50% change in the steel price compared to the base value of € 950,- per ton steel weight would result in a 10.5% change in the total cost of the ship.

The second major aspect that has a major influence on the cost of a ship is the labor cost. The extent to which labor cost per ship can fluctuate is hard to determine since not only the cost per hour vary strongly, but the productivity of workers will also vary from shipyard to shipyard. However, Tholen and Ludwig [2006] demonstrated that the annual direct labor cost of a blue collar worker on a shipyard in Germany (i.e. the most expensive country in Europe) is nearly 5 times as high as the cost of his counterpart in a low wage country like Poland[11]. As a result, substantial changes in the cost of labor compared to the base value of € 45,- per hour may occur. As an example, a change of 50% change in the labor cost compared to the base value will result in a 15% change in the total cost of the ship.

For the assessment of the third major component cost, propulsion and steering, Figure 4-13 from chapter 4.3.2 is iterated below:

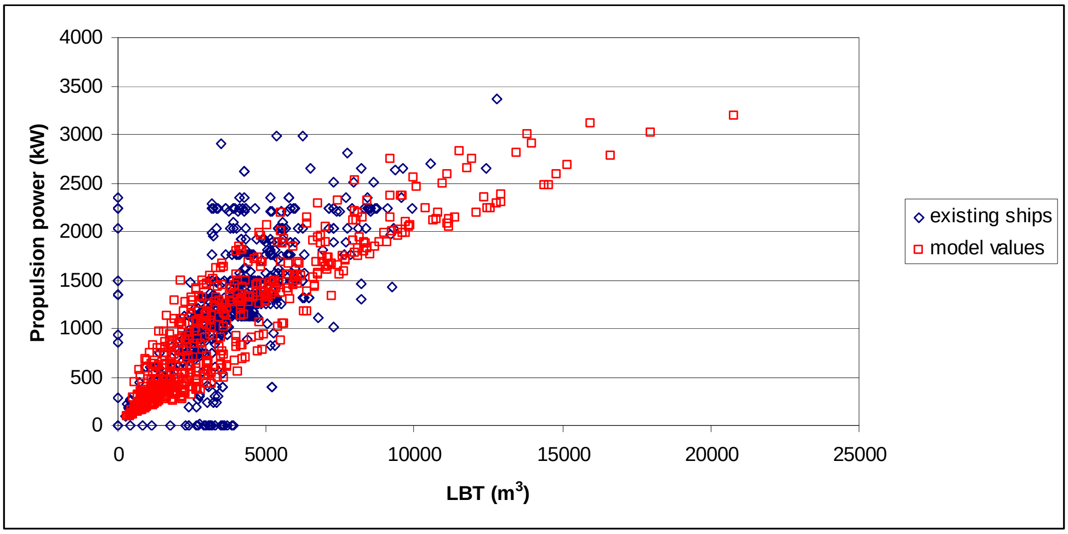


Figure 4-16: Validation of installed power

The figure shows a considerable bandwidth of installed power for ships with identical main dimensions. Furthermore, it shows that the modeled values match the values of existing ships, thereby validating that the amount of installed power in the modeled ships is acceptable. Since there is a strong link between the amount of installed power and the cost of propulsion and steering, the effect of a 30% change in the cost of this cost item is presented: a change like this would result in a 6% change in the total cost of the ship.

4.4.2 Weight

The weight of the ship is subdivided into 4 blocks: the steel hull, the piping outside the engine room, the accommodation and the machinery, equipment & outfitting. Like in the previous paragraph, the effects of a 1% change of these values on the cargo carrying capacity of a for a 110 x 11.45 x 3.5 m container ship are presented in Table 4-11.

Table 4-11: Sensitivity analysis of vessel weight

element	Weight	Effect of a 1% change of the variable on cargo carrying capacity
Steel hull	621.7 T	-0.18%
Piping	4.1 T	-0.00%
Machinery, equipment & outfitting	80.4 T	-0.02%
Accommodation	43.2 T	-0.01%

[11] The values described by Tholen and Ludwig [2006] serve only to indicate the large differences in wages, so it is not deemed necessary to correct these values to 2011 values.

From Table 4-11, it becomes apparent that steel weight is the only factor that has a significant impact on the cargo carrying capacity of the ship; a 1% increase in the steel weight of a ship will decrease its cargo carrying capacity by 0.18%. However, there is a second aspect to take into account, namely that steel weight is directly related to the material cost of the hull, as a result of which a 1% increase in steel weight will result in an increase of 0.21% in the price of the ship.

To determine the absolute sensitivity of the steel weight of the ship, the validation for the weight of a tank vessel from chapter 4.3.1 is iterated in Table 4-12 below.

Table 4-12: Comparison of actual and modeled weight of a tank vessel

	Tank vessel (real)	Tank vessel (model, transv. framing)	Tank vessel (model, longit. framing)	Tank vessel, alt. long. framing
LBD	85.9x11.4x5.05	85.9x11.4x5.05	85.9x11.4x5.05	85.9x11.4x5.05
Weight aftship	74 T	73 T	73 T	61 T
Weight midship	392 T	465 T	422 T	403 T
Weight foreship	45 T	63 T	63 T	52 T
Weight total	511 T	601 T	558 T	517 T
Weight/LBD	0.1033	0.1215	0.1128	0.1045

From Table 4-12, it becomes apparent that for a tank vessel with a length of 85.9 m, a beam of 11.4 m and a depth of 5.05 m, the steel weight can vary at least between 511 and 601 tons, which is a difference of roughly 17.5% in weight. Transferring this variation in weight to the 110x11.45x3.5 m container vessel from the other sensitivity analyses, the cargo carrying capacity of the heaviest ship will be 3.15% lower than that of the lightest ship, while it will be 3.675% more expensive.

4.5 Synthesis

It was discussed in chapter 3 that existing literature does not provide the required data or methods to determine the cost of transport by non-standard inland ships. As a result of this, it becomes necessary to determine a transport operator’s cost per unit of transported cargo on the basis of the properties of the ship: its cargo carrying capacity, building cost and the technical properties that influence its operating cost. Not all of the methods and data that are required to determine a ship’s building cost, cargo carrying capacity and technical properties are available from literature. Therefore, gaps in knowledge need to be filled and combined with existing data and methods before the main research goal of this thesis can be reached, i.e. determination of which length, beam and draught of an inland ship lead to the best competitive position for a captain-owner.

Therefore, a model was developed that can be used to determine the weight of the hull and all machinery, equipment & outfitting, amount of installed power, specification of the drive train, general arrangement and building cost of inland ships. Due to the absence of proper estimation methods for the weight of inland ships, the developed model incorporates a detailed 3D-representation of the main steel structure of the ship with which the structural weight of the ship can be estimated with sufficient accuracy. Furthermore, the model includes a powering calculation, 3D general arrangement and estimates of the weight and cost of machinery, equipment and outfitting on the basis of quotations, specifications from manufacturers and data from literature.

As a result, the model is able to determine those properties that are required to allow estimation of a transport operator’s cost per unit of transported cargo. This makes the development of the model a crucial step towards reaching the main goal of this thesis, since it makes is possible to answer the second sub-research question, i.e. how the main dimensions of an inland ship relate to its building cost and those technical properties that affect the cost of transport.

The model was validated with respect to the steel structure, amount of installed power and building cost and results show a good match with reality. From the sensitivity study it was concluded that the weight and cost of the steel hull have the largest impact on the cargo carrying capacity and building cost of the ship, which are the most important parameters for the determination of the required ship rate. Furthermore, the costs of the propulsion- and maneuvering-related equipment and machinery are important components in the overall building cost of the ship.

In the next chapters of this thesis, the model will be used to develop series of inland ship designs with systematically varied main dimensions, thus answering the abovementioned second sub-research question. For all ships in these series, their performance in a given transport chain will be determined in chapter 7 so that the optimal combination of length, beam and draught can be established, thus answering the main research question of this thesis.

5 Design model application

As discussed before, the aim of this thesis is to assess which length, beam and draught of an inland ship lead to the best competitive position for a captain-owner. Neither sufficient data nor adequate prediction methods are available to determine the transport cost for ships with main dimensions that differ from those that are common in Europe. Therefore, a model was created with which the technical properties and building cost of an inland ship with any combination of length, beam and draught can be determined. This model was discussed in chapter 4.

The technical properties and building cost that can be obtained from the technical model will provide crucial inputs for the cost model that will be discussed in chapter 6 and that will be used to determine the optimal main dimensions of an inland ship for a number of transport chains in chapter 7, thereby answering the main research question of this thesis.

There are two main ways in which the design model can be used for the identification of the optimal ship dimensions.

1) By using an optimization algorithm that lets the model create new designs until an optimum is found (e.g. a genetic algorithm or particle swarm optimization).
2) By letting the model create a series of designs in which the main dimensions of the ship are varied systematically, followed by an identification of the optimal variant.

The main difference in the approach of both methods is that an optimization algorithm is intended to find the best solution as quickly as possible and spend as little effort as possible on solutions that are far away from the optimum, while a systematic variation will simply result in a large number of pre-defined options, irrespective of whether or not they are close to the optimal solution.

Despite being a powerful tool for many applications, an optimization algorithm has a number of drawbacks:

a) It provides no systematic insight into how the optimal solution compares to ships with different main dimensions, since not all combinations of main dimensions are investigated. This is considered a shortcoming because in order to determine if the performance of an optimal solution is significantly better or only marginally better than other solutions, it is not only necessary to find the optimal solution, but also to know the performance of these other solutions.

b) An optimization algorithm introduces the risk of optimizing towards a local optimum instead of a global optimum, thereby not actually finding the best solution.

c) Since each transport chain can feature different values for important parameters like transport distance and waterway characteristics, a new optimization will need to be executed for each transport chain. As a result of this new designs need to be created for each transport chain. Since it takes roughly 10 minutes to create a single ship design with the design model from chapter 4, this will become a very time consuming process that can require several days of calculation time per case. Systematic variation on the other hand is only time consuming once, i.e. during the creation of all designs. Afterwards, the optimal ship for a specific transport chain can be determined in a couple of minutes.

Because of these drawbacks, it was decided to use the model from chapter 4 to create a number of datasets of ship designs with systematically varied length, beam and draught and to subsequently use those datasets as input for the cost model of chapter 6. As a result, the highly time consuming creation of all the ship designs is a one-time effort and the time that is required to find the optimal solution for a specific transport chain will be greatly reduced, since it can rely on the same set of design data every time. Furthermore, when a systematically varied set of designs is available, it becomes possible to not only find the optimal solution, but also to compare the performance of that solution to the performance of many other vessels, including benchmark vessels with common main dimensions.

In this chapter, the results of the systematic variation of length, beam and draught for dry bulk, container and tank ships are discussed in terms of the main technical characteristics of the ships (installed power, number of propellers and weight) as well as their building cost. This is done with a dual aim: the first aim is to discuss the basic data and underlying assumptions of the generated ship designs that are used in the next chapters. The second aim is to provide insights beyond the state-of-the-art into the relationship between main dimensions and steel weight, lightweight and required installed power.

The large datasets of systematically varied ship designs that are created also offer the opportunity to derive rules of thumb for the weight and cost of inland ships and thereby advance the state-of-the-art of weight and cost estimation of inland ships in the conceptual design stage. These rules of thumb will be discussed in the final paragraph of this chapter: paragraph 5.6.

Before going into the discussion of the results for each ship type, the design choices that are used for all designs are discussed in chapter 5.1. After that, the characteristics of the drive train of the ship, which is independent of vessel type, are discussed in chapter 5.2.

Following this generic review, the steel weight, lightweight and building cost of the ships are discussed for the three main inland ship types:

- dry bulk ships (chapter 5.3)
- container ships (chapter 5.4)
- coated tank vessels (chapter 5.5)

5.1 Discussion of ship type-independent design choices

There are a number of design choices and design constraints that are dependent on the type of ship that is designed while there are also a number of choices and restraints that are vessel type-independent. These type-independent choices are the ranges of length, beam and design draught that are explored, propeller diameter, number of propellers, design speed, length of bow and stern sections, structural arrangements and the size and location of the accommodation. Before going into the discussion of the vessel type-specific design choices, those choices that are valid for all developed series of ship designs are discussed in this paragraph. Table 5-1 provides a summary of these values while the argumentation behind the choice for these variables is provided in the remainder of this paragraph.

Table 5-1: Ship type-independent design parameters

PARAMETER	VALUE
Main dimensions	
Length	40-185 m
Beam	5- 25 m
Draught	1.5-4.5 m
Stern length	Min[1.5 * beam, 0.4 * L]
Bow length	Min[1.25 *beam, 4.2*draught]
Speed	
Design speed	Fn = 0.16
Lower speed limit	13 km/h
Upper speed limit	18 km/h
Propeller diameter	
If $T \leq 1.5$ m	0.99 T m
If $1.5 \text{ m} \leq T \leq 2$ m	1.485 + 2* (T-1.5)*(1.7-1.485) m
If $2 \text{ m} \leq T \leq 2.5$ m	1.7 + 2* (T-2)*(1.8-1.7) m
If $T > 2.5$	1.8 m
No of propellers	
1 + n	n is increased until required AeA0 <1 and $\eta_0 \geq 40\%$
Structural arrangement	
Frame spacing fore and aft	500 mm (transverse framing)
Frame spacing midship – transverse framing	600 mm
Frame spacing midship – longitudinal framing	≤ 600 mm
Webframe spacing fore and aft	3000 mm
Webframe spacing midship	1800 mm
Girder spacing – dry bulk & container	≈ 3 m
Girder spacing – tank	≈ 5 m
Accommodation	
area	≤ 100 m^2
Length	≤ 0.2 * L
Location	Aft only

Below, the argumentation behind each of the values that is shown in Table 5-1 is provided per topic.

5.1.1 Main dimensions

The range of main dimensions that are explored has been selected such that they cover and exceed the dimensions of inland ships that operate today, but can still physically fit on European waterways.

The length of the ships is varied from 40 to 185 meters. The lower limit of 40 meters equals the length of a Peniche type vessel, being the smallest inland ship that is in commercial use today. The upper limit of 185 m is nearly equal to the practical upper limit of ship length as defined in chapter 2.2 and 2.3.

The beam of the ships is varied between 5 and 25 meters. The lower limit of 5 meters is again equal to the beam of the Peniche type ship and the upper beam limit of 25 m just exceeds the practical upper beam limit as defined in chapter 2.2 and 2.3.

The draught of the ships is varied between 1.5 and 4.5 m, which is roughly equal to the upper and lower bounds of vessel draught that can be accommodated on European waterways. As was shown in Figure 2-3 in chapter 2.1, almost all ships that sail on the European waterways have a design draught between 1.5 and 4.5 m, while the vast majority of these have a design draught that is between 2 and 4 m. Furthermore the fairway classes as defined by CEMT [European Conference of Ministers of Transport, 1992] can accommodate vessels with draughts ranging from 1.6 m on the smallest waterways to 4.5 m on the largest waterways. The few existing inland vessels that have a draught that is larger than 4.5 m are typically used within port areas as bunker vessels.

To limit the number of required designs, the step size for the variation of main dimensions is small for small designs, but gets bigger as the size of the vessel increases; steps of 10 m in length and 1.5 m in beam are used for small vessels, while the intervals increase to 25 m length steps and 5 m beam steps for the larger vessels.

In order to account for the effects of various vessel draughts, vessels are designed at design draughts of 1.5 to 4.5 m at 0.5 m intervals. Furthermore, boundary conditions are set in order to prevent having to spend effort on highly unrealistic designs. Therefore, a minimum L/B ratio of 4 was maintained, as well as a maximum L/B ratio of 20. All combinations of L, B and T for which a design is made are shown in Figure 5-1 below, where each dot represents a design.

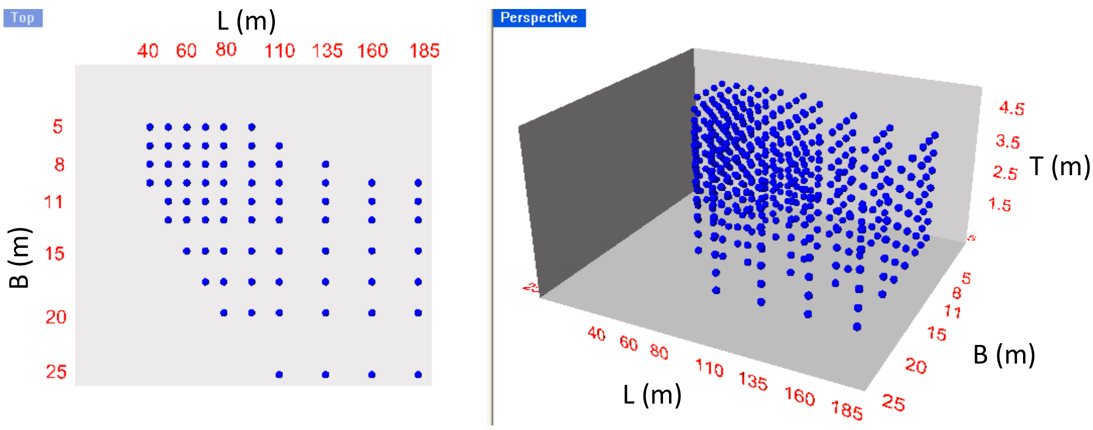


Figure 5-1: Top and 3D-view of the design points in the datasets of ship designs

5.1.2 Length of the bow and stern section of the hull

In all cases, the stern form is a pram shape with a length that is set as 1.5 B, with an upper limit of 0.4 L and a local block coefficient of 0.66. This choice for the length of the aft ship choice corresponds well with the 'typical aftship length' as discussed by Heuser [1987], who states a length between 1.9 D_{prop} + 1.85 B (single screw vessels) and 3.2 D_{prop} + 1.45 B, where D_{prop} is the diameter of the propeller.

The bow shape is chosen to be a conventional ship-shape bow (instead of a broad pontoon-shaped bow). In all cases, the length of the bow is selected to be the smallest value of 1.25 B or 4.2 T with a local block coefficient of 0.66. Common bow characteristics for actual inland ships as stated by Heuser [1987] are a length of 1.55 B or 5 T with a local block coefficient of 0.78, which is both a longer and fuller bow than the one used here, resulting in a virtually identical loss in buoyancy and a very small impact on resistance. As a result, the choice for bow length is deemed acceptable.

5.1.3 Design speed

An important variable to take into account in the design of the ships is their design speed, which leads to a specific amount of installed power and a number of propellers as well as to the weight and cost of the related machinery. The design speed is determined by setting the following boundary conditions for the sailing speed (relative to water) on deep water:

- Froude number is not larger than 0.16, which is a typical Froude number for inland ships[12].
- Minimum speed equals 13 km/h, the minimum required design speed for ships sailing on the Rhine [European Parliament and Council of the European Union 2006a].
- Maximum speed equals 18 km/h, which is a common average speed on the lower Rhine and a value that results in a close match between modeled and real amounts of installed power.

5.1.4 Propeller diameter and number of propellers

The choice for the number of propellers and their size has a large impact on the power that is required to propel a ship at a given speed. Propeller loading and diameter have a large impact on efficiency, the baseline being that the larger and more lightly loaded a propeller is, the higher its theoretically achievable efficiency will be [Kuiper, 1997, p. 205].

Achieving such lightly loaded propellers is, however, not always possible: The fact that inland ships operate in very shallow water and as a result have a very low draught means that the propeller diameter will typically be small, which leads to a high loading. This in turn results in (very) poor propulsive efficiency. Klein Woud and Stapersma [2002] make a comparison between the typical total propulsive efficiency of inland ships and that of container ships and frigates. They show a value of 40% for inland ships, while values of 65% to 75% are achieved for the other ship types. Therefore, it is a constant challenge to make optimal use of the limited space that is available in order to get efficiencies up to an acceptable level while still making sure that the propeller remains submerged to a sufficient degree when the ship is sailing empty.

[12] The Froude number is a common measure for the speed of the ship. It is expressed as follows:

$F_n = \frac{V}{\sqrt{g \cdot L_{wl}}}$, where V = vessel speed (m/s), g = gravity constant =9.81 m/s^2, L = length of vessel's waterline (m)

As a result, the following approach for the dimensioning of propellers is used. At design draughts of 1.5 m and lower, the propeller diameter is set at 99% of the ship's design draught in order to make optimal use of the limited available draught. The diameter is linearly increased to 1.7 m at a draught of 2 meters and to 1.8 m at a draught of 2.5 m. 1.8 meters is a typical upper limit for the propeller diameter of inland ships. As an example, German research institute VBD (currently named DST) advises a propeller diameter of 1.75 m for a standard 110 m vessel [VBD, 2004, p. 64].

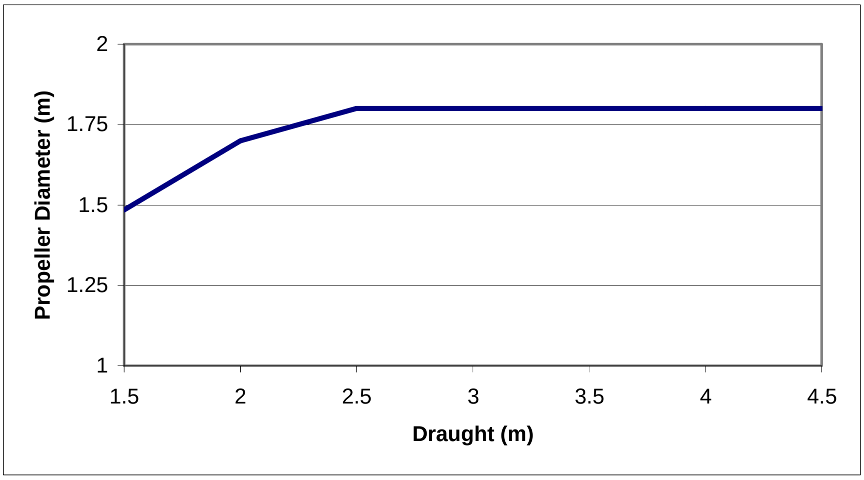


Figure 5-2: Propeller diameter as a function of design draught

Based on this propeller diameter and the ranges of propellers that were discussed in chapter 4.2.3 (Wageningen B and Ka propellers), The number of propellers that are fitted to the ship is determined by the boundary conditions that the required propeller blade area ratio, AeA0, does not exceed unity and that the highest achievable open water efficiency is at least 40%. If either of these boundary conditions is violated, propellers are added until both conditions are met. Once the number of propellers is fixed, the propeller type that has the highest efficiency and has the required AeA0 ratio is selected. For ships with a length that exceeds 110 m, at least two propellers are placed, since this is required by regulations [Lloyds Register, Pt. 5, Ch. 1, Sec. 5, 2008].

It should be noted that it is quite common for inland ships to use propellers that are different from those in the Ka and Wageningen B series, like the lesser-known Meyne-VBD series [VBD, 2002] or propellers for which no polynomials are published. Furthermore, the effects of tunnels could not been included in the designs, nor could the effect of changing wake fractions due to shallow water effects. As a result of this, the vessel designs will on various occasions have more propellers than existing inland ships with identical main dimensions. The amount of installed power in the modeled ships is, however, very close to the amount of power that is installed in existing inland ships with identical main dimensions, as is the building cost of the modeled vessels. Both of these aspects will be discussed later in this chapter.

5.1.5 Structural arrangement

The steel structures of the ships are designed on the basis of Lloyds register's structural rules for inland ships of 2008 [Lloyds Register, 2008], as was already discussed in chapter 4.2.1.

Before continuing with a discussion of the structural arrangement of the designs, a word of caution is needed: Lloyds' rules are intended for 'conventional' inland ships, i.e. ships that are not longer than 135 m, have a length to depth ratio that does not exceed 35 and a breadth to depth ratio that does not exceed 5. [Lloyds register, 2008, Pt. 4, Ch. 1, Sec. 1, 1.1.2]. The very long vessels, the very low-draught vessels and the very wide vessels of systematically varied series of designs are well outside this range and as a result, the structural weight and general feasibility for these vessels should be treated with caution. Large length, length-to-depth ratio and/or breadth-to-depth ratios do not impact the calculation of scantlings that are required to withstand local loads, nor do they affect the way bending moments and the resulting stresses are calculated. However, they will impact the torsional stiffness of the hull and the hogging and sagging deflections. Both may lead to a local reduction in realized freeboard and to deflections in the structure that may harm the ship and its cargo.

The structural arrangement of all ship designs is as follows: The aftship is transversely framed, with a frame spacing of 500 mm and a webframe spacing of 3000 mm. The structural arrangement in the foreship is identical. The midship, if framed transversely, has a frame spacing of 0.6 m and a webframe spacing of 1.8 m.

In case of longitudinal framing of the midship, the spacing of longitudinal members is determined on the basis of the ship's main dimensions. For dry bulk and container ships, the number of girders in the double bottom is set in such a way that the spacing between them is as close as possible to 3 m under the boundary condition that there is a center girder and that there are girders below the longitudinal bulkheads of the double hull. Longitudinals are fitted between these girders at a maximum spacing of 600 mm. In case of tank vessels, girder spacing is set a goal value of 5 m. In longitudinally framed sides, a maximum longitudinal spacing of 600 mm is also maintained while actual spacing is determined on the basis of the height of the sides above the tanktop.

5.1.6 Accommodation

The size of the accommodation of an inland ship is dependent on both the required number of crew members and owner's standards. Since the number of crew members is not only dependent on the main dimensions of the vessel and the equipment level (S1 or S2) but also on the sailing regime (14, 18 or 24 hours per day) and whether or not the ship pushes one or more barges, there is a large spread in possible accommodation sizes. Furthermore, even for given ship dimensions and crew complement the owner has significant freedom in determining the size of the accommodation. In practice, both very small accommodations and relatively spacious accommodations that also serve as a family home occur on ships of similar dimensions. Therefore, it was decided to design the accommodation as follows:

- The aft end of the accommodation is located 2.5 m (5 frames) forward of the vessel's stern.
- Gangways of 1 meter run alongside the accommodation.
- The accommodation is a 1-tier accommodation with a maximum floor space of 100 m^2.
- There is a limit on the length of the accommodation: accommodation space should not cover more than 20% of the vessel length.
- There is no accommodation in the foreship.

5.2 Results with regard to the propulsion system

In the previous paragraph, the design choices that are valid for all ship types have been discussed. Since all ship types have identical drive trains, the first results to be discussed about the designed vessels are these drive trains. All other results will be discussed per ship type in consecutive paragraphs.

The amount of power that is installed for propulsion purposes is dependent on vessel dimensions, hullform, design speed and drive train efficiency. This last aspect is in turn influenced by propeller diameter, propeller type and number of propellers. In this paragraph, the amount of installed propulsion power for all vessels is reviewed and an overview of the number of propellers is given.

In chapter 4.3.2, it has already been shown that the amount of installed power for propulsion is in line with the rated power of existing ships. In Figure 5-3 below, the amount of installed power is shown as a function of L, B and T_{design}. From this figure, the obvious trend of increasing power with increasing length, beam and draught becomes apparent.

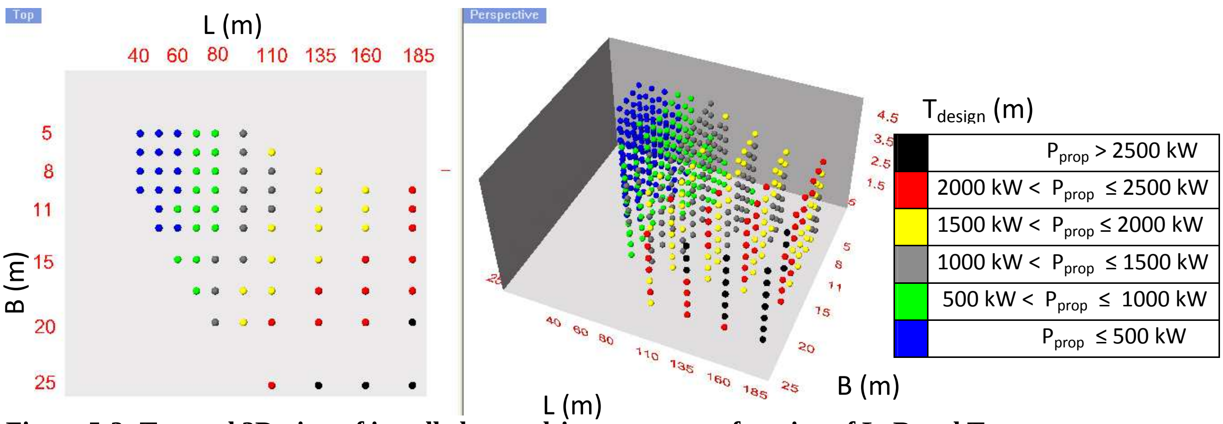


Figure 5-3: Top and 3D-view of installed propulsion power as a function of L, B and T_{design}

However, when showing propulsion power per ton of cargo carrying capacity for dry bulk vessels in Figure 5-4 below, it becomes clear that there is a relatively constant amount of power installed per ton. The short, and therefore slow, wide and deep draught vessels have the lowest amount of installed power per ton of cargo carrying capacity, while especially the long, narrow, shallow draught vessels have a high amount of propulsion power installed per ton of cargo carrying capacity. It should be noted that this effect is not only due to the characteristics of propulsion and resistance of the ship, but also due to the fact that shallow draught vessels have a relatively high lightweight compared to deadweight, as a result of which the cargo carrying capacity of these ships is low compared to their displacement.

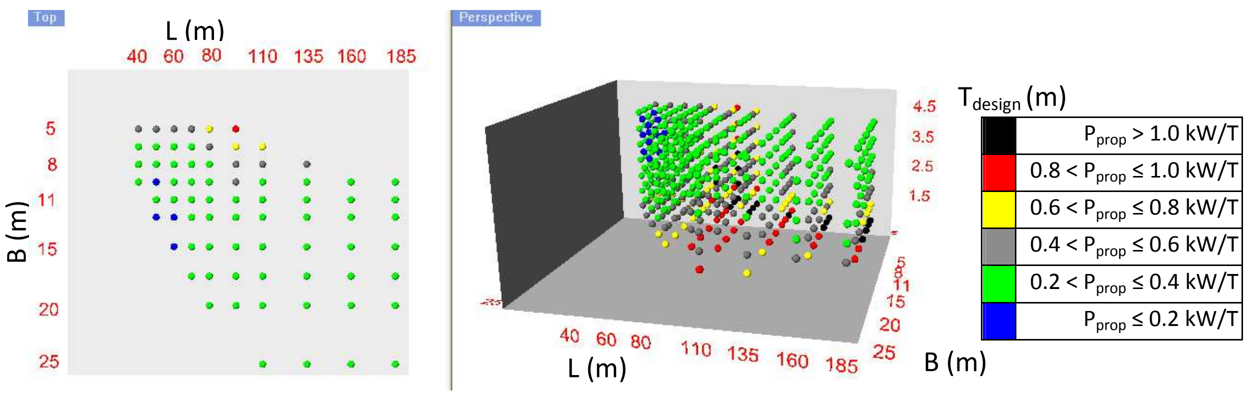


Figure 5-4: Top and 3D-view of installed propulsion power per ton cargo carrying capacity - dry bulk

In Figure 5-5, the same figure is shown for tank vessels, which have a higher lightweight than dry bulk vessels of identical length beam and draught. The resulting difference in cargo carrying capacity is, however, not large enough to significantly alter the amount of power per ton of cargo carrying capacity.

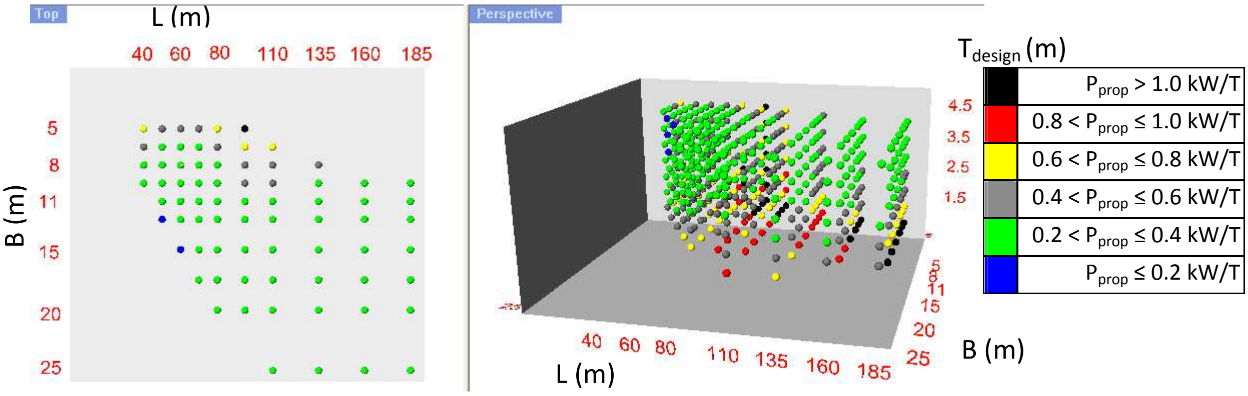


Figure 5-5: Top and 3D-view of installed propulsion power per ton cargo carrying capacity – tank vessels

When looking at an overview of the number of propellers in Figure 5-7 below, it becomes clear that due to the fact that it was not possible to include dedicated inland ship propellers in the powering calculation (as was discussed in chapter 4.2.3), the number of propellers is typically higher than for common inland ships, but still matches the propeller arrangement of existing vessels with an equally simple hullform and without tunnels like the Neokemp/Hopper type container vessels (63 x7 m), mv Frontrunner (110 x 11.4 m) and the Airbus-vessels Breuil and Brion (67 x 14 m), that are all equipped with two rudderpropellers.

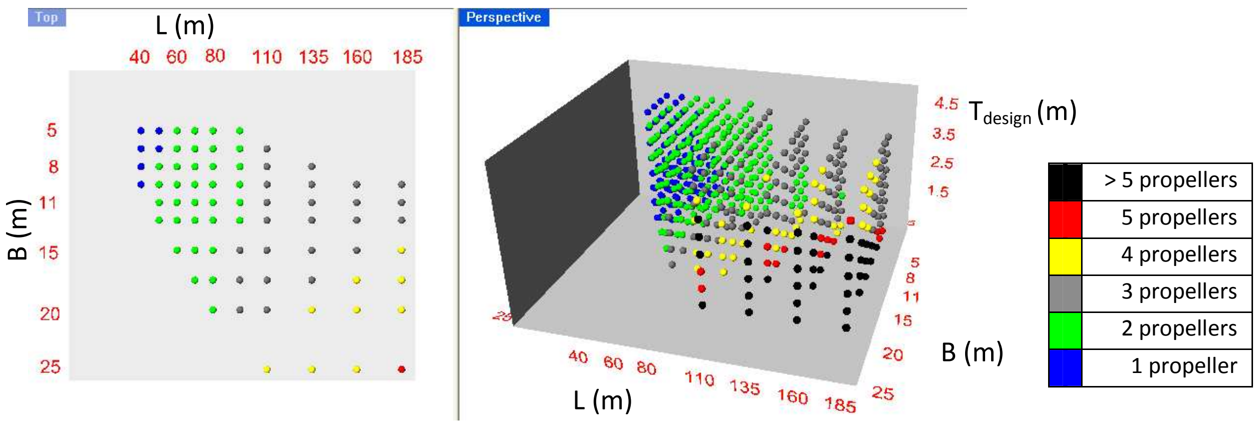


Figure 5-6: Top and 3D-view of the number of propellers as a function of L, B and T

As a consequence of the abovementioned limitations of the powering calculation, the high numbers of required propellers for the larger vessels should not be taken as absolute truths: they indicate merely that a large amount of thrust is required and that careful consideration should be given to choice of propeller and the shape of the stern of the ship in order to maximize the efficiency of the propellers.

Now, after having discussed the properties of the drive train of all datasets of ships, the ship type specific properties of the dry bulk, container and tank fleet are discussed in the following paragraphs.

5.3 Results for dry bulk ships

In this paragraph the results of the systematic series of dry bulk ship designs are discussed. First the ship type specific design parameters are treated, followed by a review of steel weight, lightweight and building cost of the designs.

5.3.1 Design parameters

The only ship type-specific parameter that is used in the design of the dry bulk vessels is their depth. The required depth is determined by the requirements of appendix II, chapter 4, article 4 of the European guideline for inland navigation [European Parliament and Council of the European Union, 2006a]. This results in a safety distance of no less than 30 cm and a freeboard of no less than 15 cm, assuming that the accommodation does not contribute to the vessel's stability in a positive way. In the datasets of ship designs, this freeboard is complemented by a 90 cm high hatch coaming.

5.3.2 Steel weight

Both the cargo carrying capacity and the building cost of inland ships are directly related to the steel weight of inland ships. Estimation formulas for the steel weight and lightweight of inland ships as provided in literature by Heuser [1986] and Germanischer Lloyd [2006] show only a relatively narrow bandwidth for the steel weight and lightweight as a function of LBD (length x beam x depth). However, it is to be expected that when the ratios between length, beam and depth of a ship deviate substantially from common values, the weight of the ship will also deviate from this bandwidth. Therefore, a more accurate steel weight analysis, like the one made in this thesis, will substantially improve the possibility to make accurate estimations of the cost and cargo carrying capacity of inland ships.

In this sub-paragraph, the results for the steel weight estimate of dry bulk vessels are discussed. First, it will be shown that the spread in structural weight is indeed much larger than proposed by Germanischer Lloyd [2006], which is the only recent estimate for the steel weight of inland ships. After that, it will be shown how steel weight relates to LBT for the entire range of vessel dimensions.

It should be noted that in this paragraph both LBT (length x beam x draught) and LBD (length x beam x depth) are used in the presentation of steel weight. The reason for use of LBD in the initial discussion of results is that this allows more easy comparison with values from literature, which are also based on LBD. However, in the discussion of nearly all results, LBT is used because the designs were systematically varied along L, B and T and because LBT-based estimates provide a more direct way of estimating the amount of deadweight the ship will be able to carry, since it takes considerations about the D/T ratio away.

Germanischer Lloyd [2006] assumes a value of 0.15 * LBD for the steel weight of vessels with a depth of 3.7 m or less and 0.1 * LBD for vessels with a larger depth, irrespective of ship type. Drawing both lines in the same graph as the results of the dry cargo vessels designed here leads to the results that are shown in Figure 5-7:

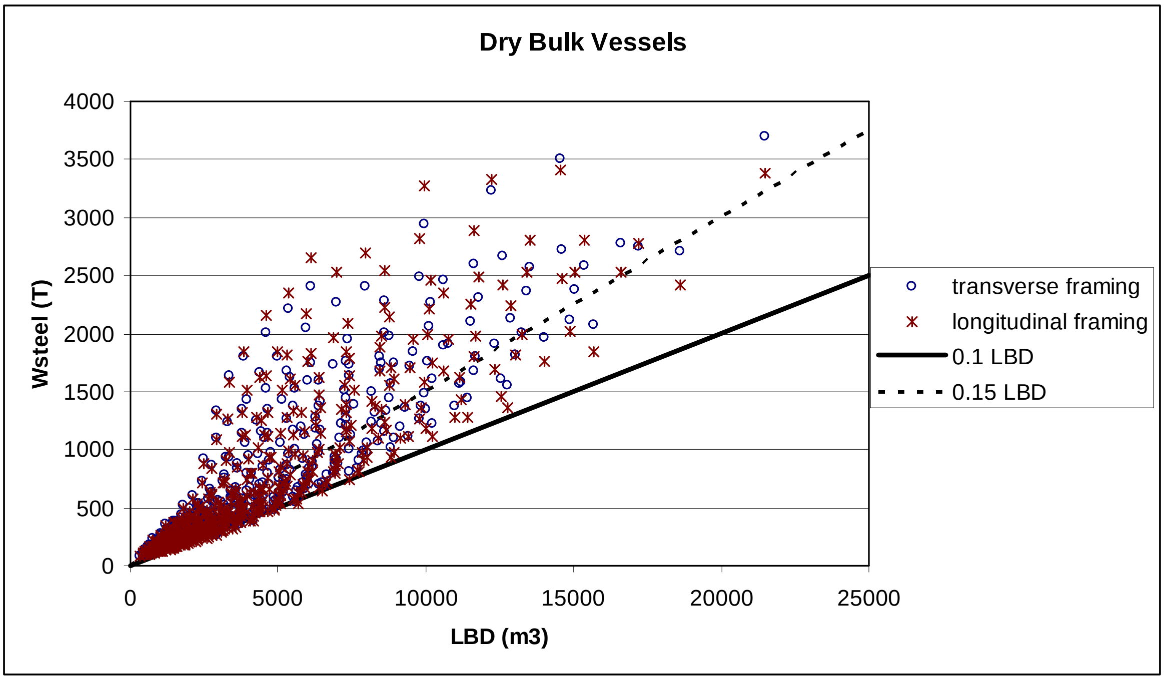


Figure 5-7: Steel weight of dry bulk vessels as a function of LBD

Figure 5-7 clearly shows that when a large design space is explored, steel weight will deviate strongly from weight estimates that are based on ships with common main dimensions in a number of cases. It also shows that vessels with main dimensions that deviate from those of common vessels are either in the same weight range as common ships or are heavier. The use of non-standard main dimensions does, however, not result in substantially lighter vessels.

For dry bulk vessels, the depth is defined as T + 0.15 meter, as was elaborated in chapter 5.3.1. When the steel weight is divided by LBT and results are plotted in a 3D graph (Figure 5-8), it becomes apparent that the steel weight-to-LBT ratio decreases as draught increases and that there is a minimum for vessels of 40 – 80 meters in length with a draught of 4.5 meters (depth of 4.65 m). At these lengths, the bending moment does not yet result in scantlings that exceed the minimum practical scantlings (i.e. being sturdy enough for day-to-day use and thick enough to weld). It should be noted, however, that the minimum is very shallow, since the lightest vessels only just dip below the 10% mark and many vessels stay below the 15% mark, as was already apparent from Figure 5-7 above.

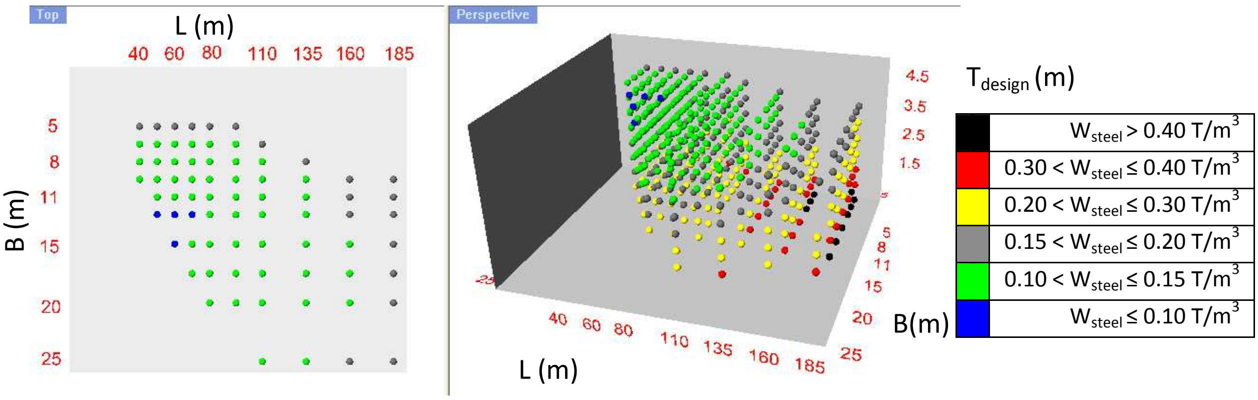


Figure 5-8: Top and 3D-view of steel weight fraction - transversely framed dry bulk vessels

For longitudinally framed dry bulk vessels, shown in Figure 5-9 below, a very similar picture appears, although these vessels are generally marginally lighter. For both types of framing, it can be observed that the steel weight-to-LBT ratio increases as draught gets smaller and that especially for very shallow draught vessels, steel weight consumes a large portion of the available displacement. This in turn results in vessels that will have high building cost and installed power per ton of cargo carrying capacity.

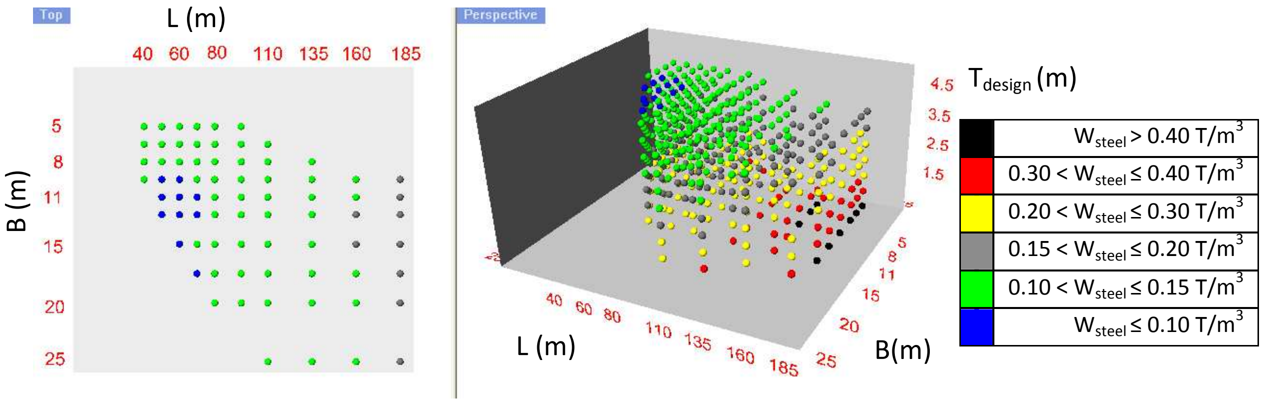


Figure 5-9: Top and 3D-view of steel weight fraction - longitudinally framed dry bulk vessels

5.3.3 Impact of framing system

As discussed above, the weight of a ship's steel structure is not only dependent on the main dimensions, but also on the framing system. In Figure 5-10, the difference between the steel weights of longitudinally and transversely framed ships is shown. In the figure, ΔW_{steel} is positive when the transversely framed vessels are heavier than longitudinally framed vessels. It becomes apparent that the relationship between weight benefits of longitudinal framing and vessel dimensions is not entirely straightforward for the modeled steel structures; for small vessels transverse framing typically results in a heavier vessel, while for most long vessels that are 12.5 to 17.5 m wide, weight gains of up to 10% can be achieved by using a transverse framing system.

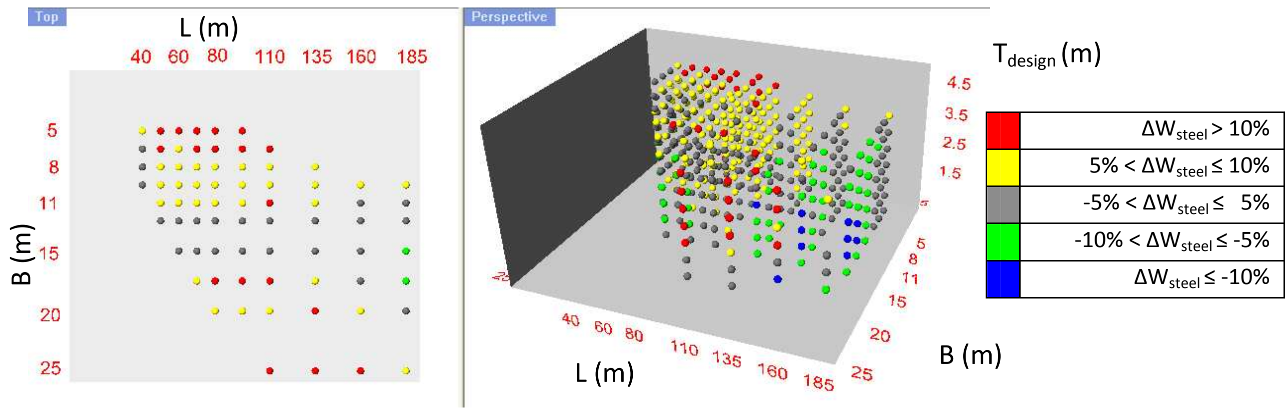


Figure 5-10: Top and 3D-view of difference in steel weight between longitudinally and transversely framed dry bulk vessels

5.3.4 Lightweight

Lightweight, the weight of the complete ship, being ready for service but empty, is obtained by adding the weight of the accommodation, piping, machinery, equipment and outfitting to the steel weight that was discussed in the previous paragraph. A graph of the lightweight for the systematically varied dry bulk vessels shows the following results:

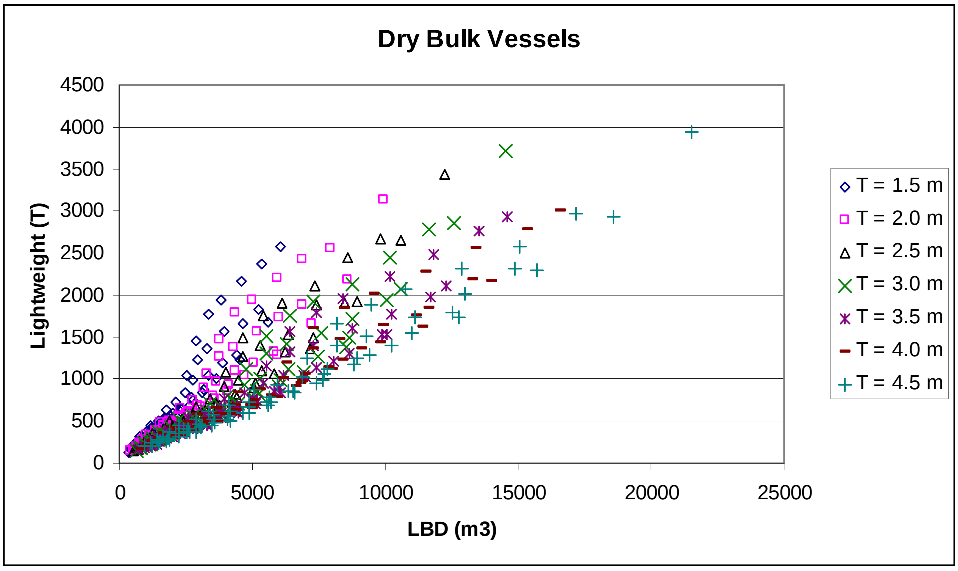


Figure 5-11: Lightweight of dry bulk vessels as a function of LBD

The graph shows that vessels with a high draught typically have a lower lightweight-to-LBD ratio than vessels with a low draught. The graph also shows that vessels with an identical draught may have a substantial scatter in lightweight-to LBD ratio, due to length and beam effects.

Despite the fact that there is virtually no recent data available from literature about the lightweight of inland ships, the data presented above allows for validation of results from the design model through comparison with the lightweight trend line that is used by Hofman [2006], who in turn refers to Heuser [1986] as the source of data for this trend line[13], which reads:

$$W_{lightship,Hofman} = -4.44 \cdot 10^{-6} \cdot (LBD)^2 + 0.195 \cdot LBD \qquad \text{Eq. 5.1}$$

Figure 5-12 below shows that results of the systematically varied dry bulk vessel designs are in the same range as those of Hofman/Heuser, where the line of Hofman/Heuser best matches the results of modeled vessels of roughly 3 meters in depth. Since a depth of about 3 meters is typical for class III and IV vessels, which would have been the main source for Heuser's trend line since they were the prevalent ship type in the 1980's, the lightweight estimates for the modeled vessels are considered to be a good match with the values provided by Heuser [1986].

The fact that, especially for the smaller vessels, the results of Hofman/Heuser are lower than the ones produced for this thesis may be explained by a number of causes including the fact that all vessels for this thesis are modeled as double hull vessels, which was not the norm for dry bulk vessels in the 1980's. Furthermore, there appears to be an absence of non-LBD-related weights like masts and wheelhouses etc. in the trend line of Hofman/Heuser, which is complemented by the physical absence of machinery like bow thrusters in older inland ships.

[13] It is confirmed by Hofman [2006] that there is no good data available to estimate the lightweight of inland ships except for the relatively old data by Heuser [1986].

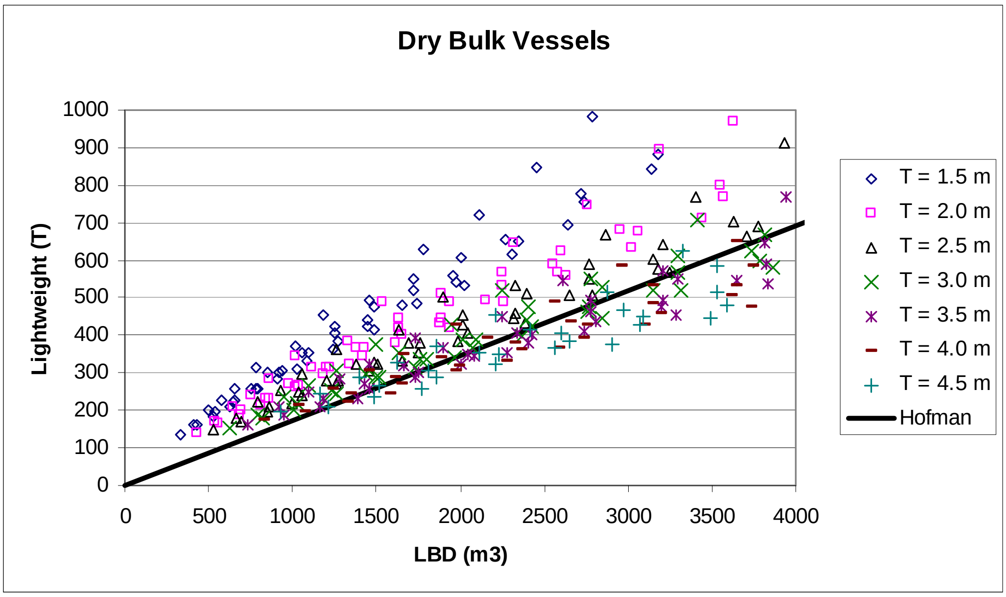


Figure 5-12: Comparison of modeled lightweight with the trend line by Heuser

Looking closer into the items that make up lightweight apart from the structure in Figure 5-13 below, it can be seen that there is relatively little scatter, even though most of the weight of machinery, equipment & outfitting is only indirectly related to LBD through the power of the main engine(s) and generator set(s), while accommodation is only related to length and beam.

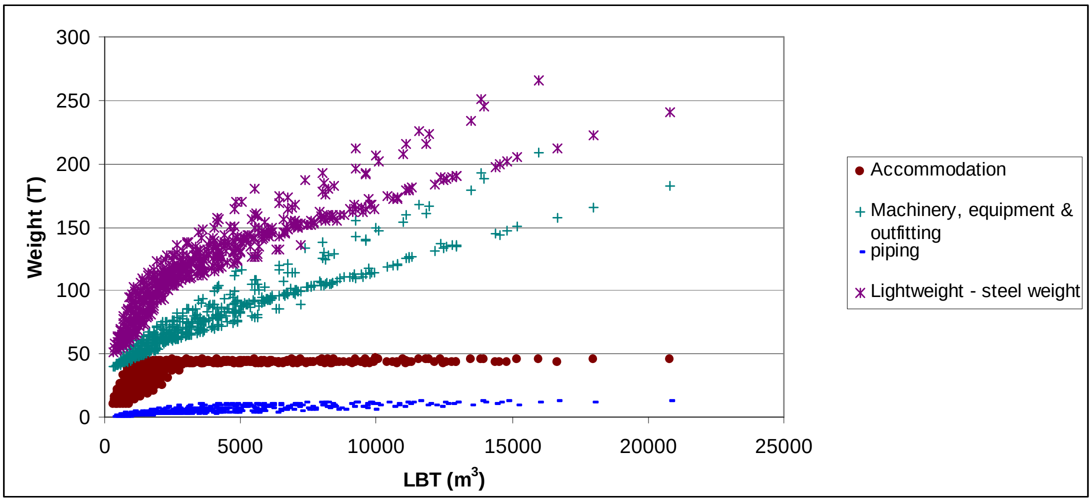


Figure 5-13: Weight of non-structure related lightweight as a function of LBT

The scatter that does occur for the weight of machinery, equipment & outfitting is caused by the vessels with the largest lengths and beams, which require a substantial number of propellers (>5). The combined weight of these propellers and their rudders & shafts increases the total weight of machinery, equipment & outfitting substantially. Furthermore, these ships rely on multiple small and, therefore, relatively heavy engines.

When lightweight is plotted against L, B and T_{design}, results are as shown in Figure 5-14. The figure shows that lightweight fractions range from just below 15% to over 40% of LBT and that the wide, deep draught vessels with lengths between 50 and 135 m have the lowest lightweight-over-LBT fraction.

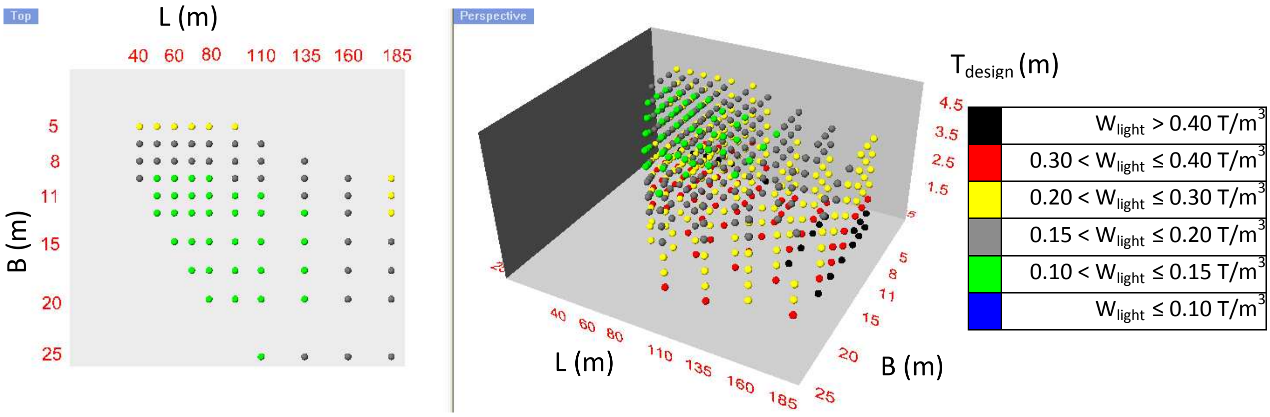


Figure 5-14: Top and 3D-view of lightweight fraction (transversely framed dry bulk vessels)

5.3.5 Building cost

As a final topic for dry bulk vessels, the building cost of the vessels, expressed in 2011 values throughout this chapter, is discussed. This building cost is determined with the model that is developed in chapter 4.2.5 and appendix C.

In absolute values, the total cost of a dry bulk vessel ranges from less than € 900.000 for the smallest vessel of 40 x 5 x 1.5 meters to over € 13 million for the largest vessels of 185 x 25 x 4.5 meters. However, to provide more insight, in Figure 5-15 the building cost per ton cargo carrying capacity is expressed as a function of L, B and T. This cost varies from €706 per ton for the largest vessel to €7050 per ton for a Peniche-sized ship with a draught of 1.5 m.

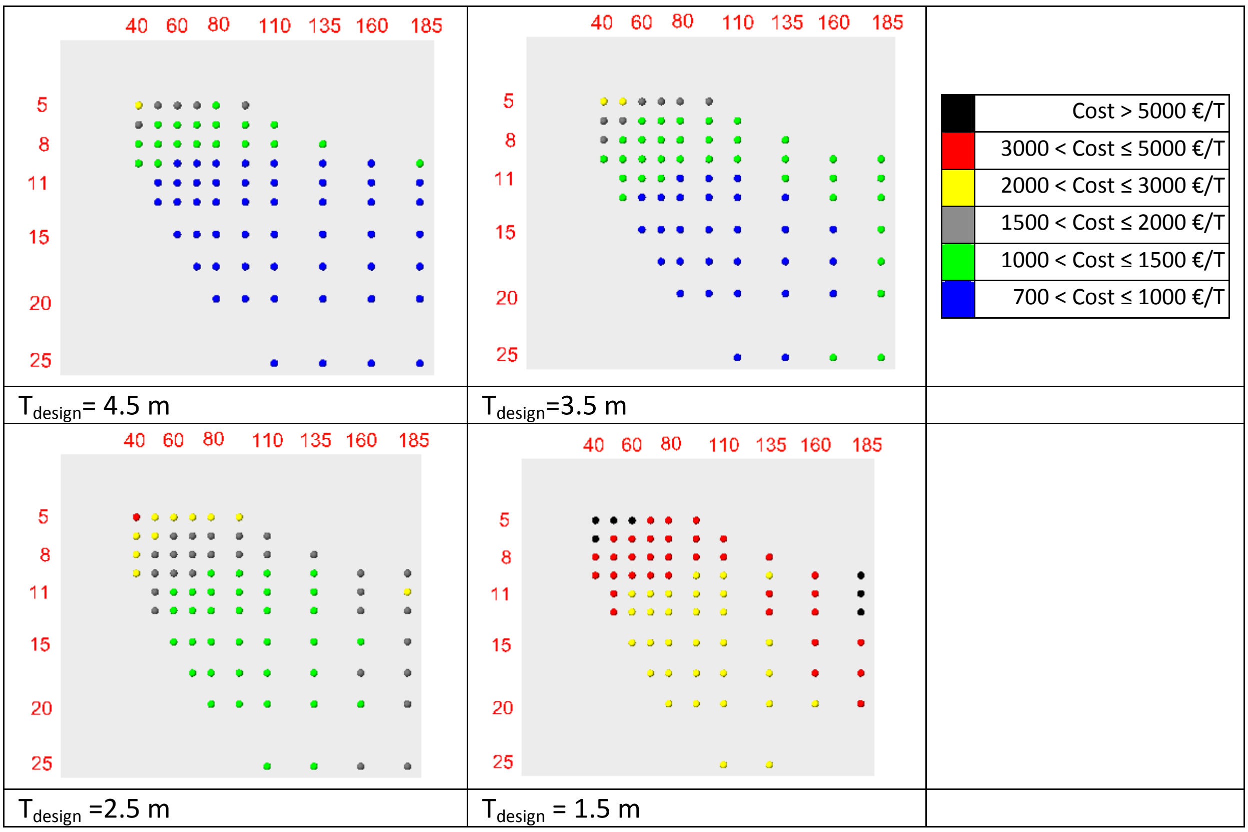


Figure 5-15: Cost per ton cargo carrying capacity as a function of L, B and T_{design} - dry bulk

From Figure 5-15 above, which shows the cost per ton of cargo carrying capacity for draughts of 4.5, 3.5, 2.5 and 1.5 m, it can be seen that there are strong economies of scale, which depend especially on vessel design draught: As draught goes down, cost per ton of cargo carrying capacity goes up.

However, for a given draught, scale effects are mainly found in the lower ranges of length and beam. For example At a draught of 4.5 m, the smallest vessel costs over € 2000 per ton, while virtually all vessels of 9.5 m beam and more cost less than € 1000 per ton deadweight, thus resulting in relatively low further economies of scale, considering that the minimum value is € 706 per ton.

The most important conclusion that can be drawn from Figure 5-15 is that especially for the vessels with a draught of 2.5 m and less, the biggest vessel does not have the lowest cost per ton of cargo carrying capacity. A shift of the cheapest vessels towards shorter vessels occurs, indicating that the large, heavy vessels might not be able to compete with their lighter and smaller counterparts at low design draughts.

The cost of the ship can be subdivided into several smaller components, which can in turn be grouped in two groups: yard cost and non-yard cost. Here the yard cost comprises the general object costs and cost of construction of the hull, while the non-yard cost are the combined cost of all machinery, equipment and outfitting.

As shown in Figure 5-16 below, yard cost comprises between 34% and 73% of the total cost. This value increases with increasing ship size but shows no significant dependency on vessel draught.

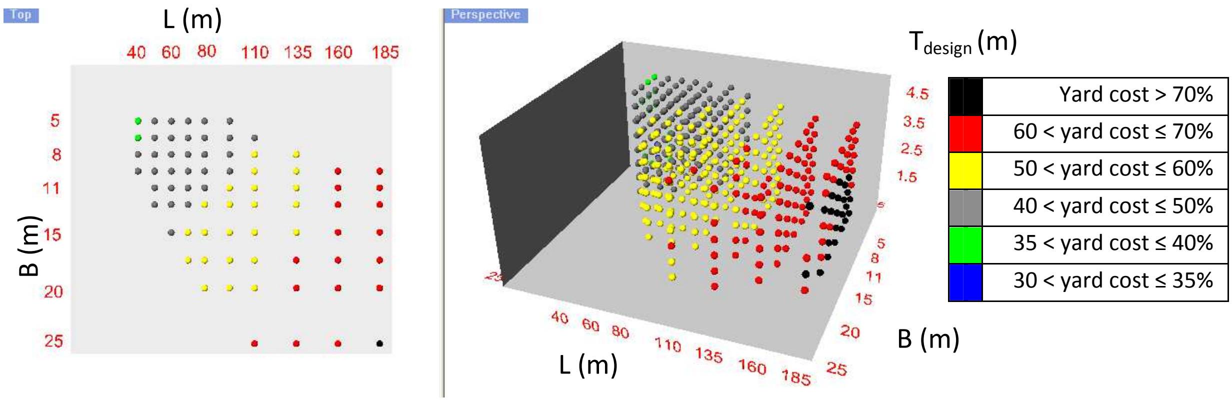


Figure 5-16: Top and 3D-view of yard cost fraction as a function of L, B and T_{design}

Here it is important to note that especially the cost of the smallest vessels is strongly influenced by the cost of the machinery, equipment and outfitting (i.e. the non-yard cost), while the cost of the steel hull is more dominant for large vessels. As a result, a number of specific items like a wheelhouse, wheelhouse raising column and navigation equipment, which are not directly related to the size of the ship, have a large impact on the cost of small vessels. This in turn leads to the conclusion that the cost of the smallest ships should be treated with caution, because they are sensitive to errors in the cost estimation. Still, overall cost values from the model match reality well, as was shown in chapter 4.3.3.

In order to provide more insight into the various cost components of the ships, Figure 5-17 shows the breakdown of cost for the smallest and largest vessel.

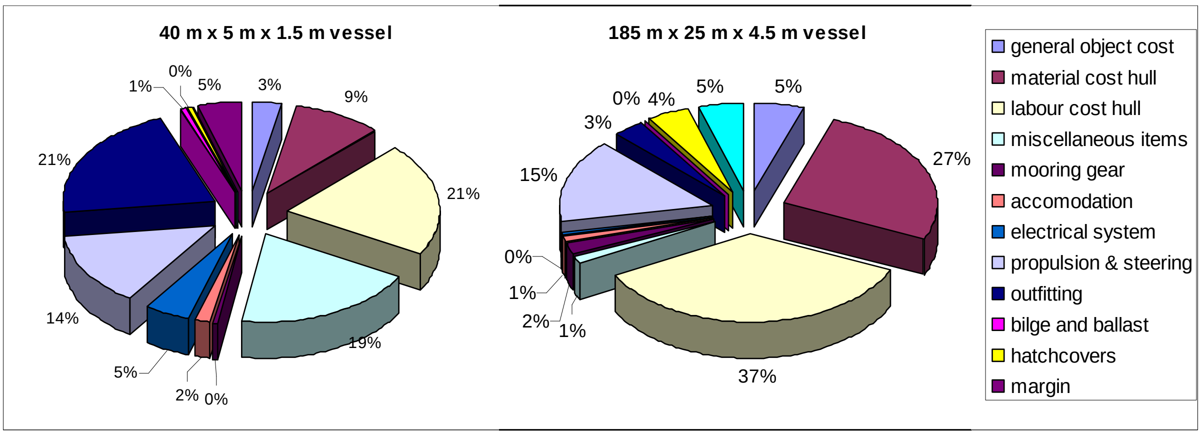


Figure 5-17: Cost breakdown for the smallest and largest dry bulk vessel

Figure 5-17 shows the large impact that miscellaneous items, which include items like navigation equipment, wheelhouse and the wheelhouse raising column, have on the overall cost of small ships. It also reveals that the impact that the cost of the hull has on the total cost is much larger for large ships than for small ships. The share of the cost of propulsion and steering, however, does not show a strong increase or decrease for these two vessels.

5.4 Results for container ships

In this paragraph, the results for the systematically varied container ship designs are discussed, like they were in the previous paragraph for dry bulk ships. Due to the fact that inland container ships are in practice often dry bulk vessels that are also used to transport containers, the only difference in the design of the ships is their depth. For container ships this becomes a function of the beam of the ship due to stability requirements, as will be discussed briefly in chapter 5.4.1.

Due to the small difference in technical properties, results will be treated only summarily. It should be noted that the beams of the container ships in the dataset of ship designs are not adjusted to the width of containers, but the designs are made at the same L, B and T values as the dry cargo vessels to allow for better and easier comparison between the ship types.

As a result, in order to arrive at vessel designs that are optimally suited for the carriage of containers, i.e. having a beam that is equal to the width of X containers plus spacing and a double hull on either side, interpolation between the data points is necessary in some cases. Furthermore, for container ships, stability and the maximum air draught on various waterways may limit the amount of cargo they can carry. Both of these aspects limit the height to which containers can be stacked, which in turn limits the weight of cargo and the resulting maximum draught of a vessel. All of these issues are dealt with in the cost model that is developed in chapter 6.

Since container ships on inland waterways can also be used for transport of dry bulk, designs with a design cargo carrying capacity that does not match the cargo carrying capacity resulting from stability and/or infrastructural limitations are not discarded yet at this point. The impact of these limitations will be demonstrated in chapter 7.3.3.

5.4.1 Design parameters

For container ships, the required depth of dry bulk vessels as determined in appendix II, chapter 4, article 4 of the European guideline for inland navigation [European Parliament and Council of the European Union, 2006a] is supplemented by the requirement in chapter 22, article 22.02 of that same document. This requirement states that the main deck shall not become submerged until a heel angle of at least 5 degrees is reached, leading to a demand for freeboard to be at least 1/23 of vessel beam. As a result, the depth of a container vessel will be larger than the depth of a dry bulk vessel with the same beam and draught and this in turn results in a heavier ship.

5.4.2 Lightweight

Since the lightweight of container ships is very similar to that of dry bulk vessels, the analysis of chapter 5.3.2 will not be repeated here, but only the difference between the lightweights will be discussed. Since only the steel structure of the ship is altered, the weight of the accommodation, piping and machinery, equipment & outfitting, does not change. However, the increased depth does result in a heavier hull. In Figure 5-18 below, the difference between the weight of a transversely framed container vessel and its dry bulk counterpart is shown.

In Figure 5-18, it can be seen that the difference between the weight of dry bulk ships and container ships increases as both length and beam increase. The increase in weight as a result of the increase in beam is caused by the fact that freeboard and beam are directly related. The increase in weight as a result of an increase in length is due to the fact that a longer ship also has a longer cargo hold, the weight of which is affected more strongly by an increase in depth than the weight of the fore and aft sections of the ship.

Apart from these global trends, Figure 5-18 also reveals that there are local fluctuations in the increase in weight, which are due to a number of causes, including how the difference in depth between dry bulk and container ships results in different plate thicknesses and stiffener dimensions.

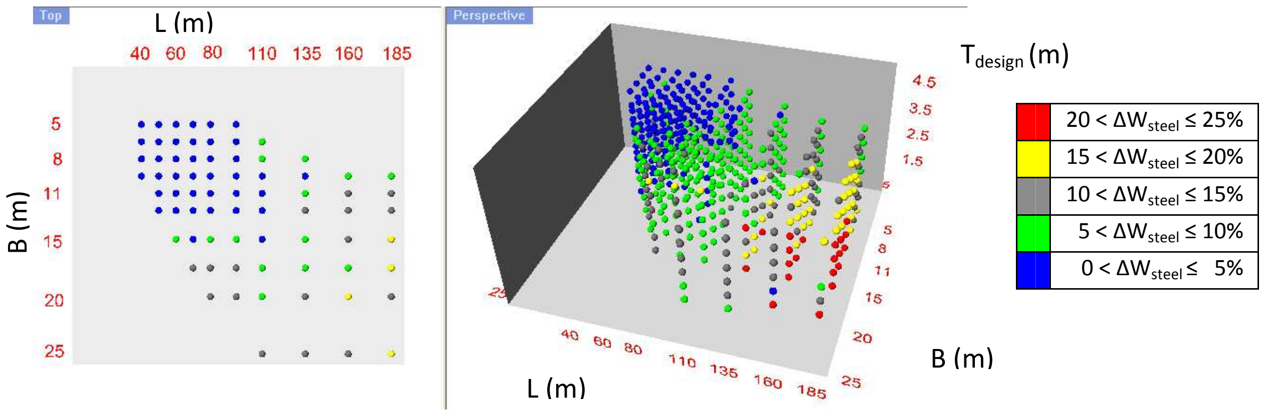


Figure 5-18: Steel weight increase for container vessels compared to dry bulk vessels

5.4.3 Cost

Since the only differences between dry bulk and container vessels are the depth and the resulting steel structure, the cost breakdown of both ship types is highly similar. As a result, Figure 5-19, which shows the building cost for all container ships with a design draught of 4.5, 3.5, 2.5 and 1.5 meters is highly similar to Figure 5-15, which displays the cost for dry bulk vessels.

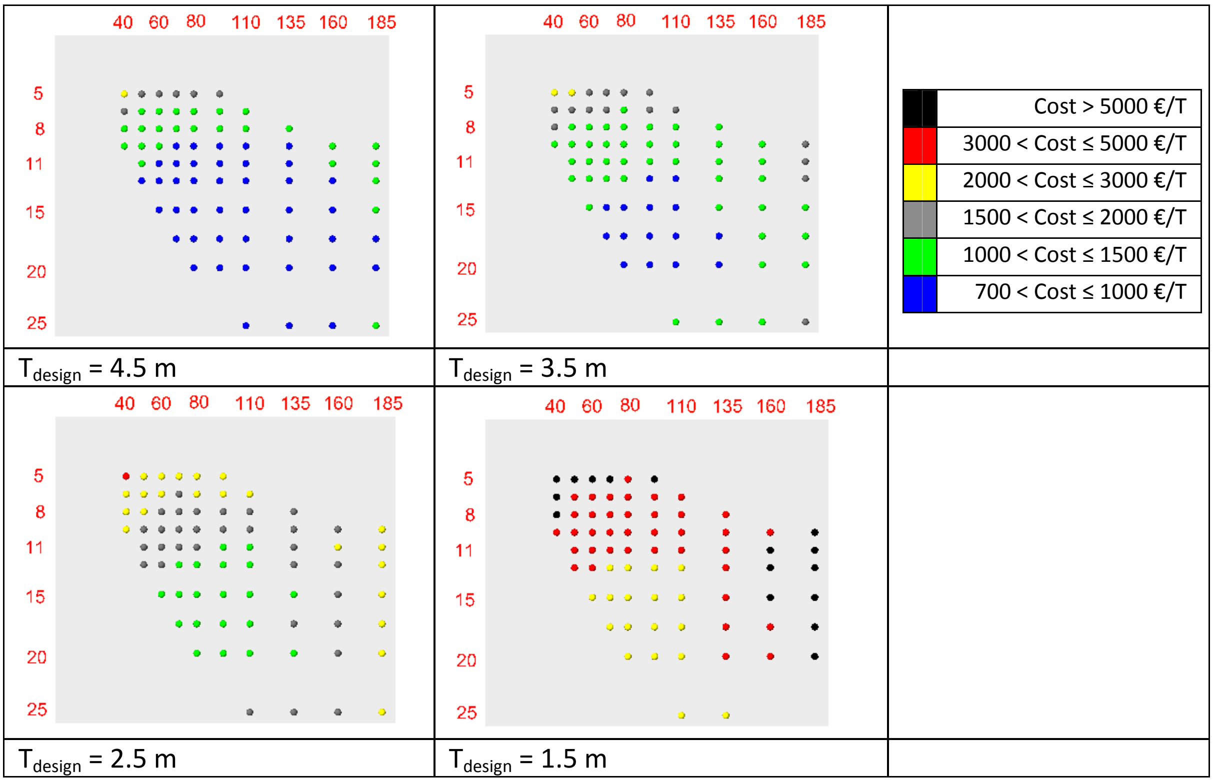


Figure 5-19: Cost per ton of cargo carrying capacity as a function of L, B and T_{design} - container ships

However, differences do occur: especially wide ships and long ships are more expensive than their dry bulk counterparts as a result of the increase in steel weight. The cost per ton of cargo carrying capacity ranges from € 780 per ton for the largest vessel to € 7836 per ton for the smallest vessel. For dry bulk vessels, these values were € 706 and € 7050.

5.5 Results for tank ships

In this paragraph, the results for the dataset of systematically varied tank ship designs are discussed. Since it is common to frame tank vessels longitudinally, only longitudinally framed designs are considered. The vessels under review are standard type C coated tankers with a loading and unloading system that is suitable for a single batch of cargo. The vessel designs do not incorporate a heating system for the cargo.

5.5.1 Design parameters

For tank vessels there are considerably more rules to adhere to than for dry cargo vessels. The rules that have the largest impact on the overall design of the ships are discussed below. The rules concern the volume of individual tanks, the application of cofferdams and the width of the hull structure.

Volume of individual tanks

ADN regulations [Economic Commission for Europe, 2009, paragraph 9.3.2.11] prescribe the maximum size of the individual tanks as follows:

Table 5-2: Maximum volume of individual tanks according to ADN regulations

$L*B*H$ in m^3	Maximum volume of a tank in m^3
≤ 600	$L*B*D_{hold}*0.3$
600-3750	$180+(L*B*D_{hold}-600)*0.0635$
≥ 3750	380

Where:
L = maximum length of the hull (m)
B = maximum beam of the hull (m)
D_{hold} = depth along the cargo hold (m)

For designs that are made, these upper limits are adhered to. Furthermore at beams exceeding 10 m, two tanks are placed abreast and at beams exceeding 17.5 m, 3 tanks are placed abreast.

Cofferdams
According to ADN, cargo tanks should be separated from accommodations, engine rooms and service areas below deck by cofferdams with a width of at least 60 cm [Economic Commission for Europe, 2009, paragraph 9.3.2.11.3]. This value is maintained in all designs.

Double hull structure
The width of the double hull should be at least 1.00 m according to ADN paragraph 9.3.2.11.7. [Economic Commission for Europe, 2009, paragraph 9.3.2.11]. This value may be reduced to 0.80 m in case a number of structural elements are reinforced. For the systematically varied designs, the value of 0.80 m is maintained and the required reinforcements are put in place.

According to that same paragraph of ADN, height of the double bottom may on average not be less than 0.70 m and may never be less than 0.60 m. For the design of all vessels in the dataset, a height of 0.70 m is maintained.

5.5.2 Steel weight

For tank ships, the calculation of steel weight is more complex than for dry cargo vessels since the required depth of the ship is not only determined by freeboard demands but also by the need to match the volume of the tanks to the density of the cargo and the maximum cargo weight that the vessel can carry. Since there is an interaction between the volume of the holds, vessel depth, vessel weight and cargo weight, finding the right vessel depth is an iterative process, which has been done twice for each of the tank ship designs, leading to good results.

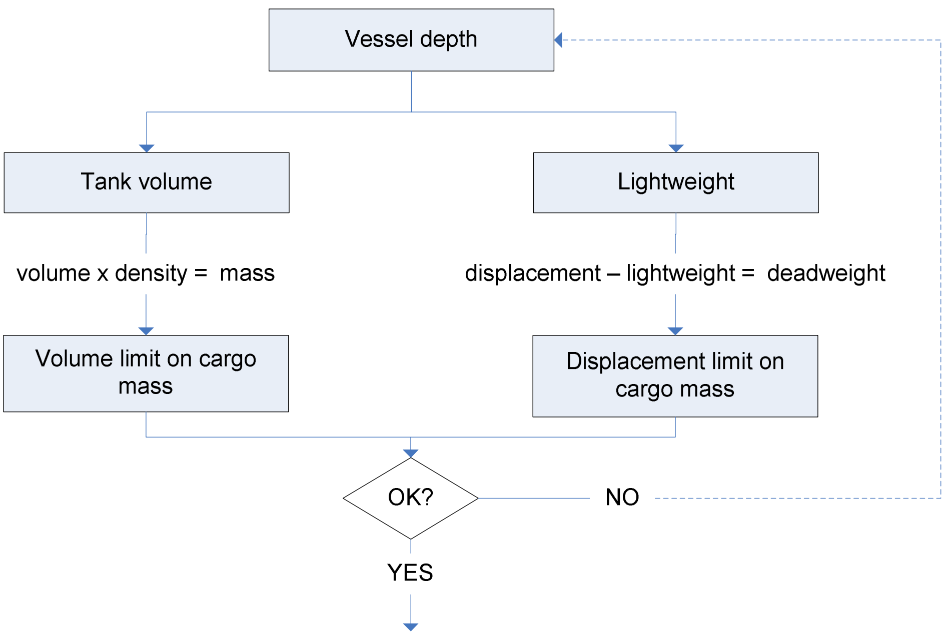


Figure 5-20: Scheme for the determination of vessel depth

For ships that are common on the European waterways, the weight to volume ratio of the cargo tanks is roughly 0.86 ton per cubic meter, based on data from [Vereniging 'De Binnenvaart'] as shown in Figure 5-21. As a result, this value is used as the target value for the ratio between hold volume and deadweight.

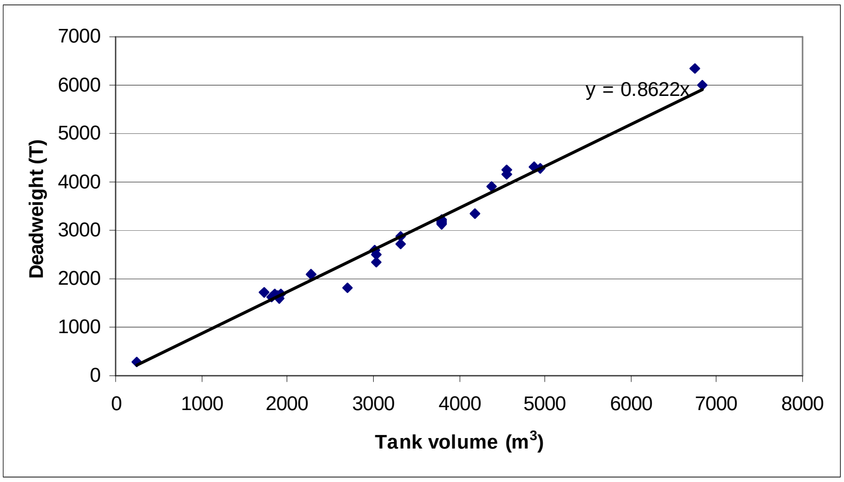


Figure 5-21: Tonnage vs. tank volume for existing ships

For the ships in the dataset of designs, the depth of the midship is increased in order to attain the required tank volume, taking into account the restrictions that are posed by double hull requirements, space required for the double bottom and space lost at the bow and stern to place forepeak, bow thruster room, engine room and accommodation. This results in a relatively large increase in depth for short, narrow vessels and only a small increase for the long and wide vessels.

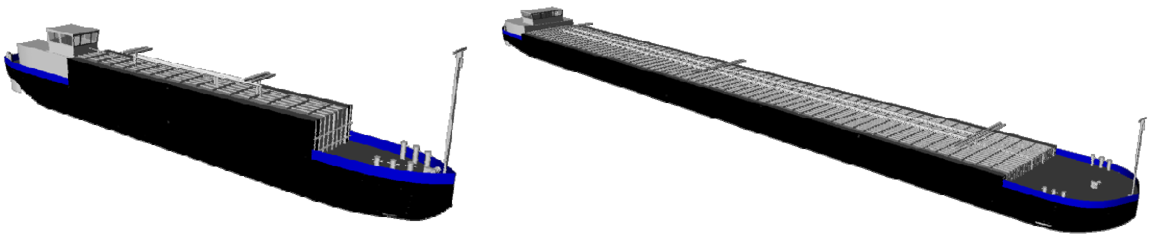


Figure 5-22: Example designs of a small and large tank vessel

After two design iterations, the realized tank volume to deadweight tonnage ratio closely resembles that of the example ships, as is shown in Figure 5-23 below, and is deemed acceptable.

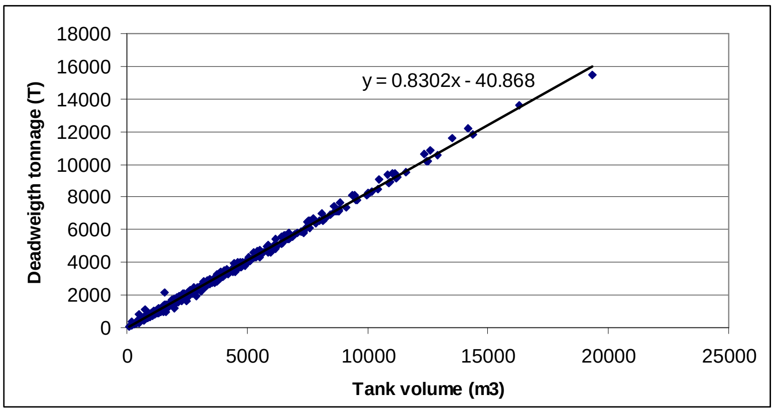


Figure 5-23: Modeled deadweight tonnage vs. tank volume

Tank vessels are substantially heavier than dry bulk and container vessels of identical length, beam and draught. This is due to the weight of the main deck, the bulkheads that subdivide the cargo space into individual tanks and due to the additional piping systems that are required to load and unload the cargo. However, the steel weight of tank vessels shows similar trends as that of dry bulk and container vessels.

The minimum steel weight of tank vessels is just below 15% of LBT for the wide deep draught vessels, while maximum weights of over 50% of LBT are reached for both long and very narrow vessels with a draught of 1.5 m, as is shown in Figure 5-24 below. Like with the other vessel types, the weight minimum is a shallow one, with many vessels that weigh less than 20% of LBT.

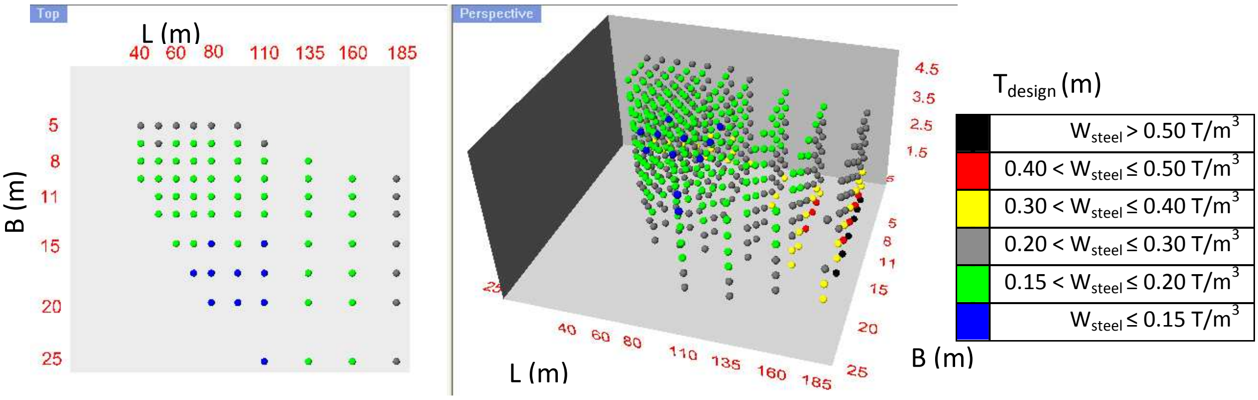


Figure 5-24: Top and 3D views of steel weight fraction as a function of L, B and T_{design} - tank vessels

5.5.3 Lightweight

The lightweight items *accommodation* and *machinery, equipment & outfitting* on tank ships are identical to their counterparts on dry bulk vessels. The main deviating weight group is the pipe system for the cargo (with attached pumps). Therefore, only the weight of the 'piping' item is reconsidered.

For piping, there is a stepwise dependency between weight and vessel beam: if the number of tanks abreast is increased because of an increase in ship width, an entire longitudinal set of pipes will be added on the deck. Figure 5-25 shows the weight of the piping system for all developed designs.

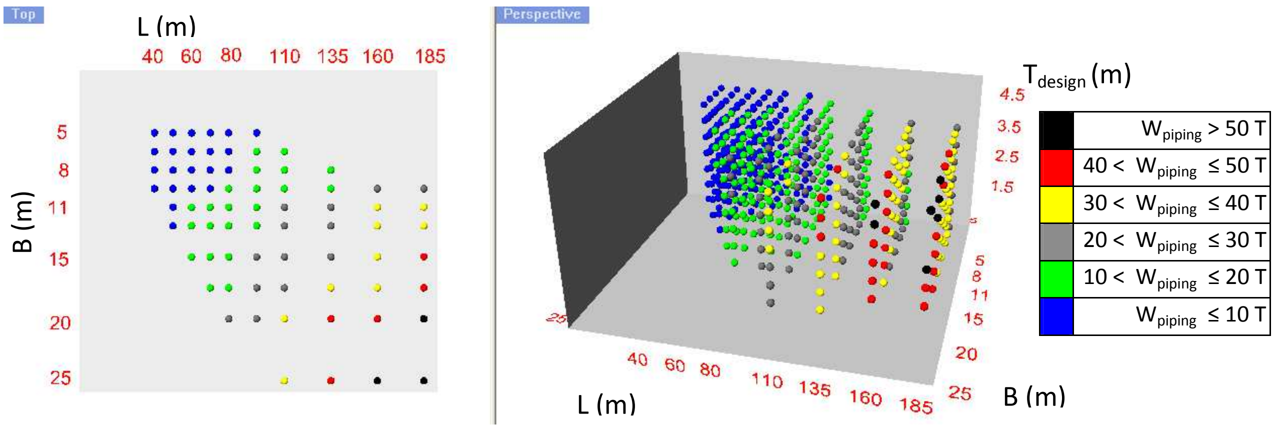


Figure 5-25: Weight of cargo piping for tank vessels

An analysis of the total lightweight-to-LBT ratio of tank ships shows that the lightest ships are wide, deep draught ships that are shorter than 185 meters and have a lightweight that is between 15 and 20%. In case of long and/or narrow vessels with a draught of 1.5 m, the lightweight-to-LBT ratio exceeds a value of 0.4 and on occasion even 0.5.

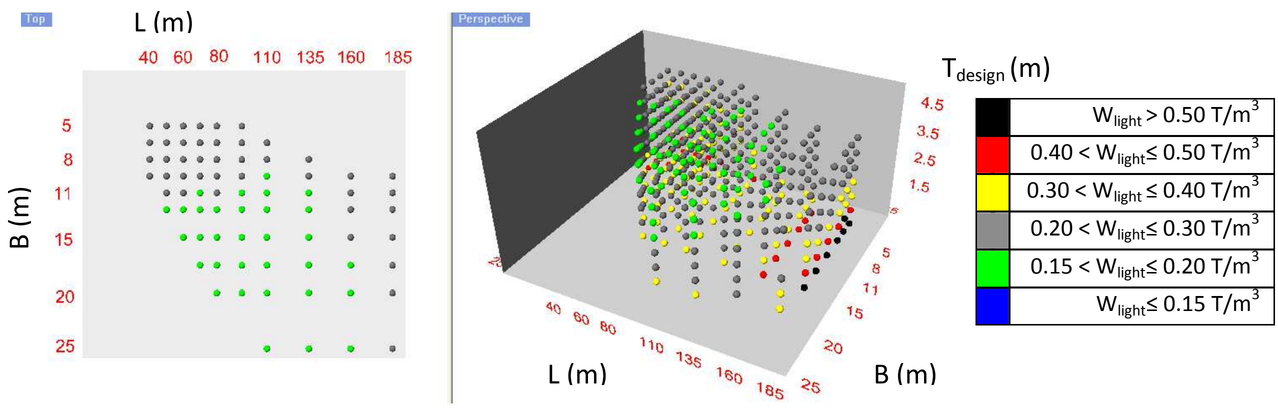


Figure 5-26: Top and 3D views of lightweight fraction as a function of L, B and T_{design} - tank vessels

5.5.4 Building cost

The building cost of tank vessels is significantly higher than for dry bulk and container ships, even for the relatively basic coated tankers that are under review here. Stainless steel tankers are even substantially more expensive. The price of the explored vessel designs ranges from 1.0 to 18.8 million Euro, with a cost distribution for the smallest and largest vessels as shown below.

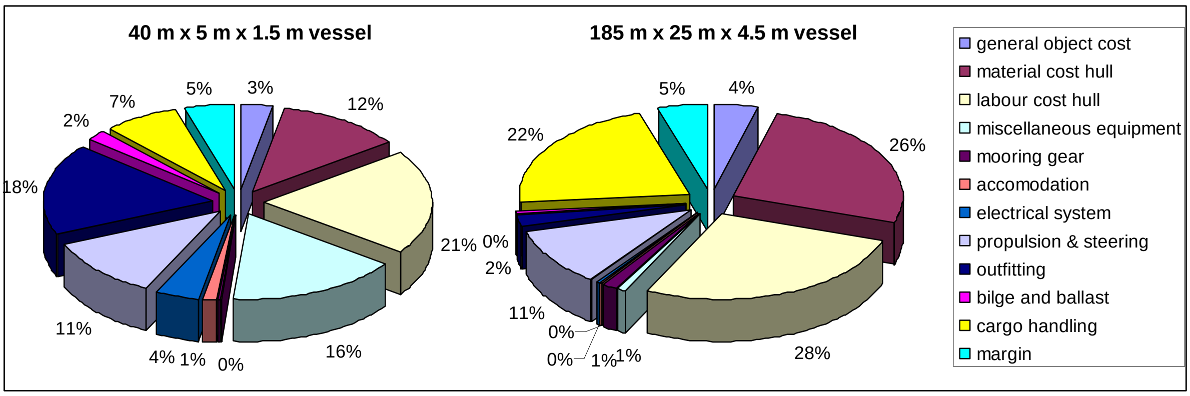


Figure 5-27: Cost breakdown for the smallest and largest tank vessels

Figure 5-27 reveals similar trends as for dry bulk and container vessels: For small vessels, the influence of a number of 'miscellaneous' items like wheelhouse and navigational instruments have a strong impact on cost, while for large vessels the cost of the hull is dominant. The main difference with the dry bulk and container vessels is the cost of the cargo handling system. Since in the design model the cost of piping and pumps is scaled linearly with the vessel's main dimensions (see appendix C), the absolute cost of these items per ton do not go down as vessel size increases. As a result, the impact of the cargo handling system on the total cost increases as the ship gets bigger since for all other cost items the cost per ton do go down.

Figure 5-28 below shows the building cost per ton of cargo carrying capacity for tank ships at design draughts of 4.5, 3.5, 2.5 and 1.5 meters, which range from € 850 to € 9500 per ton.

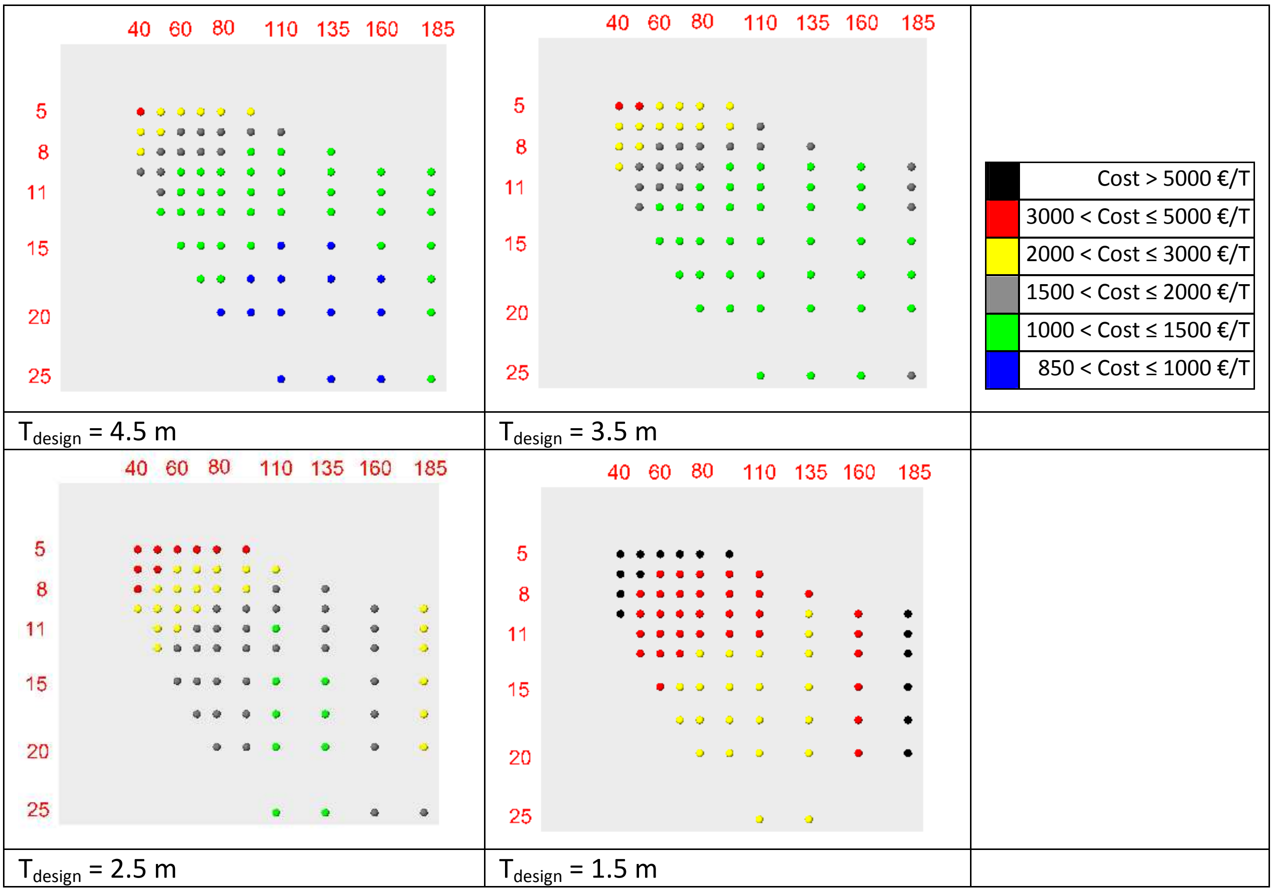


Figure 5-28 Building cost per ton of cargo carrying capacity - tank vessels

Like with dry bulk and container vessels, there are strong economies of scale at the lower end of the size range and for shallow draught vessels, while for large deep draught vessels further scale effects are more limited. It can also be observed that the longest vessels are not always cheaper than their shorter counterparts at the same draught and beam. This signals an end to scale advantages, at least in building cost. How the scale advantages turn out when operational costs are also taken into account will be discussed in chapter 7.

In the same way as dry bulk vessels, the cost of a tank ship can be subdivided in yard cost and non-yard cost. Here, yard cost represent the manhour costs of building the hull, the material cost of the hull and the general object costs.

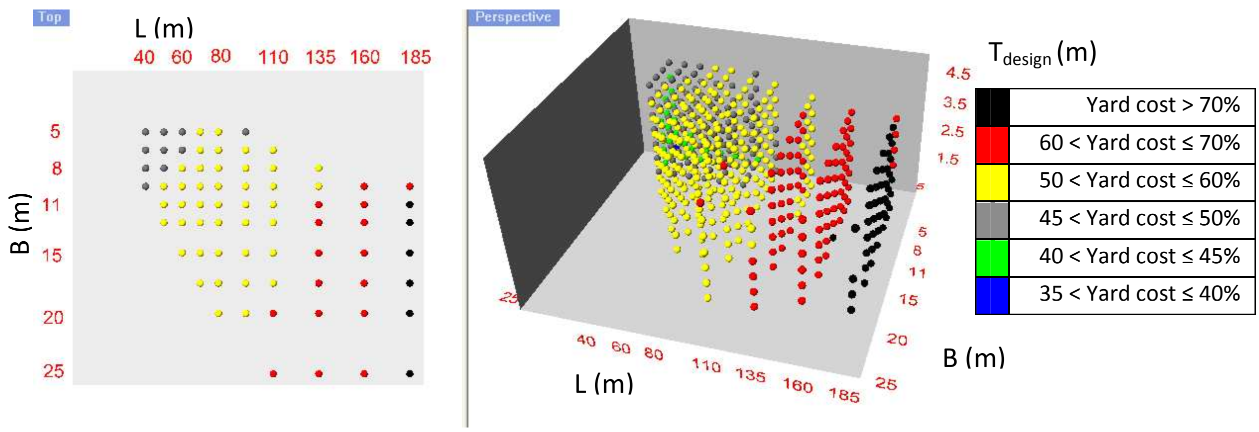


Figure 5-29: Top and 3D-view of yard cost fraction as a function of L, B and T_{design} - tank vessels

The equipment on board of a tank vessel is more expensive than on board of a dry bulk vessel, but since the additional material in the hull due to deck, tank bulkheads and additional depth also increases the price of the hull, the share of building costs that is yard-related is similar to that of dry bulk and container vessels. What also becomes apparent from Figure 5-29 is that the share of yard cost in the total cost increases as vessel length and beam increase, but that design draught has little influence.

5.6 Rules of thumb for weight and cost of inland ships

In the previous paragraphs, the results of a systematic variation of length, beam and design draught were presented for transversely and longitudinally framed dry bulk vessels, transversely and longitudinally framed container vessels and longitudinally framed tank vessels. In the next chapters of this thesis, the technical and cost data from the vessel designs that were generated will be used to determine the optimal main dimensions of an inland ship.

However, the data that was generated can also be used to derive rules of thumb for the steel weight, lightweight, cargo carrying capacity and building cost of inland ships, thereby significantly advancing the state of the art in weight and cost estimations in the conceptual design stage of inland ships. This is not only a powerful tool for ship designers but also allows researchers in the field of logistics, who typically have limited knowledge of the engineering and physics aspects that influence the cost and carrying capacity of inland ships, to better assess the cost and cargo carrying capacity of inland ships in transport analyses.

In this paragraph, the developed rules of thumb are discussed. Since these rules of thumb are intended for the very early design stages in which very little is known about the design of a ship, the ship-related input that is required to use the rules of thumb is kept to a minimum. As a result, rules of thumb are created that only require the ship’s length, beam and design draught as input.

In chapter 5.3.2, it was shown that the weight of inland ships with different main dimensions but the same LBD value shows a significant scatter, as is shown again in Figure 5-30. As a result, it is not possible to draw a ‘simple‘ trend line to predict the weight of these vessels. However, a large part of this scatter is caused by the vessels with extreme L/B values and by the large variation in draught.

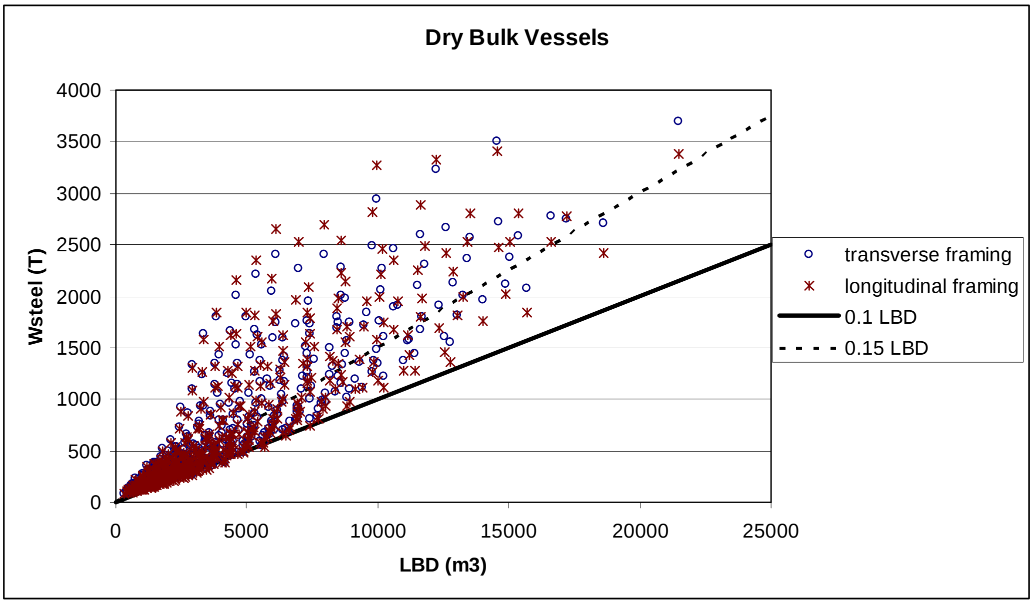


Figure 5-30: Steel weight of dry bulk vessels as a function of LBD

Therefore, two different sets of rules-of-thumb are provided for each of the five combinations of vessel type and framing system:

1) **Simple rules of thumb** in the form of 2nd order polynomial trend lines of steel weight, lightweight, cargo carrying capacity and building cost as a function of LBT with different coefficients for various draughts. These trend lines are valid for ships with a length up to 135 m and L/B values between 6 and 12, i.e. lengths and L/B values that are common for existing inland ships. Due to the limited scatter that occurs for ships that meet these boundary conditions, it is not necessary to model L, B and T_{design} as independent variables and the rule of thumb can be kept simple.

2) **Advanced rules of thumb** for each vessel type and framing system in which in which L, B and T_{design} are independent variables in a single formula that covers the entire investigated range of L/B values and lengths, i.e. L/B values between 4 and 20 and lengths up to 185 m.

These rules of thumb are derived by means of Ordinary Least Squares (OLS) regression. This method of regression is among the simplest methods for parameter estimation. Since the rules of thumb are not intended to predict the behavior of the variables beyond the limits of the dataset that was used, but simply to provide a good approximation of the values in that dataset, OLS is an adequate method of determining the rules of thumb. Since OLS regression does indeed provide good results, more complex methods are not explored.

5.6.1 Simple rules of thumbs

For a quick estimate of the properties of inland ships with L/B values and lengths that are similar to those of common inland ships, rules of thumb in the form of 2nd order polynomial trend lines of steel weight, lightweight, cargo carrying capacity and building cost, expressed as a function of LBT, have been developed. The rules of thumb are valid for L/B values between 6 and 12 for vessels with a length up to 135 m.

In appendix D, these simple rules of thumb are elaborated: The formulas are discussed, coefficients are provided for the various ship types and it is shown that the rules of thumb provide a good match with the original data by means of the presentation of the R^2 values.

As an example, Figure 5-31 shows the trend lines that form the basis of the rules of thumb for the lightweight of transversely framed dry bulk vessels. These trend lines take the form of equation 5-2.

$$W_{light} = c_1 \cdot (LBT)^2 + c_2 \cdot LBT + c_3 \qquad \text{Eq. 5-2}$$

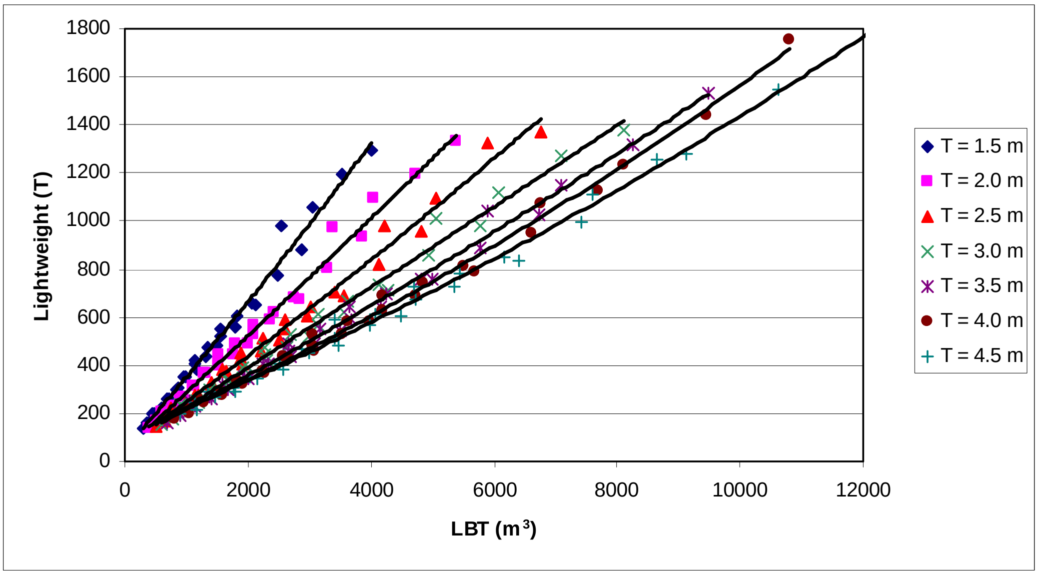


Figure 5-31: Example trend line - lightweight of transversely framed dry bulk vessels

In the Table 5-3 below, the coefficients and R^2 values that belong to these rules of thumb are given.

Table 5-3: Coefficients and R2 values for rule of thumb

T (m)	c1	c2	c3	R^2
1.5	5.34E-06	2.96E-01	4.98E+01	0.986
2	1.48E-06	2.35E-01	4.86E+01	0.990
2.5	2.88E-06	1.82E-01	6.29E+01	0.989
3	2.00E-07	1.66E-01	5.85E+01	0.991
3.5	2.01E-06	1.33E-01	8.27E+01	0.993
4	3.60E-06	1.10E-01	1.06E+02	0.994
4.5	2.73E-06	1.05E-01	1.15E+02	0.994

In appendix D, an elaborate overview of all rules of thumb is provided in an order that requires decreasing amounts of knowledge from a user, but thereby also reduces his design freedom. First the rule of thumb for steel weight is presented, which gives the user the opportunity to still make his own decisions regarding all items that need to be on board. Second, estimates of the total lightweight of the ships are provided. This provides a user with a finished weight estimate but takes away the freedom to design the equipment, machinery, outfitting and accommodation.

The third set of rules of thumb provides estimates of the cargo carrying capacity of a ship, thereby not only fixating its weight, but also its hullform and making it harder to estimate the cargo carrying capacity at reduced draught. This rule of thumb does, however, allow for a reasonable estimate of the cargo carrying capacity of a ship for people without substantial knowledge of ship technology.

As a final rule of thumb, a cost estimate for the ship as a whole is provided. Since the breakdown of the price of the ship is heavily influenced by the technical properties of the ships and these rules of thumb are intended to be usable without extensive knowledge of this, this cost price is not broken down into components. For a detailed overview of the breakdown of the cost of inland ships, reference is made to appendix C.

5.6.2 Advanced rules of thumb

In the previous sub-paragraph, simple rules of thumb in the form of second-order polynomials have been discussed. Each of these polynomials is valid for a given draught under the boundary condition that the L/B ratio of a vessel is between 6 and 12 and that vessel length does not exceed 135 m. This means that these rules of thumb are not validated for vessels with larger or smaller L/B ratios and larger lengths.

As a result, these rules of thumb are suitable for logistical studies, conceptual design and early cost estimate of inland vessels with conventional main dimensions, but are not valid for the design of more ‘exotic’ vessels. This is where the advanced rules of thumb have an added value. Their validity range covers L/B ratios between 4 and 20, lengths between 40 and 185 meters, beams between 5 and 25 meters and draughts between 1.5 and 4.5 meters.

The second main benefit of the advanced rules of thumb over the simple rules of thumb that were discussed in the last paragraph is that in the advanced rules of thumb, L, B and T_{design} are included as independent variables within a single formula. In contrast, in the simple rules of thumb there was a different set of constants for each draught, while L and B were not independent variables.

In this paragraph, the principles behind the advanced rules of thumb that provide lightweight and building cost estimates that are based on all designs in the design datasets of chapter 5 are presented. A detailed discussion of these rules of thumb, their statistical validation and their error distributions is presented in appendix E.

The advanced rules of thumb have a higher level of detail than the ones in the previous paragraphs: Lightweight is broken down into steel weight, weight of the accommodation, weight of machinery, equipment & outfitting and weight of piping outside the engine room. Building cost is subdivided in yard cost and non-yard cost. Here, yard cost is defined as the material cost of the hull, manhour cost of the hull and general object cost, while non-yard cost is defined as the cost of all machinery, equipment & outfitting. This breakdown allows a user greater freedom to apply his own knowledge to specific parts of a ship design, but to use values from the rules of thumb for the parts he does not have sufficient knowledge about.

Due to the larger range of L/B ratio range, larger maximum length and desire to be able to use L, B and T as independent variables in a single formula, the basic trend line approach that was used for the simple rules of thumb no longer suffices and parameters that are included in the rules of thumb need to be selected. Therefore, a more elaborate analysis of the regression needs to be done.

The rules of thumb that are developed by means of the OLS regression are not intended as ‘perfect’ regressions of the underlying data that pass all imaginable statistical tests, but they do lead to results that provide a close match with the original data with typical errors of no more than 5-10%. Furthermore, the basic statistical checks are executed:

- R^2 values are checked in order to ascertain that the rule of thumb explains nearly all variance in the data.
- It is checked if each of the variables in a formula meets the significance criterion.
- Beta-values are analyzed to establish how strongly each variable affects the final outcome.

In appendix E, the rules of thumb as discussed above are elaborated for dry bulk, container and tank vessels and the relevant statistical checks are elaborated. Here, as an example only the rule of thumb for the estimation of the steel weight of dry bulk vessels is elaborated, while a summary of all rules of thumb is provided in chapter 5.6.3.

For the estimation of steel weight of both transversely and longitudinally framed dry bulk vessels, the following formula has been developed:

$$W_{steel} = c_1 + c_2 \cdot LB + c_3 \cdot L^2T + c_4 \cdot LBT + c_5 \cdot L^{3.5}B + c_6 \cdot \frac{L^{1.3}T^{0.7}}{B} + c_7 \cdot \frac{1}{B^2T^{1.5}} \qquad \text{Eq. 5-3}$$

The coefficients to be used with each of the variables from equation 5-3 for the estimation of weight of transversely framed dry bulk vessels are presented in Table 5-4 below. When the significance of the variables is assessed, it can be seen that all variables are significant, with the possible exception of the last variable. This variable serves as a correction for longitudinally framed vessels, as is discussed more elaborately in appendix E. From the beta-value, it can be seen that its effect is very small. As a result, it is not harmful for the outcome of the rule of thumb and it is not removed from the formula in order to keep the variables in the rule of thumb identical for both framing systems and for both dry bulk and container vessels.

Table 5-4: Coefficients & statistical data for the rule of thumb – transversely framed dry bulk ships

	Unstandardized Coefficients		Standardized Coefficients		
	value	Std. Error	Beta	t	Sig.
c1	-2.597E+01	11.305		-2.297	0.022
c2	2.320E-01	9.047E-03	0.339	25.600	0.000
c3	-1.552E-03	3.583E-04	-0.079	-4.332	0.000
c4	4.444E-02	2.659E-03	0.226	16.715	0.000
c5	8.134E-07	1.856E-08	0.533	43.823	0.000
c6	1.024E+00	0.132	0.072	7.784	0.000
c7	7.691E+02	399.793	0.009	1.924	0.055

When applying the parameters and coefficients that are discussed above to the dataset of transversely framed dry bulk vessels, it is found that the variance in the data is explained well by the formula, as is apparent from the R-squared and adjusted R-squared values in Table 5-5.

Table 5-5: R and R^2 values for the rule of thumb

R	R^2	Adjusted R^2	Std. Error of the Estimate
0.996	0.992	0.992	56.764

That the regression provides a good match with the original data becomes apparent from Figure 5-32 below, in which the error distribution is shown: about 60% of all original data points deviate less than 5% from the value predicted by the rule of thumb, while only about 10% of the data points deviate more than 10% from the value resulting from the rule of thumb.

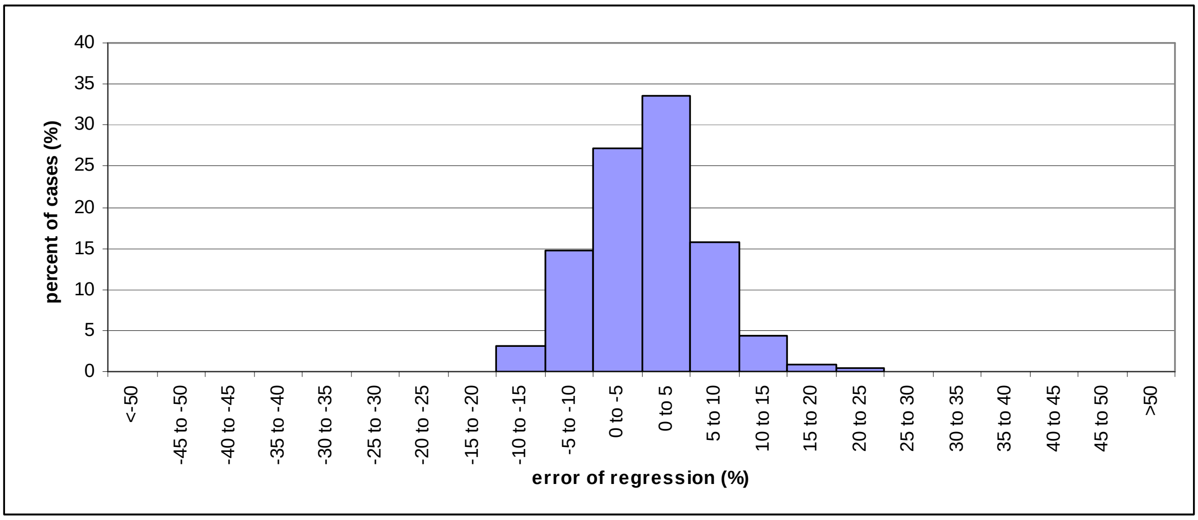


Figure 5-32: Error distribution of the rule of thumb

All other rules of thumb with their statistical validation and their error distributions are discussed in appendix E. The rules of thumb themselves are presented in the next paragraph. These rules of thumb provide estimates for the steel weight, weight of the accommodation, weight of piping and weight of machinery, equipment & outfitting as well as estimates for the yard cost and the non-yard cost.

5.6.3 Summary of the advanced rules of thumb

An overview of the advanced rules of thumb that have been developed is presented in this paragraph. Table 5-6 presents the rules of thumb for dry bulk ships, while Table 5-7 shows the results for container ships and Table 5-8 does the same for tank ships.

The rules of thumb for dry bulk ships include separate formulas for longitudinally and transversely framed ships, since the framing system affects both the weight and the building cost of the hull.

Table 5-6: Rules of thumb for dry bulk ships

Lightweight	
- Steel weight	
Transverse framing	$= -25.97 + 0.232 \cdot LB - 1.552 \cdot 10^{-3} \cdot L^2T + 4.444 \cdot 10^{-3} \cdot LBT$ $+8.134 \cdot 10^{-7} \cdot L^{3.5}B + 1.024 \cdot \frac{L^{1.3}T^{0.7}}{B} + 769.1 \cdot \frac{1}{B^2T^{1.5}}$
Longitudinal framing	$= 49.85 + 0.229 \cdot LB - 1.234 \cdot 10^{-5} \cdot L^2T + 1.91 \cdot 10^{-2} \cdot LBT$ $+9.584 \cdot 10^{-7} \cdot L^{3.5}B + 0.288 \cdot \frac{L^{1.3}T^{0.7}}{B} - 1066 \cdot \frac{1}{B^2T^{1.5}}$
- Other weight items	
Accommodation	$= 0.173 \cdot 2.5 \cdot \max[L/4 \cdot (B-2), 100]$
Machinery, equip-ment & outfitting	$= 28.04 + 4.605 \cdot T + 2.097 \cdot 10^{-2} \cdot LB + 2.24 \cdot 10^{-3} \cdot LBT - 4.258 \cdot 10^{5} \cdot \frac{1}{L^3}$
Piping outside engine room	$= -2.723 + 6.232 \cdot 10^{-2} \cdot L + 5.048 \cdot 10^{-2} \cdot B + 9.968 \cdot 10^{-2} \cdot T + 1.343 \cdot 10^{-4} \cdot LBT$

Building cost	
- Yard cost	
Transverse framing	$= 5.956 \cdot 10^4 + 771.7 \cdot LB - 136.7 \cdot (L^2T)^{0.7} + 62.41 \cdot LBT + 1.926 \cdot 10^{-3} \cdot L^{3.5}B + 3.244 \cdot 10^3 \cdot \frac{L^{1.3}T^{0.7}}{B}$
Longitudinal framing	$= 1.632 \cdot 10^5 + 782.6 \cdot LB + 185.8 \cdot (L^2T)^{0.7} - 11.06 \cdot LBT + 2.413 \cdot 10^{-3} \cdot L^{3.5}B - 438.5 \cdot \frac{L^{1.3}T^{0.7}}{B}$
- Non-yard cost	
	$= 6.075 \cdot 10^5 + 400.8 \cdot \frac{L^{1.5}}{B} + 49.05 \cdot LBT + 474.2 \cdot LB - 2.081 \cdot 10^7 \cdot \frac{1}{LT}$

The rules of thumb for container ships are very similar to those for dry bulk ships, since the only major difference between the ship types is the depth of the hull and the resulting differences in the weight and cost of the steel structure. As a result, separate rules of thumb are only developed for hull-related weight and cost, as is shown in Table 5-7.

Table 5-7: Rules of thumb for container ships

Lightweight	
- Steel weight	
Transverse framing	$= -22.0 + 0.254 \cdot LB - 1.975 \cdot 10^{-3} \cdot L^2T + 4.473 \cdot 10^{-2} \cdot LBT + 1.059 \cdot 10^{-6} \cdot L^{3.5}B + 0.96 \cdot \frac{L^{1.3}T^{0.7}}{B} + 667.6 \cdot \frac{1}{B^2T^{1.5}}$
Longitudinal framing	$= 51.07 + 0.244 \cdot LB - 1.772 \cdot 10^{-4} \cdot L^2T + 1.588 \cdot 10^{-2} \cdot LBT + 1.10 \cdot 10^{-6} \cdot L^{3.5}B + 0.312 \cdot \frac{L^{1.3}T^{0.7}}{B} - 1164 \cdot \frac{1}{B^2T^{1.5}}$
- Other weight items	
Accommodation	See Table 5-6
Machinery, equip-ment & outfitting	See Table 5-6
Piping outside engine room	See Table 5-6
Building cost	
- Yard cost	
Transverse framing	$= 6.88 \cdot 10^4 + 920.8 \cdot LB - 91.32 \cdot (L^2T)^{0.7} + 50.22 \cdot LBT + 2.668 \cdot 10^{-3} \cdot L^{3.5}B + 2651 \cdot \frac{L^{1.3}T^{0.7}}{B}$
Longitudinal framing	$= 1.646 \cdot 10^5 + 842.2 \cdot LB + 193.1 \cdot (L^2T)^{0.7} - 27.14 \cdot LBT + 2.774 \cdot 10^{-3} \cdot L^{3.5}B - 509.3 \cdot \frac{L^{1.3}T^{0.7}}{B}$
- Non-yard cost	
	See Table 5-6

Tank ships differ from dry bulk and container ships with respect to the weight and cost of their steel structure as well as with respect to the weight and cost of the piping that is used to handle the cargo. Therefore, separate rules of thumb for these elements are presented in Table 5-8.

Table 5-8: Rules of thumb for tank ships

Lightweight	
- Steel weight	
	$= 422 - 7.694 \cdot 10^{-4} \cdot L^2 T + 7.311 \cdot 10^{-2} \cdot LBT + 1.157 \cdot 10^{-6} \cdot L^{3.5} B - 7.922 \cdot 10^3 \cdot \frac{1}{(LBT)^{0.5}}$
- Other weight items	
Accommodation	See Table 5-6
Machinery, equipment & outfitting	See Table 5-6
Piping outside engine room	$= -3.949 + 8.191 \cdot 10^{-2} \cdot L - 0.4407 \cdot B + 1.065 \cdot 10^{-3} \cdot LBT + 6.966 \cdot 10^{-2} \cdot L^{0.6} B + 1.228 \cdot 10^4 \frac{B}{L^3}$
Building cost	
- Yard cost	
	$= 1.514 \cdot 10^6 + 1.437 \cdot 10^2 \cdot LBT + 3.204 \cdot 10^{-3} \cdot L^{3.5} B - 2.829 \cdot 10^7 \cdot \frac{1}{(LBT)^{0.5}}$
- Non-yard cost	
	$= 9.608 \cdot 10^5 + 84.75 \cdot \frac{L^{1.5}}{B} + 244.4 \cdot LBT + 312.9 \cdot LB - 4.116 \cdot 10^7 \cdot \frac{1}{LT}$

As was discussed before, the tables above only provide an overview of the rules of thumb. More elaborate statistical analyses of their properties as well as error distributions for all rules of thumb are presented in appendix E.

5.7 Synthesis

In order to allow determination of the optimal main dimensions of an inland ship in a given transport chain, in chapter 4 a model was developed with which the technical characteristics and building cost of inland ships with any combination of length, beam and draught can be determined. With this model, large series of systematically varied ship designs were created for transversely and longitudinally framed dry bulk and container ships as well as for longitudinally framed tank ships. These datasets represent a leap forward in the knowledge about the technical characteristics and building cost of inland ships with non-standard main dimensions. As a result, the relevant ship-related variables that influence the optimal ship dimensions in a given transport chain have been determined, thereby enabling analyses that lead to the research goal of this thesis.

In this chapter the assumptions behind the systematic series of ship designs were presented as well as the main conclusions that can be drawn from the series. It is shown how steel weight, lightweight and building cost change as a function of length, beam and draught. It was also discussed how main dimensions affect the total cost of a ship and its breakdown into yard cost and non-yard cost.

For dry bulk ships, steel weight varies between just below 10% for the widest ships with a draught of 4.5 m and lengths between 50 and 70 meters to more than 40% for the longest and narrowest ships with a draught of 1.5 meters. The lightweight of these ships, i.e. the steel weight plus all other weights of the ship itself, ranges from roughly 15% to more than 40% of LBT.

The cost of the hull is strongly related to the main dimensions of the ship while the cost of all other lightweight items has a far less distinct relationship with the dimensions of a ship. As a consequence of this the ratio between the yard-related cost of the ship (i.e. the cost of building the steel hull and management of the project) ranges between roughly 30% and 70% of the total building cost of the ship. For small ships, the majority of costs are due to the equipment, machinery and outfitting while the majority of the cost of large ships are due to the cost of the hull. The cost per ton of cargo carrying capacity ranges from € 706 to € 7050 per ton. Container ships are very similar to dry bulk ships and as a result show nearly identical trends in weight and cost.

Tank ships are heavier and more expensive than dry bulk and container ships due to the subdivision of the tanks, a main deck over the entire width of the ship and the cargo piping system. Their lightweight ranges from just over 15% of LBT to more than 50% of LBT, but the ratios between yard and non-yard costs show a similar distribution as for dry bulk ships: Yard cost ranges from approximately 35% to about 70% of the total cost. In absolute numbers, the tank ships are more expensive than their dry bulk counterparts: building cost ranges from € 850 to € 9500 per ton.

It was validated that the overall weight estimates by the design model are sufficiently reliable by comparing them with values presented by Germanischer Lloyd [2006] and Heuser [1986]. No data is available from literature with which the cost estimates can be validated, but in chapter 4.3.1 it was already shown that for those ship dimensions for which validation data was available, the model provides good results.

The series of ship designs will be used in chapter 7 to determine the performance of all ships within a series of designs in the context of a logistics chain and transport route. In this way, the optimal length, beam and draught can be found, thus answering the main research question of this thesis.

Finally, in order to make the results from the generated datasets accessible to a wider audience, they are captured in rules of thumb. This closes the gaps in knowledge about the weight and cost of inland ships that were identified in chapter 3.

6 A model to determine the cost of transport

In chapter 2, the practical upper limits of the main dimensions of inland ships were established and the research in chapters 3 to 5 has led to the creation of several large series of inland ship designs that cover the entire range of relevant lengths, beams and draughts (see Figure 6-1). As a result, the first two sub-research questions of this thesis are answered.

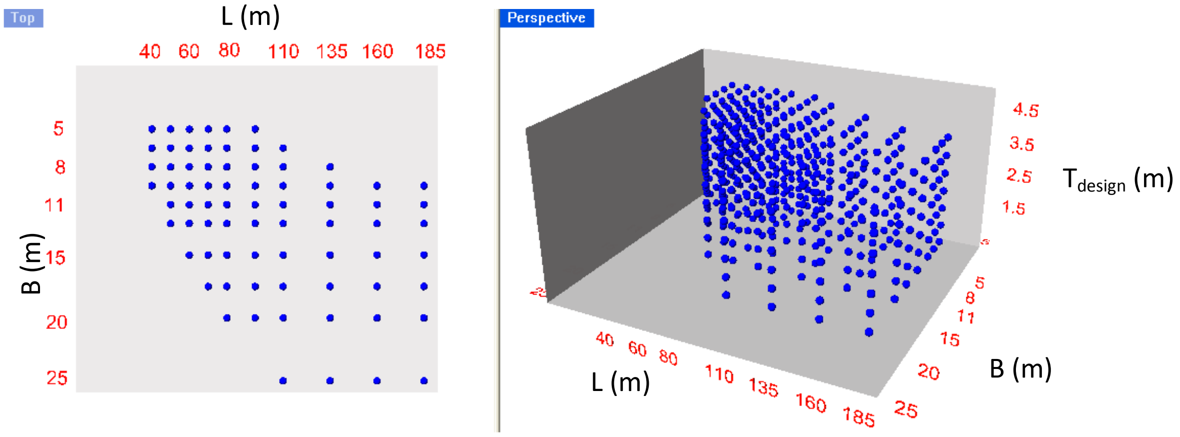


Figure 6-1: Data points of the lengths, beams and draughts for which designs are created

However, the main research goal, i.e. determination of which length, beam and draught of an inland ship lead to the best competitive position for a captain-owner, can not be reached through the analysis of the properties of inland ships alone. It also requires an analysis of the performance of a ship in the context of a transport chain. In this chapter, a model is developed with which this can be done and in chapter 7 this model is used to perform a number of cases studies that lead to the answer to the main research question of this thesis.

In chapter 1.2.2, it was concluded that improvement of the competitive position of captain-owners that transport the main commodities on the main waterways can be achieved by enabling transport at lower prices. Due to the close link between cost and price in a highly competitive market such as that of inland shipping, lowering the price of transport implies the need to lower the cost of transport. In times when supply exceeds demand, due to the price elasticity in the sector [Beuthe et al., 2001], the ship operator with the lowest cost can ensure that he will still have sufficient work by lowering his price to levels that his competitors can not sustain. In contrast, operators with higher-than-average costs will either have to transport goods at prices that do not cover their cost or will be out of work. In times when demand exceeds supply, the margins of the operator with the lowest cost will be higher than those of his competitors that offer a similar service.

As a result of the above, it is necessary to determine how the main dimensions of inland ships affect the operator's cost per unit of transported cargo in order to assess how they will influence his competitiveness. The transport price that is required to cover an operator's average cost per unit of transported cargo[14] is from now on called the <u>minimum required ship rate</u>.

However, despite the importance of transport price in a shipper's choice for a transport operator, it is not the only selection criterion. In the end a shipper will look for a transport solution that leads to the lowest <u>total logistical cost</u> i.e. the lowest sum of all costs that a shipper incurs due to the way he transports his goods. These costs include the out-of-pocket cost of transport as discussed above, but also include the cost of cycle stock, safety stock and stock-in-transit. Further elaboration of the concept of total logistical cost will be provided in chapter 6.2.4.

[14] This average cost includes a 'normal' profit rate.

As a summary of the above, the link between the cost of a transport operator and the cost for the shipper is shown in Figure 6-2.

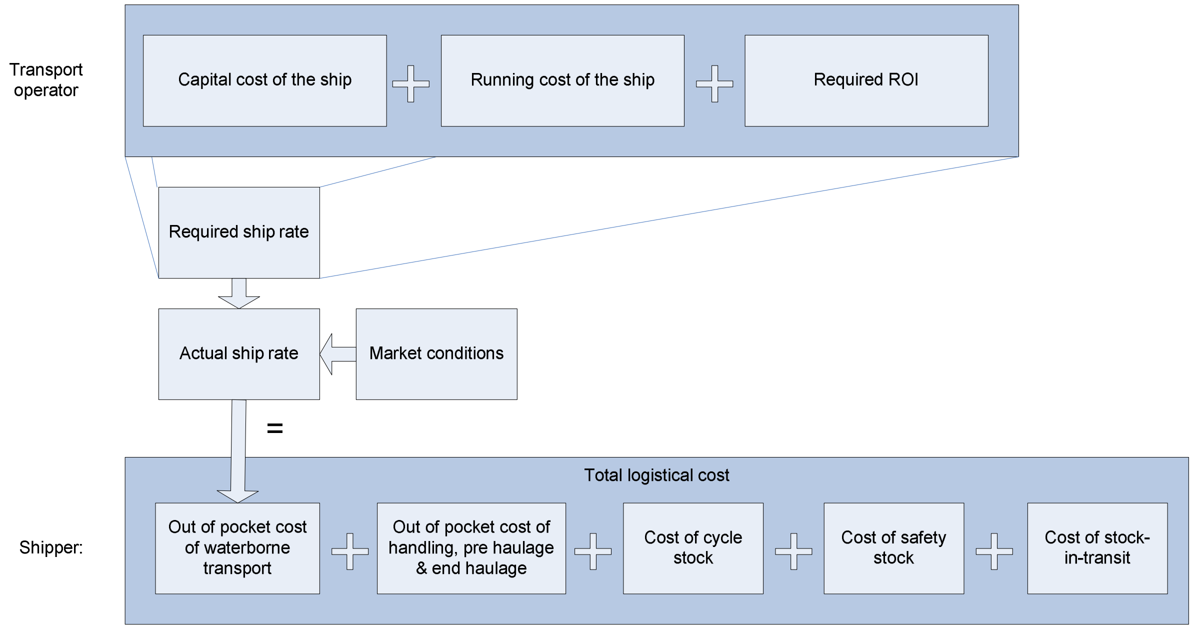


Figure 6-2: Buildup of cost for transport operator and shipper

Assuming that a shipper's demand is independent of shipment size, there is a direct link between the amount of goods that are carried in a single shipment and the interval between shipments. This in turn affects e.g. the value of the stock of the shipper as well as the required facilities for storage of the goods. As a result, for a shipper the drawbacks of receiving a limited number of large shipments at a low ship rate but with high stock costs may outweigh the advantage of transporting goods at the lowest ship rate. Therefore, a shipper may opt for a different transport solution that has a higher out-of-pocket transport cost but reduces his total logistical cost.

Concluding, the ship dimensions that lead to the best competitive position of a transport operator in a competitive market are those that lead to the lowest transport price (i.e. the lowest average cost) as long as this also leads to the lowest total logistical cost. This in turn implies that an appropriate cost model should be able to calculate both of these values.

6.1 Functional specification of the model

In this paragraph it is discussed which data the model needs to calculate in order to fulfill the requirements that are posed on it. Furthermore, the assumptions underlying the model are discussed.

6.1.1 Output of the model

The model that is discussed in this chapter is intended to model the operation of inland ships within a given transport chain, which is defined as the transport of a specified type of cargo between two given locations for one or more shippers that have a specified annual demand for these goods. The output of the model will be an overview of the required ship rate and total logistical cost of transporting these goods when using each of the ships in the previously discussed dataset of systematically varied ship designs.

Furthermore, since the external costs of inland navigation are different from those of road transport and also differ as a function of the main dimensions of a ship, internalization of external costs may improve or worsen the competitive position of inland waterway transport compared to other modes and of certain ships compared to other ships. Therefore, it is deemed worthwhile to establish how internalization of these costs will impact the competitiveness of individual ships. As a result, the following four model outputs are required:

Minimum required ship rate

1) The minimum required ship rate for all of the vessels in the ship design dataset. This will determine the optimal dimensions of a ship in case there is no direct link between the cargo carrying capacity of a ship and the size of a shipment for an individual shipper, e.g. in case of container transport or when multiple shipments are on board of a single ship.

2) The minimum required ship rate for all of the vessels in the design dataset, including internalization of the relevant external costs.

Total logistical cost

3) Total logistical cost for all vessels in the design dataset; In case there is a direct link between the cargo carrying capacity of a ship and the size of the shipment for a single shipper, this shipper will look for the lowest total logistical cost rather than for the lowest ship rate.

4) Total logistical cost including internalization of the relevant external costs.

Since inland shipping in many cases needs to compete with road transport, a comparison will also be made with the cost of road transport for the same amount of cargo with the same origins and destinations. This way, it can be established if it is likely that a ship of given main dimensions can compete with road transport. If it can not, it may be the cheapest waterborne option but it will still not attract customers and as a result will not improve its owner's competitive edge.

6.1.2 Assumptions underlying the model

The model that is created calculates the required ship rate and the total logistical cost for a given transport chain in which origin, destination, route, cargo type and annual cargo volume per shipper are predetermined. In this paragraph, the main assumptions underlying the model are discussed. These are the following:

- There is a difference between the cost of a transport operator and the price that a shipper pays for transport, which is caused by market conditions. However, the inland shipping market is a highly competitive one and in a market with severe competition, market price will effectively go down to marginal cost level [Blauwens et al. 2010, p. 462]. As a result, over a longer period of time the difference between average cost and average transport price will be small for competitive ships. Therefore, within the model, all calculations are made under the assumption that the price that a shipper pays for transport is equal to the cost of the operator. The ship that can provide transport at the lowest total logistical cost under this assumption will be the most competitive ship. Ships for which this assumption will lead to transport at higher total logistical cost will be less competitive. This implies that the model does not aim to predict the actual transport prices at a given moment in time, but uses the required transport prices to assess the relative competitiveness of different ships over the lifetime of the ship.

- There is interaction between the way transport is performed and the amount of goods that will be transported: If one mode becomes e.g. cheaper, it will draw cargo away from other modes (i.e. price elasticity) and the demand for transport using the cheaper mode will increase [Beuthe et al., 2001]. Likewise, a ship that can provide a cheaper service will draw away cargo from more expensive vessels and as such increases demand for its own services. However, since an in-depth analysis of supply and demand along the Rhine corridor has a scope that is much wider than that of this thesis, this feedback between supply and demand is not included in the model; a linear model is used in which demand is always sufficient to keep the ship in operation. This is justified by the facts that the ship types and dimensions that are researched can reach the majority of inland ports and seaports on the Rhine corridor, that hey can carry the major commodity types that are transported by inland waterways and that the demand for transport of these commodities is expected to stay constant or increase in the future (see chapter 1). As a result, there will always be sufficient demand for transport to keep the most competitive ships well-utilized.

- Since throughout its life, a ship may transport goods for multiple shippers, in the model a separation is made between the total demand for transport by ship and the demand of a single shipper; in the determination of the required ship rate of a ship, it is assumed that there is enough cargo available to supply it with work throughout the year. On individual trips, the utilization of the ship will only be limited by imbalances in the cargo flow. As a result of this, it will sail fully loaded in one direction but return with a part load or empty. However, in the determination of the *total logistical cost* the effects of demand by a single shipper, batch size and delivery interval on the shipper's cycle stock will also be explored.

- The determination of the required ship rate is done on the basis of transport chains featuring two ports between which the vessel sails and in which the amount of cargo that a ship carries does not fluctuate from trip to trip, but is the same for each round trip. In reality, throughout their lives ships will in many cases call at multiple ports, sail on various routes and carry different amounts of cargo during the various voyages they make. However, in order to be able to draw clear conclusions regarding the relationship between ship dimensions, sailing distance, water depth and cargo type, this diversification is not implemented in the model.

- There are many aspects that influence a shipper's choice for a certain transport mode including but not limited to out of pocket cost, shipment size and transport speed. As discussed in chapter 6.1, the total logistical cost of transport is analyzed within this thesis and as a result, the effects of ship speed, shipment size and delivery interval, which influence cycle stock, stock-in-transit and safety stock are included in the analysis. Other aspects like transport time, reliability or (perceived) quality of a transport mode may be important to the shipper but have no direct relationship with the dimensions of an inland ship. As a result they are not assessed. Furthermore, the differences in transport time for various ships will be limited and the typical (low value) goods transported by inland waterway are hardly time-sensitive. This further justifies that the value transport time for the shipper is excluded from the analyses.

6.2 Model description

The determination of the four forms of transport cost as discussed in chapter 6.1.1 requires the creation of a model that can create four partial results:

1) The required ship rate for the waterborne part of transport.
2) The cost of handling, pre haulage and end haulage.
3) The internalized external costs.
4) The total logistical cost.

In the implementation of the model, each of these results is calculated in a separate sub model. These models rely on data from three datasets:

1) A dataset of ship designs, containing the technical and cost data of all designs that were developed in chapter 5.
2) The case specific data, including distances, water depths, current speeds, maximum ship dimensions, cargo data etc.
3) A dataset on emissions, that allows determination of the external cost of transport by road, rail and water.

In the following sub-paragraphs, the sub models, the datasets that support them and their interaction are discussed in detail. The structure of the total model is shown in Figure 6-3. Due to the large amount of data that is transferred between the datasets and the models, this data is not shown in Figure 6-3, but is only shown in the paragraphs concerning the relevant sub models.

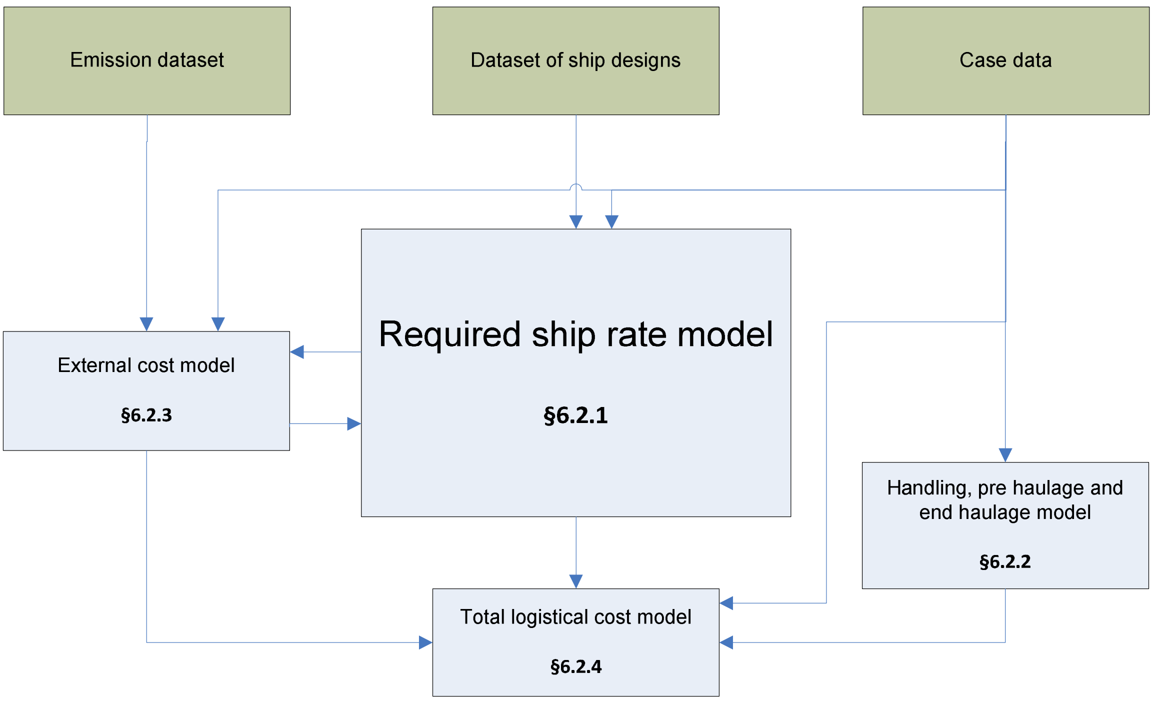


Figure 6-3: Cost model structure

Figure 6-3 shows that the *required ship rate model* receives data from the *dataset of ship designs* as well as from the *case data*. The main output of the *required ship rate model* is a required ship rate, which forms input for the *Total logistical cost model.*

The *required ship rate model* interacts with the *external cost model*; it sends out data on the amount of fuel that the ship consumes in a year and receives the associated external costs back.

The *external cost model* receives technical data on the emissions of ships as well as the external costs that are associated with road and rail transport from the *emission dataset* and receives data on the distances of single-mode transport, pre haulage and/or end haulage from the *case data*. It calculates the external costs of the waterborne leg of transport, which is input for the *required ship rate model*, and external costs of the road legs of transport, which are direct input for the *total logistical cost model*.

The *handling, pre haulage and end haulage model* receives data from the *case data* on the number of handling moves that the cargo needs to undergo. From the *case data*, it also receives data on the distances of transport for single mode transport, pre haulage and/or end haulage. The model calculates the cost of handling and of the road legs of transport and provides these to the *total logistical cost model.*

In the *total logistical cost* model, the out-of-pocket cost of the entire transport chain is calculated using the data from the three sub models discussed above. This data is combined with data from the *case data* about the shipper's cost of cycle stock, stock-in-transit and safety stock in order to determine the total logistical cost for each of the ship designs in the *dataset of ship designs*.

In the following paragraph, each of the sub-models is discussed in detail.

6.2.1 Required ship rate model

The *required ship rate model* is the core sub model of the total model and it is by far the most elaborate. It is the part of the model in which the required ship rate is determined for each of the ships in the datasets that were created in chapter 5.

The *required ship rate model* consists of three sub models, namely:

1) The cargo carrying capacity model.
2) The round trip model.
3) The annual cost model.

Figure 6-4 below provides an overview of the structure of the model and the data that are transferred from one part-model or dataset to the next. In the remainder of this paragraph, the model is discussed in detail.

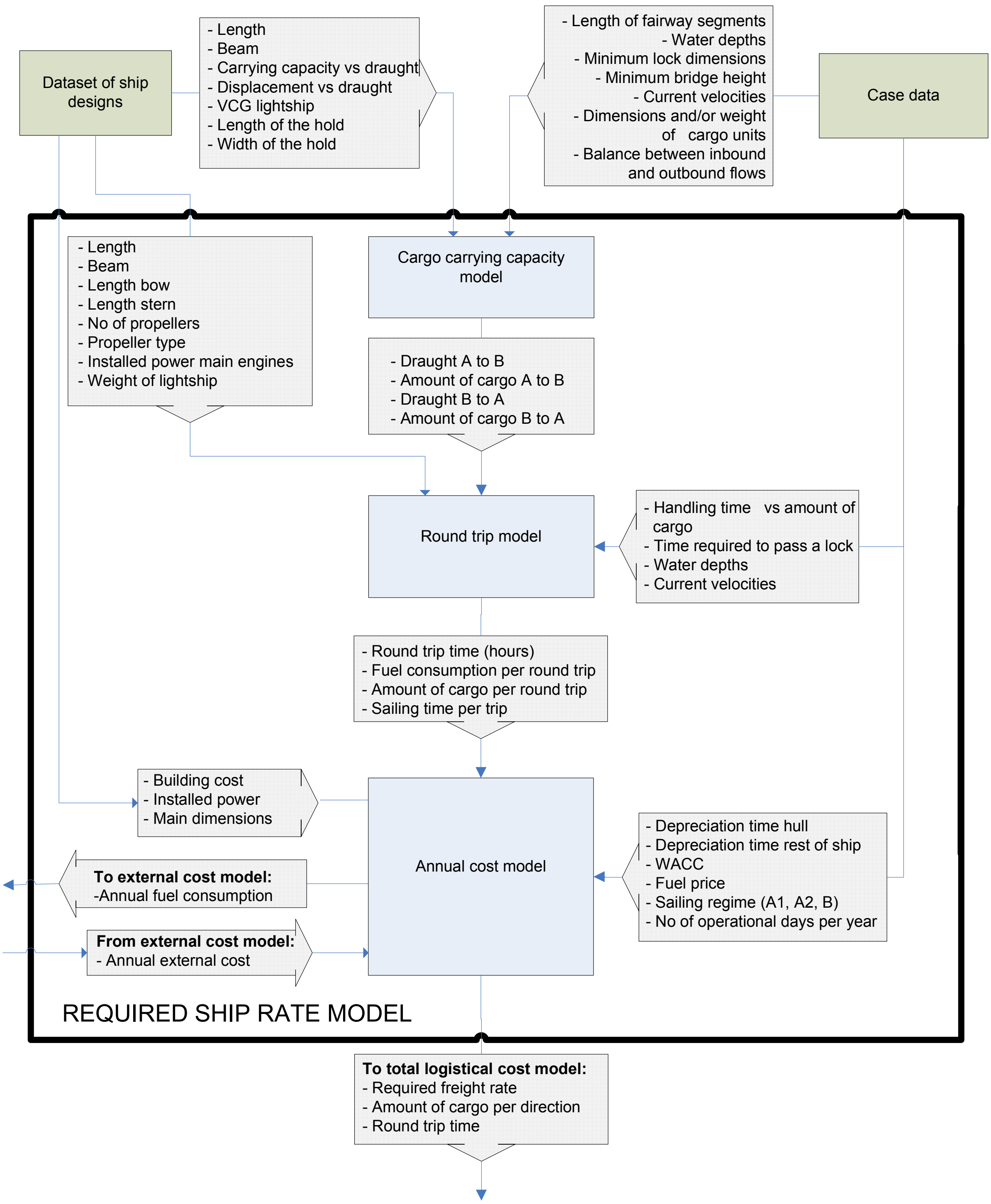


Figure 6-4: Interrelation between the datasets and models of the required ship rate model

<u>Cargo carrying capacity model</u>

In the cargo carrying capacity model, the first of the part-models of the *required ship rate model*, it is determined how much cargo the ship can carry while still being able to fit through locks, pass underneath bridges, stay afloat, stay stable and not run aground. This results in maximum length and beam limits for the ship as well as in three criteria which limit draught, air draught, and the center of gravity of the loaded ship. These limits in turn determine the amount of cargo that can be carried on a ship of given main dimensions.

The limits in length and beam result in the need for interpolation of the data from the ship design dataset, which only includes data for a given number of combinations of lengths, beams and draughts as was shown in Figure 6-1. As a first step in the model, the data from the dataset of ship designs is linearly interpolated in order to create a number of additional designs with main dimensions that are equal to the maximum allowed length and/or beam. Furthermore, in all cases where a beam larger than 11.45 m is allowed, a dataset of 11.45 m wide vessels with all combinations of length and draughts that are present in the dataset is created so that all results can always be compared with results for ships with this very common beam.

The first of the abovementioned limiting factors for the amount of cargo that can be carried is the draught of the ship. This limit is applicable to all types of cargo: containers (c), solid bulk (s) and liquid bulk (l):

$$W1_{c,s,l} = f(T) \qquad \text{Eq. 6-1}$$

With

$$T = \min[T_{design}, h - 0.5] \qquad \text{Eq. 6-2}$$

Where:
$W1_{c,s,l}$ = maximum weight of the cargo on the basis of the draught limit of the ship (T)
T_{design} = design draught of the ship (m)
T = actual draught of the ship (m)
h = water depth (m)

Equation 6-2 states that the amount of cargo that is carried can never be more than the amount at which draught exceeds the design draught or the difference between the lowest water depth on the route and the draught becomes less than 0.5 m.

For containers, a second limiting condition is applied, namely to allow the loaded vessel to pass underneath the lowest bridge on the route.

$$W2_c = f(T_{air}) \qquad \text{Eq. 6-3}$$

Where:

$$T_{air} = \min[T_{air,n}, H_{bridge}] \qquad \text{Eq. 6-4}$$

Where:
$W2_c$ = maximum weight of the cargo on the basis of the air draught limit of the ship (T)
T_{air} = actual air draught (m)
$T_{air,n}$ = air draught when the ship is loaded with n containers (m)
H_{bridge} = clearance between water surface and the underside of the lowest bridge on the route (m)

The air draught for a ship carrying a given number of containers is determined by:

$$T_{air,n} = H_{db} + H_{container} \cdot roundup[\frac{n}{TEU_x \cdot TEU_y}, 0] - T_n \qquad \text{Eq. 6-5}$$

Where:

n = number of TEU (-)
H_{db} = height of the ship's double bottom (m)
$H_{container}$ = height of a container (m)
TEU_x = number of TEU that can be placed end-to-end in the ship's hold (-)
TEU_y = number of TEU that can be placed abreast in the ship's hold (-)
T_n = draught of the ship when loaded with n containers (m)

Finally, for containers and liquid bulk, a stability calculation is performed in order to ensure the ship is stable. This may limit the amount of cargo that can be carried: containers can only be stacked to a certain height before the vessel becomes unstable, while the free surface effects of liquid bulk will reduce the vessel's stability, thereby potentially limiting the amount of cargo the vessel can carry.

$$W3_{c,l} = f(GM) \qquad \text{Eq. 6-6}$$

Where:
$W3_{c,l}$ = maximum weight of the cargo on the basis of the stability limit of the ship (T)
GM = the metacentric height, a common measure for the stability of a ship (m)

Taking into account these three limits on stability, the maximum amount of cargo a ship can carry on a given route from a technical point of view ($W_{cargo,tech}$) is:

$$W_{cargo,tech} = \min[W1, W2, W3] \qquad \text{Eq. 6-7}$$

However, it is not always the technical limits of the ship that determine how much cargo will be on board; often a shipper will wish to transport a given amount of goods at one time. Therefore, the maximum weight of the goods on board of a ship on a given leg (W_{max}) will be dependent on the technical limits of the ship and the logistical limits that are imposed by the shipper:

$$W_{\max} = \min[W_{cargo,tech}, W_{cargo,\log}] \qquad \text{Eq. 6-8}$$

Where:
$W_{cargo,tech}$ = technical limit on the weight of the cargo (T)
$W_{cargo,log}$ = maximum shipment weight as prescribed by the shipper (T)

Finally, since the demand for transport will not always be the same in both directions of the trip, it is necessary to determine the amount of cargo that is transported in each direction separately. Because the ship will sail identical round trips during the entire year (see chapter 6.1.2), the amount of goods that need to be transported in the direction of low demand will be transported in the same number of trips as the cargo in the direction of high demand. As a result, the ship's loading will reflect this imbalance: it will sail fully loaded in the direction of high demand and only partially loaded in the direction of low demand. As a result, the amount of cargo that is carried in each of the two directions is defined as follows:

$$W_{cargo,high} = W_{max} \qquad \text{Eq. 6-9}$$

$$W_{cargo,low} = W_{max} \cdot \frac{W_{demand,low}}{W_{demand,high}} \qquad \text{Eq. 6-10}$$

Where:
$W_{cargo,high}$ = weight of cargo transported in a single shipment in the direction of high demand (T)
$W_{cargo,low}$ = weight of cargo transported in a single shipment in the direction of low demand (T)

Round trip model
The number of round trips that a ship can make in a year strongly affects the amount of revenue that the ship can generate as well as the total amount of fuel that is consumed in a year. In order to determine how many round trips the ship can make in a year, it is necessary to determine how long it takes the ship to make a round trip. The round trip calculation model is the sub model where the time that is required for a round trip is calculated as well as the ship's fuel consumption on a single trip. Both elements are split up into five parts of the trip: sailing in both directions, the stay in each port and the passage of locks. First, the calculation of trip time is discussed, followed by the discussion of the fuel consumption.

Taking into account the five elements that were discussed above, the roundtrip time of a ship can be determined using a formula of the following form:

$$t_{trip} = \left(t_{sailing,AB} + t_{sailing,BA} + t_{locks} + t_{port,A} + t_{port,B}\right) \cdot \frac{24 \cdot 7}{hoursperday \cdot daysperweek} \qquad \text{Eq. 6-11}$$

Where:
t_{trip} = time needed to make a round trip (h)
$t_{sailing,AB}$ = number of operational hours needed to sail from port A to port B, excluding locks (h)
$t_{sailing,BA}$ = number of operational hours needed to sail from port B to port A, excluding locks (h)
t_{locks}= number of operational hours needed to pass all locks on the route (h)
$t_{port,A}$ = number of operational hours that the ship spends in port A (h)
$t_{port,B}$ = number of operational hours that the ship spends in port B (h)
hoursperday = number of operational hours per day (h/day)
daysperweek = number of operational days per week (days)

Below, the way each of the time elements is calculated is elaborated.

Sailing time
To determine the time a ship needs to sail from A to B and back, the hullform data as well as the propellers and amount of installed power are taken from the *dataset of ship designs* and combined with the draught resulting from the *cargo carrying capacity model* as well as with the water depths and current velocities of the various waterway stretches over which the vessel navigates, taken from the *case data*. Using this data, the sailing speed and required power to reach that speed are calculated using the propulsion model that was developed and discussed in chapter 4.2.3. The final speed is limited in two ways: by limiting the maximum speed of the ship to 70% of the critical speed [15] and by limiting the power output of the engines to 85% of their maximum value, i.e. a common

[15] Critical speed is defined as $V_{critical} = \sqrt{9.81 \cdot h}$, where $V_{critical}$ is measured in m/s and h, water depth, is measured in meters. When ships sail faster than 70% of this speed the required power to propel them rises quickly [Hengst, 1995]

upper limit for normal power output for ship engines. When also taking into account the effect of currents on the waterway, the final time to sail a given distance is:

$$t_{sailing} = \frac{Dist}{3.6 \cdot \left(\min[0.7 \cdot V_{critical}, V_{power}] \pm V_{current}\right)} \qquad \text{Eq. 6-12}$$

Where:
Dist = distance of the sailing leg (km)
$V_{critical}$ = critical speed (m/s)
V_{power} = speed at 85% of maximum power (m/s)
$V_{current}$ = speed of the current (m/s)

<u>Time spent in ports and locks</u>

Time spent in ports and locks is determined on the basis of the following values, stored in the *case data* dataset:

For lock passages, a waiting time of 30 minutes and a transit time of 15 minutes is assumed per lock [Rijkswaterstaat, 2011b] while time spent in port is specified per type of cargo. For liner services, container ships are assigned time slots in which they are loaded and unloaded, while for other vessels, there are legal limits on the amount of time that a terminal can take to load or unload a ship.

For containers, a handling speed of 25 TEU per hour (0.04 hours per container) is maintained, based on a handling speed of 16 containers per hour ± 25% as stated by Via Donau [2007, D2-4] and an own assumption on the ratio between the number of 20 ft and 40 ft containers on board. A margin of 2 hours on this value is assumed to allow for mooring of the ship, starting the operation and finishing it. This leads to the following formula:

$$t_{port,cont} = \left(n_{loaded} + n_{unloaded}\right) \cdot t_{unit} + 2 \qquad \text{Eq. 6-13}$$

Where:
$t_{port,cont}$ = time a container vessel spends in a port (h)
t_{unit} = time to handle 1 container (h)
n_{loaded} = number of containers loaded in a port (-)
$n_{unloaded}$ = number of containers unloaded in a port (-)

For other cargoes the loading times as prescribed by Dutch law for inland shipping are used [Staatsblad, 2011]. The maximum time in which a ship needs to be loaded or unloaded after a pre-announced and timely arrival (i.e. 'short' time) is stated in Table 6-1 below:

Table 6-1: Loading and unloading times for inland ships (source: Staatsblad, 2011)

Weight in 1000 kg		Loading time in hours of working time	Unloading time in hours of working time
At least	Less than	Short	
0	400	27	36
400	900	30	40
900	1400	33	44
1400	2200	36	48
2200	3300	39	52
3300	5500	42	56
5500		45	60

Since the ship design model has led to designs with cargo carrying capacities up to 15800 tons, the table above is not satisfactory, since it implies that a 15800 T vessel needs to be unloaded in the same time as a vessel just over a third of its size. Therefore, the table is extended. Since the carrying capacity of a coupled unit of 110 m vessel plus a Europa II barge of 76.5 m is about 5500 tons and has a length that is roughly equal to the longest ships in dataset of ship designs, it is assumed that no further increase in loading and unloading speed will occur since an increase in the size of the ship will not lead to additional space for equipment along the quayside. As a result, 3 and 4 hours are added to the loading and unloading times respectively for each 2200 T increase in the amount of cargo that is carried.

Table 6-2: Own expansion of loading and unloading times for inland ships

Weight in 1000 kg		Loading time in hours of working time	Unloading time in hours of working time
At least	Less than	Short	
5500	7700	45	60
7700	9900	48	64
9900	12100	51	68
12100	14300	54	72
14300	16500	57	76
16500		60	80

Within the model the loading and unloading times as stated above are used. The working time mentioned in the table starts on Monday at 6:00 AM and ends on Saturday at 18:00 PM, thus equalling 132 hours per week. when vessels operate outside working hours (e.g. in case of 24/7 operation), average waiting times are increased proportionally to the time that the vessel is in operation outside normal working hours. E.g. in case of 24/7 operation, loading and unloading times are increased by a factor of 24*7/(132) = 1.273. This leads to the following formula for the time non-container ships spend in port.

$$t_{port,bulk} = \left(t_{loading,law} + t_{unloading,law}\right) \cdot \frac{t_{total}}{t_{work}} \quad \text{Eq. 6-14}$$

Where:

$t_{port,bulk}$ = time that a bulk vessel spends in a port (h)

$t_{loading,law}$ = loading time according to Staatsblad [2011] (h)

$t_{unloading,law}$ = unloading time according to Staatsblad [2011] (h)

t_{total} = total number of operating hours of the ship per week (h)

t_{work} = number of working hours for loading and unloading (h)

Now that all elements of equation 6-11 have been discussed, the time that a ship needs to make a round trip can be determined.

Fuel consumption

As is shown in Figure 6-4, time and fuel consumption of each round trip are calculated in the round trip calculation model. In the previous paragraph, it was elaborated how the times that are spent in ports, in locks and sailing on the waterway are calculated. Fuel consumption can now be determined by multiplying the power usage during each of these stages by their duration and the specific fuel consumption of the engine. Assuming that power is used only for propulsion and for domestic use (i.e. the hotel function of the ship), this leads to the following formula:

$$M_{fuel,trip} = \frac{sfc \cdot (\sum_{x=1}^{n} (P_{req,prop,x} + \mathrm{P}_{req,dom}) \cdot t_{sailing,x}) + sfc \cdot P_{req,dom} \cdot (t_{lock} \cdot l + \sum_{x=1}^{m} t_{port,m})}{10^6} \quad \text{Eq. 6-15}$$

Where:
$M_{fuel,trip}$ = mass of fuel consumed during a trip (T)
sfc = specific fuel consumption of the engine (g/kWh)
n = number of different fairway stretches in a round trip (-)
m = number of port calls in a round trip (-)
$P_{req,prop,x}$ = required propulsion power on waterway stretch x (kW)
$P_{req,dom}$ = required domestic power (kW)
$t_{sailing,x}$ = sailing time of the ship over a fairway stretch with given water depth and current velocity at a given draught (h)
t_{lock} = total time required to pass a lock (h)
l = total number of lock passages on route
$t_{port,n}$ = time spent in a port (h)

This fuel consumption is passed on to the annual cost model together with the total time of the trip.

Annual cost model

The round trip model outputs the time that it takes the ship to make a round trip, the amount of cargo it takes on this trip and the amount of fuel it consumes during that trip. These data are crucial elements that are required for the determination of the required ship rate since they allow determination of the amount of cargo that the ship can transport in a year and the amount of fuel that is consumed during the transport of this cargo. All other costs that need to be added in order to be able to determine a required ship rate are added in the *annual cost model,* being the third and final part-model of the *required ship rate model*.

The annual cost model takes the building cost, main dimensions and installed power of the ship from the *dataset of ship designs*. Fuel consumption and time per round trip are taken from the *round trip model*, while the *case data* dataset provides the depreciation time of the hull and of the rest of the ship, the fuel price, the Weighted Average Cost of Capital, the sailing regime (14, 18 or 24 hours per day) and the number of operational days per year.

The annual amount of cargo that is transported by the ship is determined as follows:

$$Units_{annual} = \frac{Units_{trip}}{t_{trip}} \cdot t_{operational} \quad \text{Eq. 6-16}$$

Where:
$Units_{annual}$ = number of units of cargo transported annually (-)
$Units_{trip}$ = number of units of cargo transported per trip (-)
$t_{operational,year}$ = annual number of operational hours; hours per day x days per year (h)
$t_{operational,trip}$ = number of hours of operation required per trip (h)

The required ship rate for each of the cargo units is determined by dividing the annual revenues by the number of transported units. The required annual revenues should cover all costs, while also earning back the investment within the required time. These required revenues (i.e. required ship rate multiplied by the number of transported units) are determined on the basis of the demand for a positive net present value at the end of the life of the ship, based on the Weighted Average Cost of Capital.

Use of the Weighted Average Cost of Capital allows for a comparison that does not require an explicit statement about the financing structure of the ship. The WACC is the weighted average cost of debt and equity, weighed by the percentage of the investment that is financed with debt and the percentage that is financed by equity.

In order to determine the annual earnings that are required in order to achieve a positive net present value equation 6-17 should be solved. This equation states that the present value of all earnings should be equal to the investment minus the present value of the remaining value at the end of the depreciation time of the ship. Furthermore, in the equation it is assumed that the ship's hull lasts twice as long as all equipment and outfitting, leading to re-investment in year y.

Solving the equation provides the required value of the annual EBITDA. This can in turn be used to determine the required ship rate, i.e. the ship rate at which this value of EBITDA is reached, by means of equation 6-18.

$$\sum_{x=1}^{z} \frac{EBITDA_x}{(1+WACC)^x} = I_{mach} + I_{hull} - \frac{R_{mach}}{(1+WACC)^y} + \frac{I_{mach}}{(1+WACC)^y} - \frac{R_{hull} + R_{mach}}{(1+WACC)^z} \qquad \text{Eq. 6-17}$$

Where:
$EBITDA_x$ = Earnings Before Interest, Taxes, Depreciation and Amortization in year x (€)
I_{hull} = height of the investment for the hull (€)
I_{mach} = height of the investment for the entire ship minus investment for the hull (€)
R_{hull} = remaining value of the hull (€)
R_{mach} = remaining value of the entire ship minus remaining value of the hull (€)
z = depreciation time of the hull (years)
y = depreciation time of the machinery = 0.5 z (years)
WACC = weighted average cost of capital (%)

The cost of capital that is used in the inland waterway transport sector is typically around 5%. Buck [2008] use 5%, while NEA [2004] use 4.7% as the interest percentage for equity and 5.95% for debt. EBITDA is calculated as earnings minus the cost of crew, fuel, maintenance, insurance, overhead and internalized external cost, as is shown in Table 6-3.

Table 6-3: EBITDA calculation scheme

(1)	**Earnings**
(2)	Crew cost
(3)	Fuel cost
(4)	Maintenance cost
(5)	Insurance cost
(6)	Overhead cost
(7)	Internalized external costs
8 =1-2-3-4-5-6-7	**EBITDA**
(9)	Depreciation
(10)	Amortization
11=8-9-10	**EBIT**
(12)	Interest
13=11-12	**Result before tax**
(14)	Tax
13-14	**Result after tax**

As a result of the above, the required ship rate is calculated as follows:

$$RSR = \frac{\sum_{x=1}^{z} \frac{EBITDA_{req,x} + C_{crew,x} + C_{fuel,x} + C_{maint,x} + C_{ins,x} + C_{oh,x} + C_{ext,x}}{(1+WACC)^x}}{\sum_{x=1}^{z} Units_{annual,x}} \quad \text{Eq. 6-18}$$

Where:
RSR = required ship rate (€/unit)
$EBITDA_{req,x}$ = required Earnings Before Interest, Taxes, Depreciation and Amortization in year x (€)
$C_{crew,x}$ = crew cost in year x (€/year)
$C_{fuel,x}$ = fuel cost in year x (€/year)
$C_{maint,x}$ = maintenance cost in year x (€/year)
$C_{ins,x}$ = insurance cost in year x (€/year)
$C_{oh,x}$ = overhead cost in year x (€/year)
$C_{ext,x}$ = cost of internalized external costs in year x (€/year)
$Units_{annual}$ = number of units of cargo transported annually in year x (-)
z = depreciation time of the hull (years)

The methods that are used for the calculation of each of the abovementioned cost components are discussed below. Of these components, crew cost requires most elaboration and is, therefore, treated last.

Fuel cost
Annual fuel cost is determined as:

$$C_{fuel} = M_{fuel,trip} \cdot P_{fuel} \cdot \frac{t_{operational}}{t_{trip}} \quad \text{Eq. 6-19}$$

Where:
C_{fuel} = annual cost of fuel (€/year)
$M_{fuel,trip}$ = mass of fuel consumed during a trip (T)
$t_{operational,year}$ = annual number of operational hours; hours per day x days per year (h)
$t_{operational,trip}$ = number of hours of operation required per trip (h)
P_{fuel} = fuel price (€/Ton)

The price of fuel fluctuates strongly. Backer van Ommeren [2011] shows values between roughly 75 €/1000 L in the late 1990's to 700 €/1000 L at the peak in 2008. The effects of variations in fuel cost will be investigated in chapter 7.3.

Maintenance cost
Maintenance cost is among the most poorly researched and documented cost of ship operation. Several approximations are in use, as is discussed e.g. by Stapersma [2001]. These options relate maintenance either to the initial investment cost of the engine, to number of running hours times installed power or to cost of fuel. Of these approaches, the approach in which maintenance cost is estimated on the basis of running hours and installed power is deemed the most logical. Stapersma's equation reads:

$$sumc = 3 \cdot \frac{9.5}{\mathrm{c_m}} \cdot \frac{\lambda_S}{1.25} \cdot \frac{\mathrm{rps}}{10} \text{ euro/MWh}$$ (2001 values) Eq. 6-20

Where:
Sumc = specific unit maintenance cost (€/MWh)
c_m = mean piston speed (m/s)
λ_s = stroke/bore ratio (-)
rps = engine rotational speed (rev/s)

Applying this equation to a typical inland ship engine (a Caterpillar C12 ACERT engine with an rpm of 2300 and λ_s =130/150) results in maintenance costs of 6.6 Euro/MWh. The maintenance of the engine is, however, only part of the maintenance of the ship, since all other equipment also needs to be maintained and repaired.

A limited (confidential) dataset from actual ships shows a large scatter of actual repair and maintenance costs of which 0.009 € per kWh (2011 values) appears to be a reasonable average. The fixed costs of maintenance, mainly consisting of surveys, are estimated at 5 € per m^3 of LBT per year (2011 values), again based on a limited dataset of existing ships. As a result, the following formulation of maintenance costs is used:

$$C_{maintenance} = C_{maint,\,fixed} \cdot L \cdot B \cdot T + C_{maint,variable} \cdot \frac{t_{sailing}}{t_{trip}} \cdot t_{operational} \cdot P_{inst}$$ Eq. 6-21

Where:
$C_{maintenance}$ = annual maintenance cost (€/year)
$C_{maint,fixed}$ = fixed maintenance cost (€/m^3/year)
$C_{maint,variable}$ = variable maintenance cost (€/kWh/year)
L = ship length (m)
B = ship beam (m)
T = ship draught (m)
$t_{sailing}$ =sailing time per trip (h)
t_{trip} = total time per trip (h)
$t_{operational}$ = annual number of operational hours; hours per day x days per year (h)
P_{inst} = installed power (kW)

However, it should again be stressed that the accuracy of the abovementioned estimations is very limited. Beelen [2011, p. 161], who reviews a dataset of the maintenance cost of 40 vessels with over a 5-year period, also finds a large scatter in cost and a low correlation between maintenance cost and year of build, length or tonnage of the vessel.

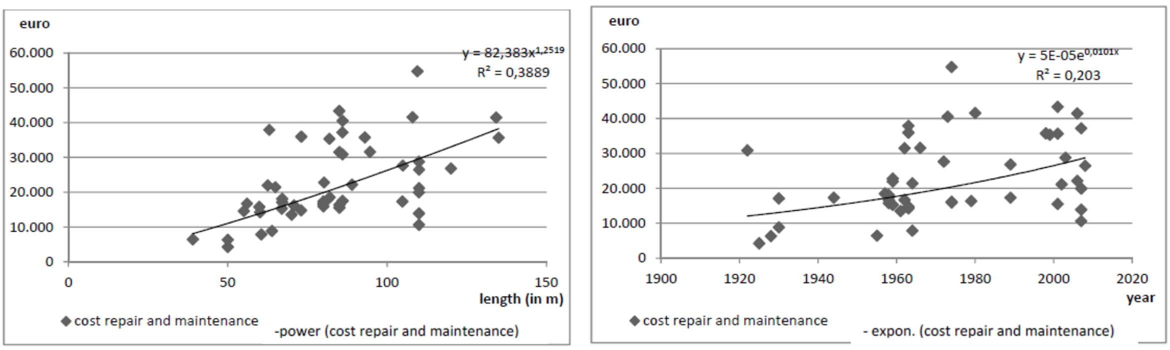


Figure 6-5: Repair and maintenance cost as a function of vessel length and year of build (Source: Beelen, 2011)

Depreciation

Beelen, [2011, p. 109] states a depreciation period of 20-35 years for inland ships, with a residual value of 15-20% of its original value at the end of the depreciation period. For a main engine, the depreciation time is 10-15 years, with a remaining value of 5-10%, while 10 years is the minimum depreciation period for the equipment items requiring a large investment according to Beelen [2011]. The equation that is used to describe depreciation cost in this thesis is:

$$C_{dep} = \frac{I_{hull} - R_{hull}}{t_{dep,hull}} + \frac{I_{mach} - R_{mach}}{t_{dep,mach}} \quad \text{Eq. 6-22}$$

Where:
C_{dep} = annual depreciation cost (€/year)
I_{hull} = building cost hull (€)
I_{mach} = building cost ship minus building cost hull (€)
R_{hull} = remaining value hull (€)
R_{mach} = remaining value ship minus hull (€)
$t_{dep,hull}$ = depreciation period hull (years)
$t_{dep,mach}$ = depreciation time of the ship minus hull (years)

In chapter 7, the effects of different choices in the depreciation periods of hull and main equipment & machinery will be investigated.

Insurance costs

Insurance cost varies from case to case. Via Donau [Via Donau, 2007 p. D13] use values between 2 and 3% of the actual value of the vessel, while Buck Consultants use values of 1% and less [Buck, 2008, p. 12]. Beelen, [2011, p. 111-117] provides a more in depth review of the various aspects that have a role to play in insurance cost, but provides no quantitative values. As a result of the above, insurance cost will be set at 1.5% of the ship's newbuilding price.

Overhead

Overhead is not a directly ship-related cost element by definition. As a result, it is not affected by the dimensions of a ship. Furthermore, since the vast majority of inland ship operators are captain-owners that live on board, the overheads are very limited. Therefore, overhead is not incorporated in the analyses.

Crew cost

The cost of crewing a ship depends on the number of crew members that are required, the salary they earn and the additional employer's cost. The number of crew members is dictated by law in the ROS-R rules [Central Commission for Navigation on the Rhine, 2007], which specify a number of crew members, differentiated by job description (i.e. captain, helmsman, sailor,…..) as a function of a vessel or convoy's dimensions, composition (no of barges) and sailing regime (A1, A2 or B) and the level of equipment on board (S1 or S2) as is shown in Table 6-4 for single ships.

The total cost of the crew will, however, vary strongly: in different countries, different wages are paid and different amounts of employer's costs are incurred. Furthermore, in case of a captain-owner, he may (and regularly does) decide not to pay himself and his partner any wages other than a minimum compensation for entrepreneurs and live from what is left after all expenses are paid. As a result, the crew cost model developed for this thesis provides a suggestion for crew cost based on the ROS-R regulations, the salary tables from a collective workers' agreement for the inland navigation sector and an estimate of the employers' cost involved, but it also provides an alternative where the two most expensive crew members are replaced by a husband-wife team that pay themselves a total of € 30.000 per year.

Table 6-4: Crew requirement for a non-coupled inland ship

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[1)]	2[1) 3)]
70 m< L ≤ 86 m	Captain	1 or 1	1	2		2	2
	Helmsman	- -	-	-		-	-
	Full sailor	1 -	-	-		-	-
	Ordinary sailor	- 1	1	-		2	1
	Basic sailor	- 1	1	1[1)]		-	1
L >86 m	Captain	1 or 1	1	2	2	2 or 2	2
	Helmsman	1 1	1	-	-	1 1[2)]	1
	Full sailor	- -	-	-	-	- -	-
	Ordinary sailor	1 -	-	1	-	2 1	1
	Basic sailor	- 2	1	1[1)]	2[1)]	- -	1

1) the basic sailor or one of the basic seamen may be replaced by a deckhand
2) the helmsman needs to be in possession of the patent required by the Rhine patent rules
3) one of the basic sailors needs to be over 18 years of age

For the purpose of this thesis, crew costs per year are determined for the following combinations of sailing regime and crew rotation:

- A1 sailing regime (14 h/day), where the crew have a normal 5-day working week.
- B sailing regime (24 h/day), where a crew is on board for 50% of the year, 7 days/week.

For A1 sailing regime, crew cost is determined by:

$$C_{crew,A1} = \sum_{1}^{n} C_{crewmember,n} \cdot \frac{t_{crew,day} \cdot daysperyear_{ship}}{t_{crew,year}} \qquad \text{Eq. 6-23}$$

Where:
C_{crew} = annual crew cost (€)
$C_{crewmember,n}$ = cost of an individual crew member of type n (€/year)
$t_{crew,day}$ = number of working hours per day for a crewmember (h/day)
$daysperyear_{ship}$ = number of operational days per year for the ship (days/year)
$t_{crew,year}$ = number of working hours per year for a crewmember (h/year)

For B sailing regime, this changes to

$$C_{crew,B} = \sum_{1}^{n} C_{crewmember,n} \cdot 2 \qquad \text{Eq. 6-24}$$

The cost per crewmember is determined by the following equation:

$$C_{crewmember,n} = Wage \cdot \left(1 + \frac{Cont_{empl} + Cont_{coll} + Cont_{holl}}{100}\right) \cdot 12 + \left(C_{food} + C_{travel}\right) \qquad \text{Eq. 6-25}$$

Where:
Wage = gross monthly wage (€)
$Cont_{empl}$ = employer's contribution (%)
$Cont_{coll}$ = fee for employers' organization (%)
$Cont_{holl}$ = holiday allowance (%)
C_{food} = food allowance (€/year)
C_{travel} = travel allowance (€/year)

Considering the fact that a large percentage of the European inland fleet is Dutch, the salary tables of the non-official Dutch collective workers' agreement for the inland navigation sector are used to estimate crew cost. This leads to the following twelve options for the annual crew cost of a ship.

Table 6-5: Annual crew cost as a function of ship length and sailing regime (2011 values)

	A1		B	
Vessel length	Full cost	Reduced cost	Full cost	Reduced cost
L ≤ 70 m	€ 61,197	€ 34,533	€ 265,366	€ 225,977
70 m < L ≤ 86 m	€ 75,036	€ 47,660	€ 286,784	€ 238,705
L > 86 m	€ 91,848	€ 48,906	€ 377,475	€ 311,775

Now that all costs are known, it is possible to solve equation 6-17 and 6-18 and thereby to determine which ship rate leads to an annual EBITDA that leads to a positive net present value at the end of the life of the ship, which is the most important outcome of the model. For completeness, equations 6-17 and 6-18 are repeated below.

$$\sum_{x=1}^{z}\frac{EBITDA_x}{(1+WACC)^x} = I_{mach} + I_{hull} - \frac{R_{mach}}{(1+WACC)^y} + \frac{I_{mach}}{(1+WACC)^y} - \frac{R_{hull}+R_{mach}}{(1+WACC)^z} \qquad \text{Eq. 6-26}$$

Where EBITDA is calculated as revenue minus the sum of crew cost, fuel cost, insurance cost, maintenance cost and overhead.

$$RSR = \frac{\sum_{x=1}^{z}\frac{EBITDA_x + C_{crew,x} + C_{fuel,x} + C_{maint,x} + C_{ins,x} + C_{oh,x} + C_{ext,x}}{(1+WACC)^x}}{\sum_{x=1}^{z} Units_{annual,x}} \qquad \text{Eq. 6-27}$$

Where:
RSR = required ship rate (€/unit)
$EBITDA_x$ = Earnings Before Interest, Taxes, Depreciation and Amortization in year x (€)
$C_{crew,x}$ = crew cost in year x (€)
$C_{fuel,x}$ = fuel cost in year x (€)
$C_{maint,x}$ = Maintenance cost in year x (€)
$C_{ins,x}$ = insurance cost in year x (€)
$C_{oh,x}$ = overhead cost in year x (€)
$C_{ext,x}$ = cost of internalized external costs in year x (€)
$Units_{annual}$ = number of units of cargo transported annually in year x (-)
z = depreciation time of the hull (years)

6.2.2 Handling, pre haulage and end haulage model

In the previous paragraph, the model was elaborated that is used to calculate the required ship rate for inland ships with various main dimensions. However, inland waterway transport is often preceded or followed by road transport in order to get the cargo from its origin to the waterfront or to get it from the waterfront to its destination, so-called pre haulage and end haulage.

Since the competitive position of an inland ship is not only dependent on its ability to compete with other ships, but also on its ability to compete with road and rail transport, it is deemed desirable to also be able to compare the transport cost of combined transport (i.e. waterborne or rail transport with pre and/or end haulage) with that of pure road transport. Therefore, the main *required ship rate model* is complemented with a model for handling, road and rail transport. This model has a lower level of complexity and detail than the *required ship rate model* and relies more directly on data from literature. The model takes transport distances, number of moves for handling and the cost of handling directly from the *case data* dataset.

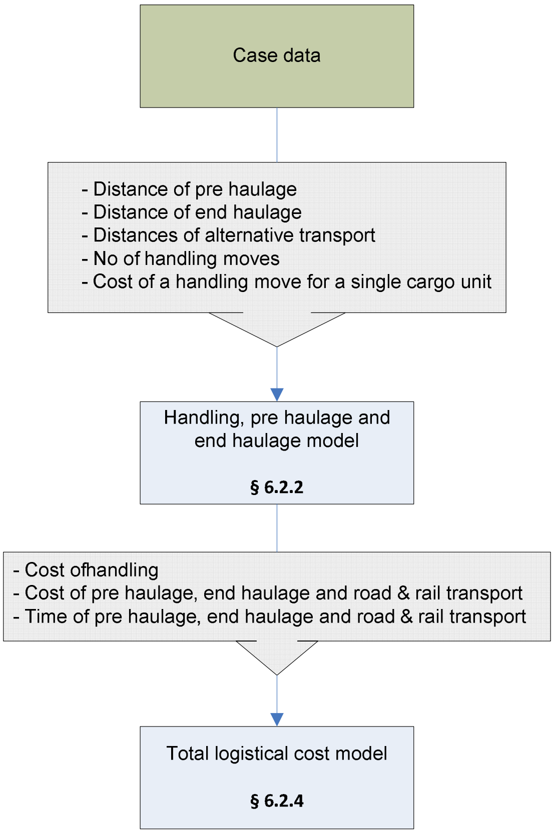


Figure 6-6: Relationship between handling, pre haulage and end haulage and the other sub models

In the paragraphs below, the way that the cost of handling and the cost of road & rail transport are calculated is discussed.

Handling cost

Handling costs are based on commercial tariffs, as were quoted by a number of terminals for various commodities. Results of this inventory are shown in Table 6-6 below, taken from the CREATING project [Lundoluka et al., 2005]. Here it is important to notice that cost of loading and unloading may depend heavily on the transport mode that is used. E.g. [Blauwens, et al, 2010] state that the rate asked by operators at seaports to unload a container to a barge are higher than for unloading to a truck, but in other cases flat rates are used by operators. Furthermore, prices fluctuate strongly from terminal to terminal. E.g. Decisio [2002, p. 16] states a price range of 14 to 68 €/TEU with an average of 40 €/TEU. For this thesis, the values presented by CREATING are used [Lundoluka et al., 2005], indexed for 2011 according to the OECD's producers price index [OECD, 2012].

Table 6-6: Handling cost of various commodities (Source: own adaptation of Lundoluka et al., 2005)

Product	Cost price (€, 2011 values)	Speed	Source
Dry bulk	2.5-3.1 €/Ton	Loading: 500-800 T/h Unloading: 300-500 T/h	European Bulk Services, Rotterdam
Agri bulk	3.72 €/Ton	500-1000 T/h	IGMA B.V. Amsterdam
Coal/ore*	2.73 €/ton (capesize-shore) 2.5 €/ton (capesize-inland) 1.55 €/ton (shore-inland)	40.000T/day ore (guarant.) 25.000T/day coal (guarant.) 2500-4000 T/h 2500-4000 T/h	EMO B.V., Rotterdam
Containers	28.5 €/unit** (Duisburg)***		Duisburg cont. Terminal

*) storage price of ore: 0.007-0.015 E/day/ton, depending on storage period
storage price of coal: 0.017-0.035 E/day/ton, depending on storage period
**) price independent of container size
***) price does not include € 6.60 wharfage for the ship

Within the model, handling costs are assumed to be independent of shipment size, vehicle type or whether cargo is loaded or unloaded. Furthermore, costs are assumed to be linearly dependent on the number of moves in the entire transport chain. This results in the following formula:

$$C_{handling,u} = n \cdot C_{move,u} \quad \text{Eq. 6-28}$$

Where
$C_{handling,u}$ = cost of handling a unit of cargo of type u (€/unit)
n = number of moves (-)
$C_{move,u}$ = cost for 1 move of a cargo unit of type u (€/unit)

Road transport

The cost of road transport is commonly subdivided in time and distance cost. Furthermore, in order to determine how much it costs to transport a unit of cargo by truck, it is necessary to know how much cargo the truck can carry and what its average degree of utilization is. Costs for trucking are herefore expressed as:

$$C_{truck} = \left(\left(t_{terminal} + t_{driving}\right) \cdot c_{time} + Dist \cdot c_{dist}\right) \cdot Cap_{truck} \cdot Util_{truck} \quad \text{Eq. 6-29}$$

Where:
C_{truck} = costs of truck transport (€/unit)
$t_{terminal}$ = time the truck spends at the terminal (h)
$t_{driving}$ = time the truck spends driving (h)
c_{time} = time cost (€/h)
Dist = distance traveled (km)
c_{dist} = distance cost (€/km)
Cap_{truck} = loading capacity of a truck (units)
$Util_{truck}$ = degree of utilization of the truck (-)

The cost of road transport is based on average values from literature for a tractor-trailer with a loading capacity of 27 T or 2 TEU. For the time and distance cost of such a vehicle, Blauwens et al. [2011] indicate a cost of 29.24 €/h and 0.50 €/km (2011 values).

Like ships, trucks are not always fully loaded when they operate and as a result, the costs need to be spread out over the amount of goods that are actually transported. For the average utilization degree of trucks, NEA provides figures [NEA, 2004].

Table 6-7: Average utilization of various truck s (source: NEA, 2004)

	Small general cargo	Medium general cargo	Medium container	Large tank/bulk	Large General cargo	Large container
Util. by content	0.46	0.58	0.60	0.96	0.66	0.60
Util. by distance	0.80	0.80	0.80	0.80	0.80	0.80
Total utilization	0.37	0.46	0.48	0.77	0.53	0.48

From Table 6-7 above, the values for the ‘large’ trucks are used.

With regard to the driving time of a truck over a given distance, NEA [2001] names an average speed of 55 km/h for transport within the Netherlands and 68 km/h for international transport. If it is assumed that a distance of 5 km is needed to get to/from a loading or unloading site from/to a highway, that for this distance an average speed of 30 km/h is achieved and that once on a highway an average speed of 70 km/h is achieved, values for the average speed of trucks are achieved that match the values by NEA well. As further confirmation of the assumptions, NEA [NEA 2004] uses an average speed of 31 km/h for delivery vans.

For the time that is spent at the terminal, Beelen et al. [2007] find an average time of just less than 1 hour. Therefore, a time of 1 hour per terminal is used.

As a result of the above, the following formula is used to determine the time that is required to transport cargo from A to B.

$$t_{road} = t_{driving} + t_{terminal} = \frac{\max[dist, 10]}{30} + \frac{\max[dist - 10, 0]}{70} + 2 \qquad \text{Eq. 6-30}$$

Rail transport

The cost of rail transport is estimated on the basis of three case studies by Grosso [2011]. Grosso calculates the cost per ton for the routes Antwerp - frankfurt (400 km), Antwerp – Strasbourg (580 km) and Antwerp – Basel (718 km). A linear trendline through the datapoints that are calculated by Grosso [2011] lead to the following cost equation with a near perfect fit of the data points:

$$\mathrm{C_{rail}} = 2.36 + 0.0250 \cdot \mathrm{dist} \qquad \text{Eq. 6-31}$$

Where:

C_{rail} = cost of rail transport (€/T)

dist = transport distance (km)

6.2.3 External cost model

In the previous paragraphs, the models were discussed with which the out-of-pocket costs can be calculated for a logistics chain consisting of a waterborne main leg and pre end/or end haulage. However, the cost of transporting goods is not limited to the costs that are actually paid by shippers and transport operators. There are also costs that are paid for by society, so-called external costs.

External costs are *costs that the transport user causes to a third party and for which he does not pay* [Blauwens et al., 2010, p. 391]. Blauwens describes four types of external cost: marginal congestion cost, marginal infrastructure cost, marginal environmental cost and marginal accident cost [Blauwens et al. 2010, p. 395]. For a fair comparison of transport alternatives, these costs should be charged to the one who causes them, i.e. they should be internalized. In this paragraph, first it is explored which external costs should be internalized and how external costs are related to the size of a ship. After this, the implementation of the external cost model will be elaborated.

External costs that are eligible for internalization

In general, four forms of external costs are distinguished: environmental, accident, congestion and infrastructure costs. For inland waterway transport, congestion costs as well as infrastructure costs are internalized at a cost of zero according to the *Handbook on estimation of external cost in the transport sector* [CE Delft et al., 2008b, p. 110] This reflects observations by others that waterways still have sufficient spare capacity. [Bureau Voorlichting Binnenvaart, 2007], [UNECE Inland Transport Committee, 2010]. As a result, no matter which ship design is considered, it will not impact congestion costs.

The costs of accidents on inland waterways are generally very small, with about 6% of the mortalities and 32% of the injuries per vehicle kilometer compared to road transport, regardless of vessel size [NEA, 2001]. Since the carrying capacity of a ship is many times that of a truck, these numbers go down even further when a comparison is made on the basis of tonkilometers of transport performance. As a result, external accident costs per tonkilometer of transport are negligible for inland waterway transport. This is confirmed by the *Handbook on estimation of external cost in the transport sector* [CE Delft et al., 2008b, p. 110], which also internalizes accident cost for inland waterway transport at a value of zero. In this thesis accident cost is, therefore, also set at 0.

This leaves environmental costs as the main external costs to be internalized: These costs vary significantly from ship to ship, they can be quantified with a relatively high level of detail and they are most likely to actually be internalized in the future through emission charges.

In the next paragraphs, first an introduction to the link between the specifications of a ship, external costs and the emissions of various substances is provided, followed by a description of the way this is incorporated in the model.

Environmental cost and emissions

First and foremost, it is important to realize that there is a direct link between the amount of energy that a ship consumes, the type of engine that it has and the amount of pollutants that it emits. The amount of energy that a ship consumes is among others related to its size. CE Delft [2003] provide an overview of the energy use of various modes, including trucks and ships of various sizes, data from which is incorporated in Figure 6-7 below. The figure displays the energy consumption of various vessels and vehicles expressed in MegaJoules (MJ) per tonkilometer.

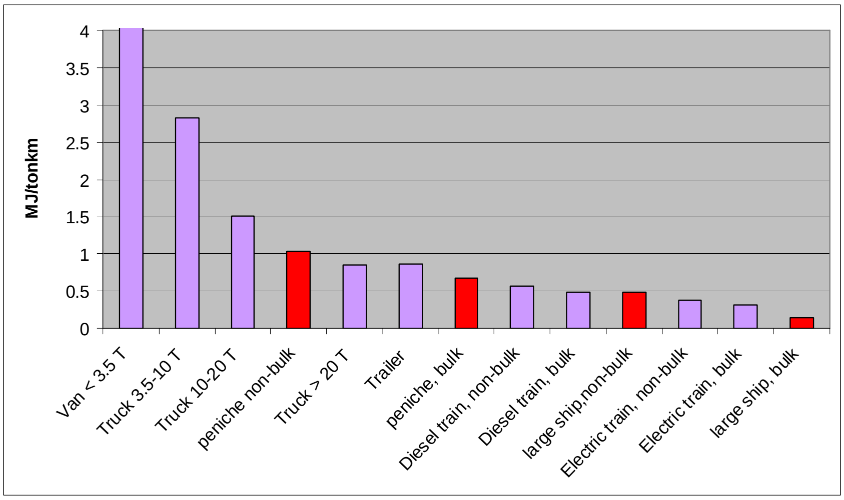


Figure 6-7: Energy consumption of various vehicles and vessels. Source: adapted from CE Delft [2003]

What is important to note here is that size of a vessel has an important role to play: when vessels get smaller, the fuel consumption advantage that those vessels have over other modes of transport also becomes smaller. However, the data presented here is too crude for the assessment of performance of individual inland ships since it levels out factors like the main dimensions of the ship, fairway characteristics (width, depth, cross-section, current velocity), vessel speed and degree of loading, all of which influence the amount of energy that a ship consumes in order to sail over a given distance. This is why the fuel consumption calculation that is used in this thesis is far more elaborate, as discussed in chapter 6.2.1.

All ships use fossil fuels to generate energy and the combustion of these fuels results in emissions of a number of substances that are harmful to the environment and/or people and thereby generate external costs. The most important substances are:

- CO_2 (Carbon dioxide), which is a greenhouse gas.
- NO_x (nitrogen oxides), which is a greenhouse gas.
- SO_x (sulphur oxides), which affects the respiratory system and causes acid rain.
- PM (particulate matter or soot), which affects the respiratory system.

The various forms of PM (soot with various particle sizes, usually divided in $PM_{2.5}$ and PM_{10}) have a negative impact on the respiratory system, but only in the direct vicinity of the location where the PM is emitted. CO_2, NO_x and SO_x have a global effect.

As a result of these different forms and ranges of impact, the negative impact and associated external costs of the various substances is valued differently at different geographical locations (e.g. metropolitan, urban or rural). CE Delft et al. [2008b] provide an elaborate overview of the valuation of various emissions, differentiated by among others transport mode, substance and nation. As a more easily digestible example, CE Delft [2008c, p. 2] provides some basic values per location type and substance type for the Netherlands.

Table 6-8: External costs of various substances, 2011 values. Source: adapted from CE Delft [2008c]

<table>
<tr><th>Substance</th><th>year</th><th>Metropolitan</th><th>Urban</th><th>Rural</th></tr>
<tr><td rowspan="3">PM2,5 (transport: combustion emissions)</td><td>2007</td><td>505 €/kg</td><td>163 €/kg</td><td>99 €/kg</td></tr>
<tr><td>2010</td><td>527 €/kg</td><td>170 €/kg</td><td>103 €/kg</td></tr>
<tr><td>2020</td><td>605 €/kg</td><td>195 €/kg</td><td>118 €/kg</td></tr>
<tr><td rowspan="3">PM10 (transport: other emissions, tires etc.)</td><td>2007</td><td>202 €/kg</td><td>65 €/kg</td><td>39 €/kg</td></tr>
<tr><td>2010</td><td>211 €/kg</td><td>68 €/kg</td><td>41 €/kg</td></tr>
<tr><td>2020</td><td>242 €/kg</td><td>78 €/kg</td><td>47 €/kg</td></tr>
<tr><td rowspan="3">PM10 (Electricity generation, chimney)</td><td>2007</td><td>19 €/kg</td><td></td><td>16 €/kg</td></tr>
<tr><td>2010</td><td>20 €/kg</td><td></td><td>17 €/kg</td></tr>
<tr><td>2020</td><td>23 €/kg</td><td></td><td>19 €/kg</td></tr>
<tr><td rowspan="3">NOx</td><td>2007</td><td colspan="3">7.9 €/kg</td></tr>
<tr><td>2010</td><td colspan="3">8.2 €/kg</td></tr>
<tr><td>2020</td><td colspan="3">9.5 €/kg</td></tr>
<tr><td rowspan="3">SO2</td><td>2007</td><td colspan="3">16 €/kg</td></tr>
<tr><td>2010</td><td colspan="3">16 €/kg</td></tr>
<tr><td>2020</td><td colspan="3">18 €/kg</td></tr>
<tr><td rowspan="2">CO2</td><td>2010</td><td colspan="3">25 €/ton</td></tr>
<tr><td>2020</td><td colspan="3">40 €/ton</td></tr>
</table>

In order to limit the emission of various substances by inland vessels, the Central Commission for Navigation on the Rhine (CCNR) has issued legislation in the form of the CCNR stage I standard and its follow-up CCNR stage II for engines that are built after 30 June 2007, as described in Directive 2004/26/EC. The emission limits of these standards, as taken from [Official Journal of the European

Union, 25-6-2004, Annex XIV and XV] are expressed in terms of upper limits per kWh of energy produced, as is shown in Table 6-9. Due to lack of better data on the actual emissions of the inland fleet, these values will be used to estimate the emissions of ships in the external cost model.

Table 6-9: CCNR stage I and II regulations for inland ship engines

CCNR stage I				
P_N (kW)	CO (g/kWh)	HC (g/kWh)	NO_x (g/kWh)	PM (g/kWh)
$37 \le P_N < 75$	6.5	1.3	9.2	0.85
$75 \le P_N < 130$	5.0	1.3	9.2	0.70
$P \ge 130$	5.0	1.3	$n \ge 2800$ rpm = 9.2 $500 \le n < 2800$ rpm = 45 x $n^{(-0.2)}$	0.54

CCNR stage II				
P_N (kW)	CO (g/kWh)	HC (g/kWh)	NO_x (g/kWh)	PM (g/kWh)
$18 \le P_N < 37$	5.5	1.5	8.0	0.8
$37 \le P_N < 75$	5.0	1.3	7.0	0.4
$75 \le P_N < 130$	5.0	1.0	6.0	0.3
$130 \le P_N < 560$	3.5	1.0	6.0	0.2
$P \ge 560$	3.5	1.0	$n \ge 3150$ rpm = 6.0 $343 \le n < 3150$ rpm = 45 x $n^{(-0.2)}$-3 $n < 343$ rpm = 11.0	0.2

For road transport, emission norms are more numerous and more stringent. EURO I to VI norms as presented among others by Dieselnet [Dieselnet, 2010] are shown in the table below. Again, due to lack of more accurate data on the actual emissions of trucks, these values are used in the external cost model.

Table 6-10: EURO I-VI regulations for truck engines. source: Dieselnet [2010]

Tier	Date	CO (g/kWh)	HC (g/kWh)	NOx (g/kWh)	PM (g/kWh)
Euro I	1992, <85 kW	4.5	1.1	8.0	0.612
	1992, > 85 kW	4.5	1.1	8.0	0.36
Euro II	1996.10	4.0	1.1	7.0	0.25
	1998.10	4.0	1.1	7.0	0.15
Euro III	2000.10	2.1	0.66	5.0	0.1
Euro IV	2005.10	1.5	0.46	3.5	0.02
Euro V	2008.10	1.5	0.46	2.0	0.02
Euro VI	2013.01	1.5	0.13	0.4	0.01

What becomes clear from Table 6-9 and Table 6-10 is that modern truck engines have substantially better emission characteristics in terms of g/kWh than inland ships, thereby potentially negating the effects of the lower fuel consumption of the ships that was shown in Figure 6-7.

A final emitted substance, SO_x, is directly related to the sulphur content of the fuel that is used. For road transport this is typically between 10 and 50 ppm. For inland waterway transport, maximum allowed values have been lowered from 2000 to 1000 ppm recently and as of January 1st 2011 the sulphur limit is even identical to that of trucks. One of the reasons to do this is that a high sulphur content in diesel fuel prevented the use of emission control techniques like filters [Partnership for Clean Fuels and Vehicles, 2010, p. 5].

Model implementation

For ships, the *external cost model* combines the legislation on the emissions from the engines as shown in Table 6-9 with the fuel consumption of the ship that is calculated in the *required ship rate* model in order to estimate the amount of emitted substances according to equation 6-32.

$$M_{subst,trip} = \frac{M_{fuel,trip} \cdot 10^6}{sfc} \cdot se_{subst} \qquad \text{Eq. 6-32}$$

Where:
$M_{subst,trip}$ = mass of substance emitted per trip (g)
$M_{fuel,trip}$ = fuel consumption per trip (T)
sfc = specific fuel consumption of the engine (g/kWh)
Se_{subst} = upper limit on specific emissions of a substance according to legislation (g/kWh)

When the emission figures from equation 6-32 are combined with the external cost of the various substances, this results in the external cost per trip. The values as stated in Table 6-8 for 2010 in rural areas are used. When this external cost is divided by the number of transported units of cargo, this leads to the external cost per transported unit of cargo, as is shown in equation 6-33.

$$C_{ext,unit} = \frac{\sum_{x=1}^{m} M_{subst,x} \cdot 10^6 \cdot C_{subst,x}}{n} \qquad \text{Eq. 6-33}$$

Where:
$C_{ext,unit}$ = external costs per unit of cargo (€)
$M_{subst,x}$ = mass of substance x emitted per trip (T)
$C_{subst,x}$ = external cost per quantity of substance (€/g)
m = number of substances that result in external costs (-)
n = number of units of cargo transported per round trip (-)

For trucks and trains a less elaborate approach is used, since these vehicles are not researched in the same detail. Values are taken directly from the *Handbook on estimation of external costs in the transport sector* [CE Delft, 2008, p. 57, p. 85 and p. 113], indexed to 2011 values using the producers' price index [OECD, 2012]. The resulting external costs are zero for electric trains and 0.0101 €/tkm for diesel driven trains. For modern EURO V trucks, external emission costs are 0.00316 €/tkm, based on a truck with maximum loading capacity of 28 tons and an average utilization of 50%.

For road and rail transport, the external costs per trip are direct input for the total logistical cost model. For waterborne transport, however, they become input for the calculation of the required ship rate (see equation 6-18) which is based on a summation of annual costs. As a result, the fuel consumption of all trips is summed and the external costs are based on that. As a result, for the calculation of the external costs of a ship in a year, equations 6-32 and 6-33 are transformed to equation 6-34:

$$C_{ext,annual} = \sum_{x=1}^{m} \frac{M_{fuel,year} \cdot 10^6}{sfc} \cdot se_{subst} \cdot 10^6 \cdot C_{subst,x}$$ Eq. 6-34

Where:
$M_{fuel,year}$ = fuel consumption per year (T)
$C_{ext,annual}$ = external costs per year (€)
$C_{subst,x}$ = cost per quantity of substance (€/g)
sfc = specific fuel consumption of the engine (g/kWh)
se_{subst} = upper limit on specific emissions of a substance according to legislation (g/kWh)
$C_{subst,x}$ = cost per quantity of substance (€/g)

In order to determine the amount of emitted substances, the *external cost model* takes data about the external cost of trucks and trains as well as the emission limits for ship engines from the *emission dataset*. Distances for road and rail transport are taken from the *case data,* while the amount of fuel that is consumed by a ship during a round trip is taken from the *required ship rate model*.

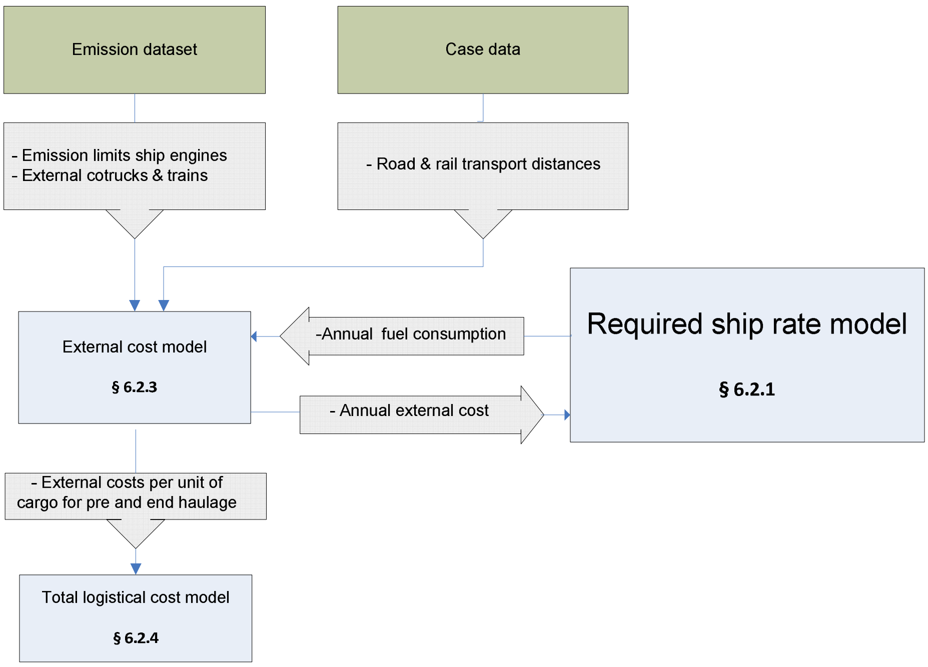


Figure 6-8: Relationship between the external cost model and other sub models

6.2.4 Total logistical cost model

In the previous paragraphs, the transport costs by ship as well as the additional costs incurred due to pre and end haulage have been discussed. Furthermore, the way in which external costs can be internalized has been discussed. However, when comparing the cost of using various transport alternatives from the point of view of the shipper instead of from the point of view of the transport operator, it is important to take into account all of the cost that are incurred by the shipper as a result of the way goods are transported. These costs consist not only of the out of pocket cost of transport, but also of the cost of cycle stock, the cost of stock in transit and the safety stock that is required to handle fluctuations in supply and demand. Despite the fact that this thesis is aimed at improvement of the competitive position of the ship operator rather than that of the shipper, determination of the total logistical cost of a shipper is required since it is an important criterion for shippers to select a transport operator, as was discussed earlier.

For the determination of the total logistical cost, Blauwens et al. [2006] use the following formula in which the four previously mentioned elements (direct transport cost, cost of cycle stock, cost of stock in transit and cost of safety stock) are reflected:

$$TLC = TC + \left(\frac{1}{R_g}\cdot\frac{Q}{2}\cdot v\cdot hc\right) + \left(Lt\cdot v\cdot\frac{hc}{365}\right) + \left(\frac{1}{R_g}\cdot v\cdot hc\cdot K\cdot\sqrt{(L\cdot d_g)+(D_g{}^2\cdot l)}\right) \quad \text{Eq. 6-35}$$

Where:

TLC = total logistic costs (€/unit)
TC = transport cost (€/unit)
R_g = annual volume (units)
Q = loading capacity/shipment size (units)
v = value of the goods (€/unit)
h = holding cost (fraction of value/year)
Lt = average lead-time / travel time (days)
l = variance of lead times (days^2)
K = safety factor
D_g = average daily demand (units/day)
D_g = variance of daily demand (units^2/day)

In this formula, TC is the actual out of pocket cost of transport, i.e. the cost that someone needs to pay to have the goods transported from A to B. How this cost is calculated was elaborated in chapter 6.2.1.

The term $\left(\frac{1}{R_g}\cdot\frac{Q}{2}\cdot v\cdot hc\right)$ relates to the cost of cycle stock, basically stating that on average half the amount of goods of a shipment are in stock as a cyclic part of the shipper's stock and that he has to deal with the associated cost. As an example, if a company uses 500 tons of raw materials annually, which get delivered in fifty 10-ton batches that are spread out evenly throughout the year, the average cycle stock will be 5 tons. If supplies are delivered in only five 100 ton batches, the average stock will be ten times higher, and cost of that stock will increase accordingly.

The third term in the total logistical cost equation, $\left(Lt\cdot v\cdot\frac{hc}{365}\right)$, denotes the fact that goods are also part of the stock of the owner while they are still en route to the production site, thus increasing stock without giving the owner direct access to it.

The final term, $\left(\frac{1}{R_g}\cdot v\cdot hc\cdot K\cdot\sqrt{(L\cdot d_g)+(D_g{}^2\cdot l)}\right)$ relates to the safety stock a company need to deal with expected fluctuations in supply and demand, determining the amount of additional stock that is required to prevent running out of stock.

Model implementation

The total logistical cost model is an implementation of the formula discussed above. It takes data on the transport chain from the *required ship rate model*, the *external cost model* and the *handling, pre haulage and end haulage model* and combines that with data on the amount of cargo that is used annually, the value of the goods and their holding cost as defined in the *case data*.

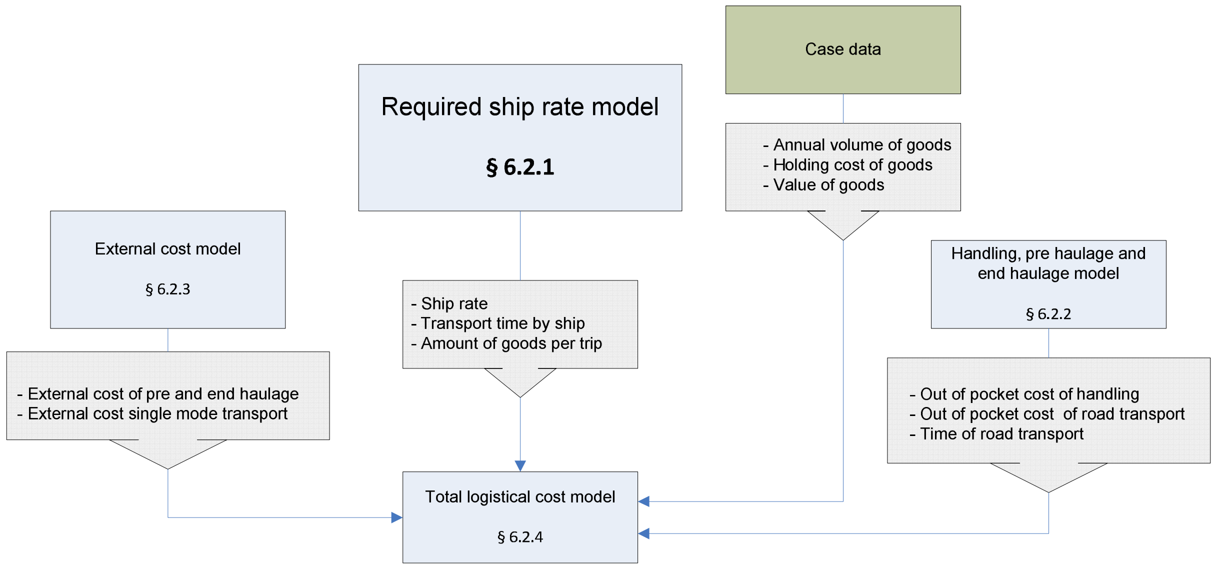


Figure 6-9: Relationship between the Total logistical cost model and the other sub models

The first term of the total logistical cost equation, the out of pocket transport cost for the shipper, is determined by the formula:

$$TC = C_{pre,end} + C_{main} + C_{handling} + C_{ext} \qquad \text{Eq. 6-36}$$

Where:
TC = transport cost
$C_{pre,end}$ = cost of pre and end haulage by road (€)
C_{main} = cost of transport by water = ship rate (€)
$C_{handling}$ = cost of handling (€)
C_{ext} = internalized external costs (€)

The second term in the total logistical cost equation, $\left(\frac{1}{R_g} \cdot \frac{Q}{2} \cdot v \cdot hc\right)$, concerning cycle stock takes values R_g (annual volume), v (value of the goods), and hc (holding cost) directly from the *case data*. Shipment size Q is equal to the maximum amount of cargo that the ship will carry on a leg, based on draught, air draught and stability requirements as well as on logistical boundary conditions like imbalance in freight volume as was discussed in chapter 6.1.2.

The third term under consideration is the cost of stock in transit, $\left(Lt \cdot v \cdot \frac{hc}{365}\right)$. V and hc are again taken from the *case data*. Lt (transport time) is the sum of transport times of the legs of the trip:

$$Lt = t_{pre,end} + t_{main} \qquad \text{Eq. 6-37}$$

Where:
Lt = transport time (days)
$t_{pre,end}$ = transport time of pre and end haulage (days)
t_{main} = transport time of the main leg (days)

The fourth and final term in the TLC equation is the cost of safety stock. Since the variance of lead time and daily demand of individual shippers are not investigated, this is set at 0.

6.3 Validation & sensitivity analysis

The model that is created and discussed in this chapter consists of five sub models: the *required ship rate model,* the *handling, pre haulage and end haulage model,* the *external cost model* and the *total logistical cost model.* Of these five models, the last four rely heavily on data and calculation methods from literature. Only the output of the *required ship rate model* relies mainly on data that is generated within the framework of this thesis (i.e. the ship design and cost data from the *ship design dataset*) and on an interpretation of the way various elements of the model should be combined to arrive at the desired outcome, which is the ship's required ship rate. Therefore, only the *required ship rate model* will be validated here.

For the validation, all monetary values are indexed to 2011 values according to the OECD's producers' price index for Europe [OECD, 2012]. The model will be validated by comparing known commercial ship rates with the required ship rate that is calculated by the model for a comparable ship. There are several advantages and disadvantages to this way of validation, which will be discussed after the data from practice have been presented.

Bureau Voorlichting Binnenvaart [unknown year] provide values of the ship rates for a number of specific trips in 2006 while stating that deviations of +30% may occur in good times and deviations of -30% may occur in bad times. These values are shown in Table 6-11 below.

Table 6-11: Selected ship rates from 2006.

Cargo type	From	To	Dist.	Weight	Cost per ton	Cost per 1000 tkm
Salt	Hengelo	Leverkusen	268 km	1250 ton	€ 6.03 ± 30%	€ 15.77-€ 29.23
Fertilizer	Amsterdam	Meppel	100 km	1250 ton	€ 4.76 ± 30%	€ 33.29-€ 61.82
Raw minerals	Liege	Nijmegen	167 km	2500 ton	€ 4.64 ± 30%	€ 19.49-€ 36.19
Cereals	Reims	Den Bosch	523 km	350 ton	€ 24.36 ± 30%	€ 32.59-€ 60.55

For the same period, Buck Consultants International [2008] presents Figure 6-10 of the average ship rate for ships of various sizes in the domestic trade in the Netherlands and in international trade. The value of 100 in Figure 6-10 represents a ship rate of 1.46 Eurocent per tonkilometer.

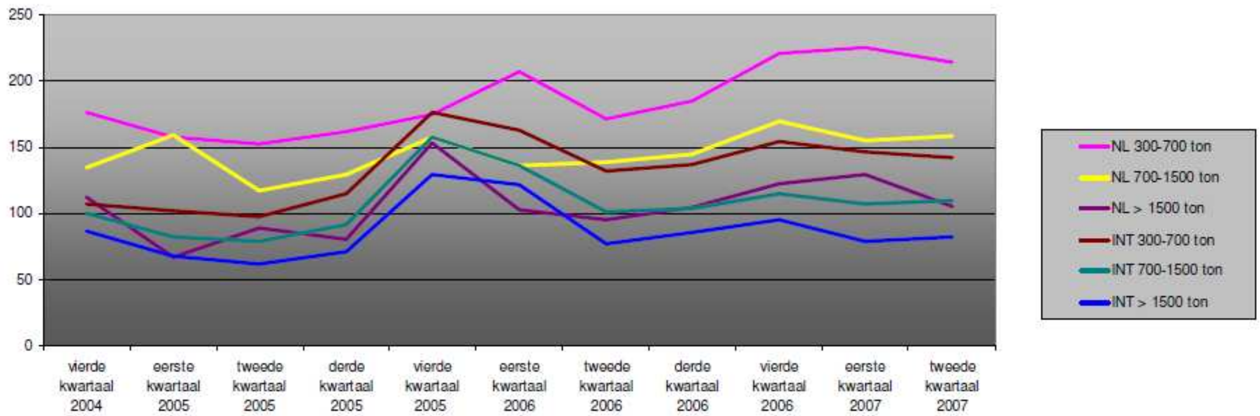


Figure 6-10: Development of ship rates in 2005-2007. Source: taken from Buck [2008]

Estimating maximum and minimum values from Figure 6-10 leads to the following upper and lower limits for the various ship categories:

Table 6-12: Upper and lower limits of ship rates, indexed to 2011 values

Tonnage	Lower bound ship rate (€/1000 tonkm)	Upper bound ship rate (€/1000 tonkm)
550 (NL)	€ 25.40	€ 38.16
550 (INT)	€ 16.93	€ 29.69
1100 (NL)	€ 19.49	€ 28.77
1100 (INT)	€ 13.57	€ 27.14
3000 (NL)	€ 11.02	€ 23.78
3000 (INT)	€ 9.28	€ 22.85

Although a comparison between calculated required ship rates and actual ship rates is the best way of validating the outcomes of the model with publicly available data, it needs to be noted that there is a substantial amount of uncertainty in this way of validating due to a number of reasons:

1. Actual ship rates are not only based on the minimum required ship rate for sound operation of a ship (which is what is calculated by the model), but also on the balance of supply and demand. As a result ship rates will vary over time, sometimes forcing transport operators to carry cargo at a ship rate that does not cover all costs and at other times providing them with a very good profit margin. However, the inland shipping sector is a sector where profit margins in general are very low and, therefore, it can be stated that the ship rate that is required for sound operation will lie somewhere between the upper and lower bound of actual ship rates as discussed above.

2. The detailed cost structure of each actual ship is different due to a different purchasing price, different age, different crew cost, different interest rates and so on. Furthermore, since is also not known how many tonkilometers of transport individual ships provide in a year, it is not possible to determine which ship rate results in a sound way of exploiting the ship on which the data from practice is based. The model can only provide an acceptable approximation.

As a result, it is not possible to provide an exact validation of the model output, but it can only be shown that the model produces representative values. To validate the model, results will be presented for the following ships and routes, which are also discussed by Bureau Voorlichting Binnenvaart [unknown year]:

Table 6-13: Selected ship dimensions and routes

	Ship	**From**	**To**	**Dist.**	**Weight**
1	Class IV (86 x 9.6 x 2.5 m)	Hengelo	Leverkusen	268 km	1250 ton
2	Class IV (86 x 9.6 x 2.5 m)	Amsterdam	Meppel	100 km	1250 ton
3	Class V (110 x 11.4 x 3 m)	Liege	Nijmegen	167 km	2500 ton
4	Class I (40 x 5 x 2.5 m)	Reims	Den Bosch	523 km	350 ton

For the calculation of the required ship rates, the following values are used:

Table 6-14: Selected values for the determination of the required ship rate

Utilization factor	50%, Based on [NEA, 2004]
Fuel price	€ 700,- (2011 values) , Based on [Backer van Ommeren, 2011]
Depreciation hull	30 years, 15% remaining value
Depreciation rest of ship	15 years, 5% remaining value
WACC	5%, Based on [Buck, 2008]
Insurance	1.5% of the newbuilding price
Sailing regime	A1 – 5 days per week
Crew cost	Reduced, i.e. with 2 crew members working for € 30.000,- in total

Running the cost model with these parameters and comparing the results with the ship rates as indicated by Buck and Bureau Voorlichting Binnenvaart leads to the results that are shown in Table 6-15. What becomes clear from Table 6-15 is first of all that in some cases there is quite a large gap between the ship rates as presented by both literature sources. This is believed to be due to the more generalized results of Buck. As a result, the ship rates that are presented by Bureau Voorlichting Binnenvaart (BVB) are believed to be the most accurate since they are based on the same routes as the model calculations.

Table 6-15: Comparison of calculated and reference ship rates

		Ship rate per 1000 tkm		
	Ship	**Calculated (required)**	**Buck (actual)**	**BVB (actual)**
1	Class IV (86 x 9.6 x 2.5 m)	€ 24.07	€ 13.57 - € 27.14	€ 15.77 - € 29.23
2	Class IV (86 x 9.6 x 2.5 m)	€ 39.00	€ 19.49 - € 28.77	€ 33.29 - € 61.82
3	Class V (110 x 11.4 x 3 m)	€ 22.04	€ 11.02 - € 23.78	€ 19.49 - € 36.19
4	Class I (40 x 5 x 2.5 m)	€ 39.55	€ 16.93 - € 29.69	€ 32.59 - € 60.55

From Table 6-15, it becomes apparent that the calculated required ship rates fall within the limits of the actual ship rates by BVB in all cases. In order to determine the robustness of the calculation, for each of the cases, a sensitivity analysis is performed in which the main variables that influence the required ship rate are changed. Results of this sensitivity analysis are presented in three ways:

1) The absolute change in the required ship rate as a result of a realistic change in a parameter (e.g. a rise in fuel price of from € 700 to € 800 per ton).
2) The percentage of change in the required ship rate as a result of the abovementioned change in the value of the parameter.
3) The percentage of change in the required ship rate as a result of a 1% change in the value of the parameter.

In some cases, e.g. the number of sailing days or the sailing regime, it is not possible to quantify the effect of a 1% change, since the parameter can not be changed in 1% increments. These variations are listed last.

Sensitivity analysis case 1:

The effects of changes in the main parameters of the model for case 1, being the transport of 1250 tons of dry bulk from Hengelo to Leverkusen, are presented in Table 6-16 below:

Table 6-16: Sensitivity analysis case 1

Variable changed	Difference with base value (€)	Difference with base value (%)	Effect of 1% change of variable (%)
Crew cost (increased by 10%)	€ 0.30	1.22%	0.12%
Fuel price (increase to 800 €/t)	€ 1.01	4.20%	0.17%
WACC (increase to 10 %)	€ 6.12	25.44%	0.25%
Vessel price (increased by 10%)	€ 1.31	5.42%	0.54%
Depreciation time (20 years for hull, 10 years for rest of ship)	€ 3.10	12.85%	-0.38%
Internalization of external costs	€ 4.59	19.06%	0.19%
Number of working days (increased to 6)	-€ 1.26	-5.24%	-
Full crew cost	€ 1.70	7.08%	-
Sailing regime B at reduced crew cost	€ 4.22	17.57%	-
Sailing regime B at full crew cost	€ 6.39	26.57%	-

From Table 6-16, it becomes clear that all variations except a switch to a "B" sailing regime at full crew cost result in a required ship rate that is within the limits that are proposed by Bureau Voorlichting Binnenvaart. The reason that sailing regime B has such a large negative impact on exploitation may be found in the fact that the ship spends a lot of time loading, unloading or waiting at the quayside. Since the loading and unloading times are prescribed as a number of hours based on a 24-hour workday (see chapter 6.2.2), the number of hours during which the crew is paid while doing nothing is much larger for B-operation than it is for A1-operation. What also becomes apparent is that working 6 days per week does not result in a proportional decrease in required ship rate, due to the same reason: after Saturday 18:00 PM the terminals no longer have to handle the vessel and it, therefore, needs to spend that operational time waiting.

Furthermore, due to the fact that the base case involves sailing at reduced crew costs, which is a common practice, the effect of a 1% change in one of the variables related to capital cost has a much stronger influence than a 1% change in the crew cost. The change from reduced crew cost to full crew cost immediately has a strong impact on the required ship rate.

Sensitivity analysis case 2:
The effects of changes in the main parameters of the model for case 2, being the transport of 1250 tons of dry bulk from Amsterdam to Meppel are presented in Table 6-17 below:

Table 6-17: Sensitivity analysis case 2

Variable changed	Difference with base value (€)	Difference with base value (%)	Effect of 1% change of variable (%)
Crew cost (increased by 10%)	€ 0.60	1.57%	0.16%
Fuel price (increase to 800 €/t)	€ 1.00	2.58%	0.10%
WACC (increase to 10 %)	€ 11.60	29.72%	0.30%
Vessel price (increased by 10%)	€ 2.50	6.37%	0.64%
Depreciation time (20 years for hull, 10 years for rest of ship)	€ 5.90	15.14%	-0.45%
Internalization of external costs	€ 4.70	12.09%	0.12%
Number of working days (increased to 6)	- € 1.30	-3.32%	-
Full crew cost	€ 3.20	8.22%	-
Sailing regime B at reduced crew cost	€ 14.90	38.22%	-
Sailing regime B at full crew cost	€ 19.80	50.77%	-

In case 2, the required ship rate stays within the limits of the actual ship rate as given by Bureau Voorlichting Binnenvaart. The sensitivity study for case 2 reveals similar results as the sensitivity study for case 1, with as the main exception that the negative effects of a B-sailing regime are even larger than before. This is due to the shorter sailing distance, as a result of which the vessel spends even more time in port and the number of unproductive hours during which the crew is still paid increases correspondingly.

Sensitivity analysis case 3:
The effects of changes in the main parameters of the model for case 3, being the transport of 2500 tons of dry bulk from Liege to Nijmegen are presented in Table 6-18 below:

Table 6-18: Sensitivity analysis case 3

Variable changed	Difference with base value (€)	Difference with base value (%)	Effect of 1% change of variable (%)
Crew cost (increased by 10%)	€ 0.18	0.79%	0.08%
Fuel price (increase to 800 €/t)	€ 0.90	4.12%	0.17%
WACC (increase to 10 %)	€ 5.93	26.94%	0.27%
Vessel price (increased by 10%)	€ 1.20	5.44%	0.54%
Depreciation time (20 years for hull, 10 years for rest of ship)	€ 2.88	13.07%	-0.39%
Internalization of external costs	€ 4.07	18.43%	0.18%
Number of working days (increased to 6)	- € 0.78	-3.51%	-
Full crew cost	€ 1.80	8.16%	-
Sailing regime B at reduced crew cost	€ 6.41	29.05%	-
Sailing regime B at full crew cost	€ 8.68	39.40%	-

In case 3, the required ship rate stays well within the limits of the actual ship rate as given by Bureau Voorlichting Binnenvaart for all cases. What becomes apparent from the sensitivity analysis of case 3 is that for a 110 m ship, the effects of changes are still within the same range as for the 86 m ships of case 1 and 2. However, due to the increase in size, the effect of an increase in crew cost on the required ship rate is smaller than for case 1 and 2. Again, due to the short sailing distance, the ship will spend a lot of time in port and as a result, a B-sailing regime results in a large increase in the required ship rate.

Sensitivity analysis case 4:
The effects of changes in the main parameters of the model for case 4, being the transport of 350 tons of dry bulk from Reims to Den Bosch are presented in Table 6-19 below:

Table 6-19: Sensitivity analysis case 4

Variable changed	Difference with base value (€)	Difference with base value (%)	Effect of 1% change of variable (%)
Crew cost (increased by 10%)	€ 0.80	1.99%	0.20%
Fuel price (increase to 800 €/t)	€ 1.24	3.17%	0.13%
WACC (increase to 10 %)	€ 9.58	24.19%	0.24%
Vessel price (increased by 10%)	€ 2.14	5.44%	0.54%
Depreciation time (20 years for hull, 10 years for rest of ship)	€ 5.49	13.86%	-0.42%
Internalization of external costs	€ 5.89	14.86%	0.14%
Number of working days (increased to 6)	- € 3.63	-9.15%	-
Full crew cost	€ 6.24	15.76%	-
Sailing regime B at reduced crew cost	€ 13.18	33.34%	-
Sailing regime B at full crew cost	€ 18.49	46.75%	-

In case 4, the required ship rate stays within the limits of the actual ship rate as given by Bureau Voorlichting Binnenvaart for all cases, while similar effects occur as in the previous three cases. Here it is noteworthy that the impact of crew cost is relatively large due to the small capacity of the vessel. What is also a significant difference is the effect of a switch from reduced crew cost to full crew cost: due to the fact that the ship is operated by two people, the effect of using a husband-wife team that work at a reduced income leads to a large cost reduction compared to a fully paid crew and as a result, it has a strong positive effect on the required ship rate.

From the required ship rates that were calculated in the four cases, it can be concluded that the model provides good results for all of the investigated routes and ship sizes and, as a result, the model in general is considered to lead to reliable results. Furthermore, none of the variations that were made in the sensitivity analysis shows any extreme or unexpected sensitivity in the model and it is, therefore, considered sufficiently stable.

6.4 Synthesis

The purpose of this chapter was to develop a model that can be used to determine which of the ships from the ship design datasets from chapter 5 can perform transport at the lowest cost. It was concluded that in order to allow a transport operator to select the optimal ship dimensions for a given transport chain, it is necessary to determine what the required ship rate of a ship is per unit of transported cargo between a given origin and destination. It is however also necessary to be able to judge the impact of ship rate, shipment size and delivery interval on the total logistical cost of his customer, i.e. the shipper. Furthermore, it was considered useful to be able to judge the effects of internalizing external costs on the required ship rate.

The model that is developed in this chapter includes separate sub-models which determine the required ship rate, the cost of handling, pre haulage and end haulage, external costs and the other elements in the total logistical cost. This makes it possible to reach the goal of this thesis, i.e. the identification of the optimal ship dimensions as a function of the characteristics of a specific logistics chain and route. Furthermore, the model allows for comparison of waterborne transport with road and rail transport.

Validation of the model is done through a comparison of calculated required ship rates with actual ship rates. This validation is complicated by the fact that actual ship rates depend on the supply and demand for transport while the required ship rate is only a function of the cost of the transport operator. However, since it is known that in practice transport operators cannot cover all their costs when ship rates are low and that they make a good profit when ship rates are high, it can be concluded that the required ship rate should lie somewhere between the lower and upper bound of the actual ship rates. Since the model validation shows that this is the case, the model is considered to provide reliable results.

To determine whether the results that are provided by the model are stable, a sensitivity analysis is performed in which the effect that a 1% change in a cost parameter has on the total calculated required ship rate is investigated. As a second sensitivity analysis, the main cost parameters are increased by larger amounts, like in practice (e.g. a 10% rise in price of the ship, increase of fuel price from 700 to 800 Euro, …). Since none of the variations that are reviewed in the sensitivity analysis shows any extreme or unexpected sensitivity in the model, it is considered sufficiently stable for use in the remainder of this thesis.

In the next chapter, the model will be used to demonstrate which ship dimensions may be considered optimal for a number of specific transport chains and it will be quantified how large the benefits of using an optimal ship in stead of a standard ship are for these cases.

7 The optimal main dimensions of inland ships

In the previous chapters all the data and methods that are required to assess the cost of operating an inland ship of given dimensions as well as the total logistical cost that a shipper incurs through the use of that ship have been created. As a result, it is now possible to assess the performance of inland ships with various main dimensions in a number of transport scenarios. This in turn makes it possible to achieve the main research goal of this thesis, i.e. to assess which length, beam and draught of an inland ship lead to the best competitive position for a captain-owner.

The chapter starts with a generic review of how the main dimensions of an inland ship impact its building and running cost in sub-chapter 7.1. In sub-chapter 7.2 the various transport scenarios that are assessed are described. In sub-chapter 7.3 to 7.6, it is assessed what the optimal ship dimensions are for the four previously defined assessment criteria: required ship rate, required ship rate with internalization of external costs, total logistical cost and total logistical cost with internalization of external costs. As a summary of the results of these sub-chapters, in sub-chapter 7.7 flowcharts are provided with which the optimal ship dimensions can be determined as a function of ship type, route, water depth and assessment criterion. In sub-chapter 7.8, it is assessed which ships are likely to be able to compete with road and rail transport from an out-of-pocket transport cost point of view and from an external costs point of view.

In order to verify that the optimal ship dimensions as discussed in chapter 7.3 to 7.6 are stable optimums that do not change significantly when the main cost parameters of the ships are changed, several cost variations are assessed for each transport scenario. In appendix F, the optimal ship dimensions for each of these variations are shown and in sub-chapter 7.9 the effect that these changes have on the required ship rate of all analyzed ships are discussed. Finally, in sub-chapter 7.10, a number of qualitative considerations are discussed that may lead to the choice for main dimensions that deviate from those that were identified as 'optimal' in sub-chapter 7.3 to 7.6. Finally, in sub-chapter 7.11, the chapter is synthesized.

All monetary values mentioned in this chapter are 2011 values.

7.1 Generic review of the impact of ship main dimensions on building and running cost

Before assessing the performance of ships as a function of the logistics chain in which they operate, first the impact that a ship's main dimensions have on its building cost, distance cost, time cost and the amount of time that is spent in port are reviewed in a generic way. The relationship between main dimensions and building cost is discussed in paragraph 7.1.1, the relationship between ship dimensions and distance cost is explored in paragraph 7.1.2 and the relationship between ship dimensions and time cost is presented in paragraph 7.1.3. The relationship between cargo carrying capacity and port times is evaluated in chapter 7.1.4.

7.1.1 Building cost

In chapter 5, the relationship between building cost and deadweight for various vessel types was already elaborated. For completeness, the relevant figures are iterated below. They indicate that in general building cost per ton deadweight decreases as vessel size increases, with the notable exception of long, low draught vessels, which are relatively heavy and as a result have a relatively high building cost per ton deadweight. Figure 7-1 shows values for dry bulk vessels, while Figure 7-2 shows values for tank vessels. Container vessels are not discussed separately here since they are very similar to dry bulk vessels.

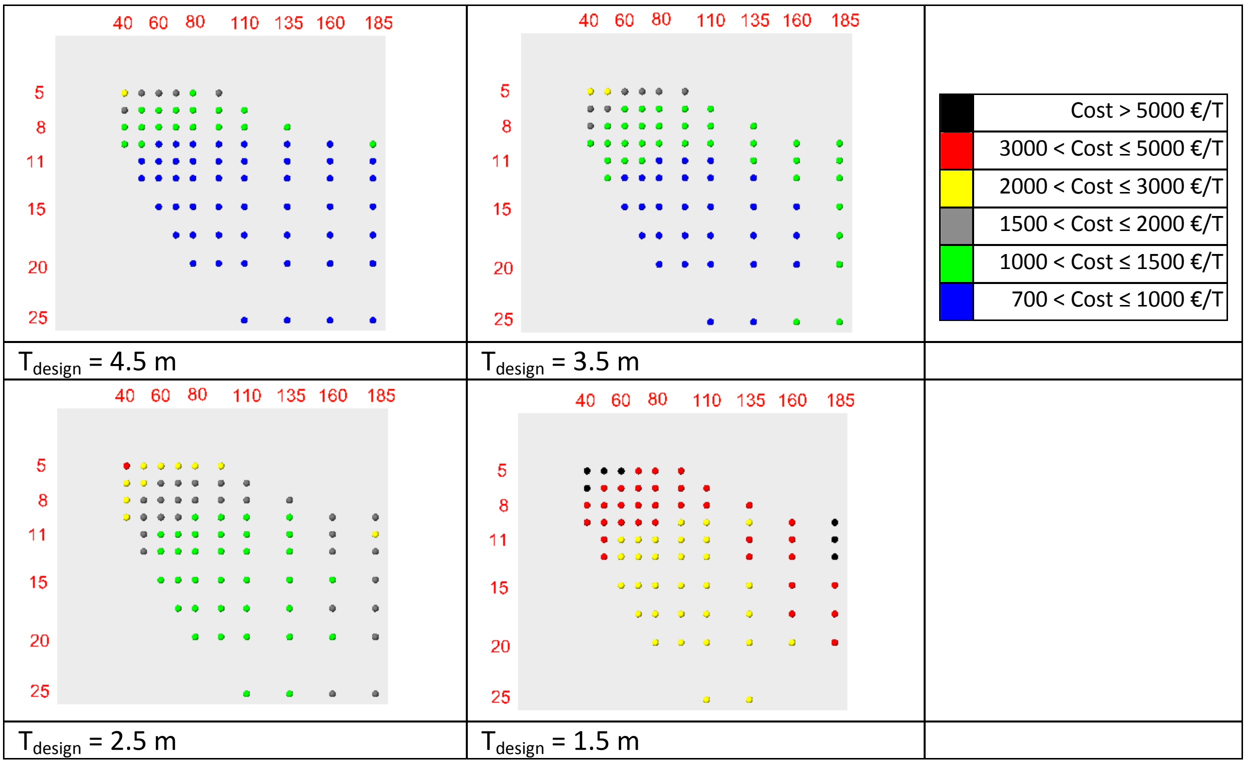


Figure 7-1: Building cost of dry bulk vessels per ton cargo carrying capacity vs. L, B and T_{design}

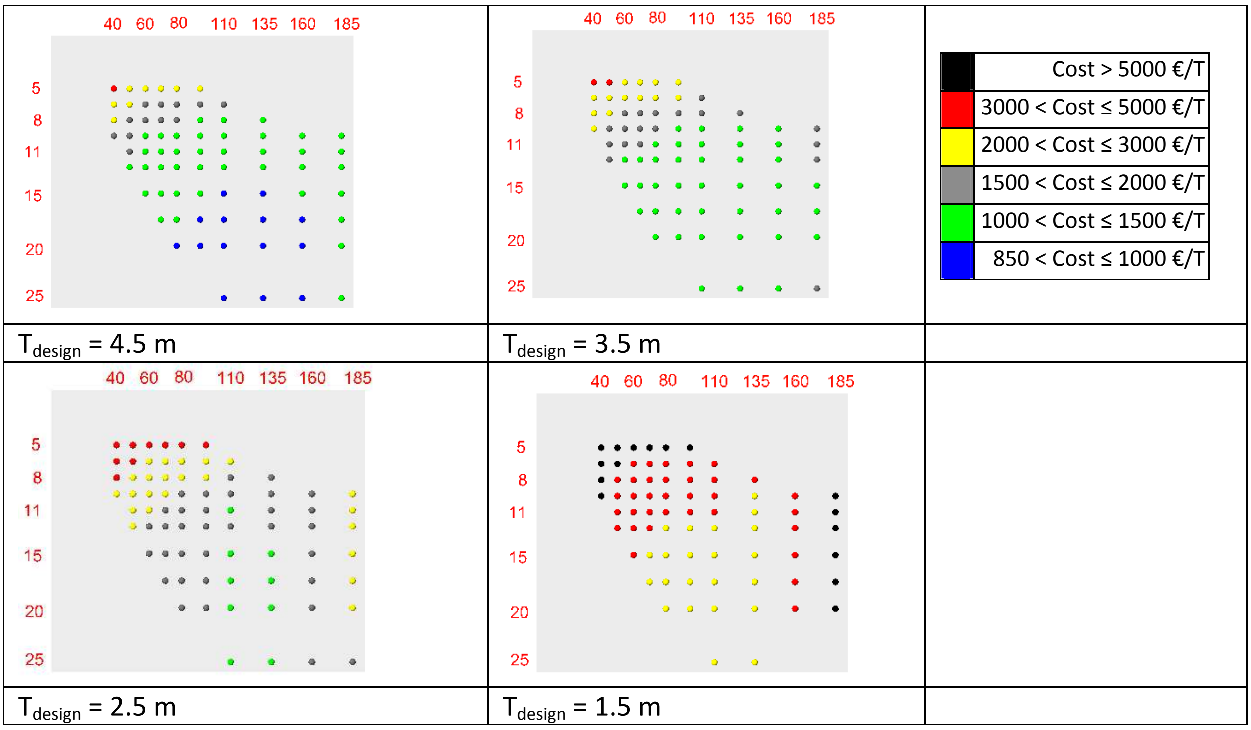


Figure 7-2: Building cost of tank vessels per ton cargo carrying capacity vs. L, B and T_{design}

7.1.2 Distance costs

Distance costs of a vessel, i.e. the costs that are incurred as a result of actually sailing, consist of fuel cost and of variable maintenance costs. Of these two, fuel cost is by far the most significant one, as is also shown in the cost breakdown by Beelen [2011] in appendix A. As a result, it is worthwhile to review how fuel consumption per tonkilometer of transport performance develops as a function of vessel dimensions and water depth, assuming that the vessel is running at the design speed and is loaded to its design draught or the draught at which it has a keel clearance of 50 cm in case this results in a smaller draught. This analysis is discussed below.

When sailing in water that is deep enough for all vessels, i.e. 5 m water depth, it is shown in Figure 7-3 that fuel consumption per tonkm of transport performance in fully loaded condition is more or less constant for the majority of ships with a design draught of 2.5 m and larger, while for ships with a design draught of 1.5 m it is considerably higher due to the fact that large ships can still carry only a small amount of cargo. It also becomes clear that scale effects with regard to fuel consumption are limited for vessels with a beam of 9.5 m and wider. Furthermore, the figure reveals that the relative fuel consumption is not only dependent on vessel dimensions but shows some fluctuation. This is among others due to the choice of type and number of propellers, as a result of which the achieved efficiency of the drive trains is not exactly equal for all ships.

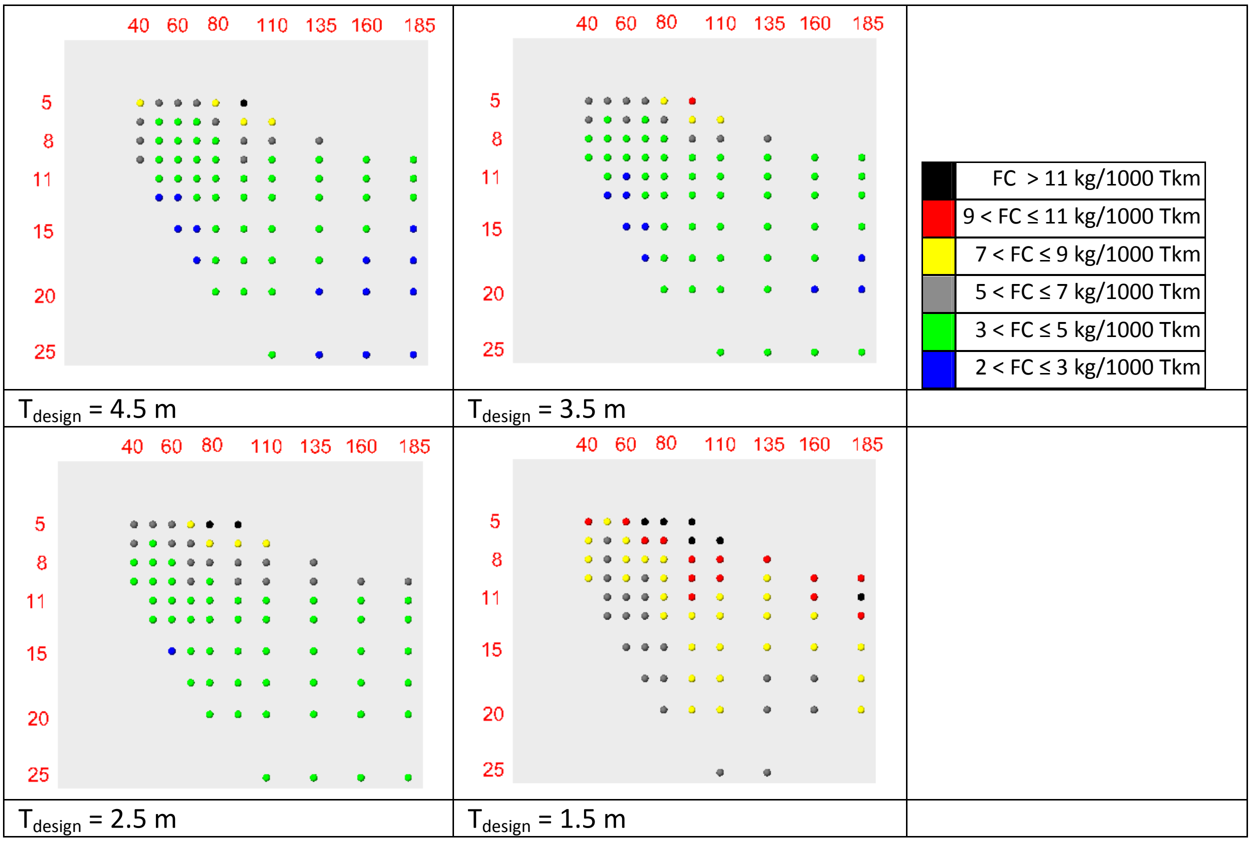


Figure 7-3: Fuel consumption in deep water

As a comparison with these figures, a fully loaded 27 T truck, consuming 3 liters of diesel per kilometer, consumes roughly 10.5 kg of fuel per 1000 tonkilometers of transport performance. This brings fuel consumption of trucks in the same range as that of the smallest ships as well as of quite a few of the low draught ships. An interesting effect that can be observed is that the vessels of 80 to 110 m in length consume more fuel per tonkilometer than their shorter and longer counterparts with identical beam and draught. The cause for this is found in two elements: The first is that power increases less than linear with displacement at a given speed, as a result of which the fuel consumption of larger ships is relatively low. However, the shorter ships have a lower design speed and since fuel consumption is roughly proportional to the square power of speed, their fuel consumption is also relatively low. The transition between these two effects occurs in the 80-110 m length region.

To show the effects of water depth on fuel consumption, Figure 7-3 is iterated below for a water depth of only 2 m. From Figure 7-4, the potential drawbacks of ships with a high design draught become apparent: due to the fact that vessels can only be loaded to a draught of 1.5 m, the scale advantage of the deep draught vessels is negated. Their high design draught and matching ship depth result in higher lightweight, which in turn reduces their cargo carrying capacity at low draughts and thereby increases fuel consumption per tonkilometer of transport performance. What also becomes apparent is that for most vessels, the advantages in terms of fuel consumption that they had over trucks is negated at very low water depths (note the different scales of Figure 7-3 and Figure 7-4).

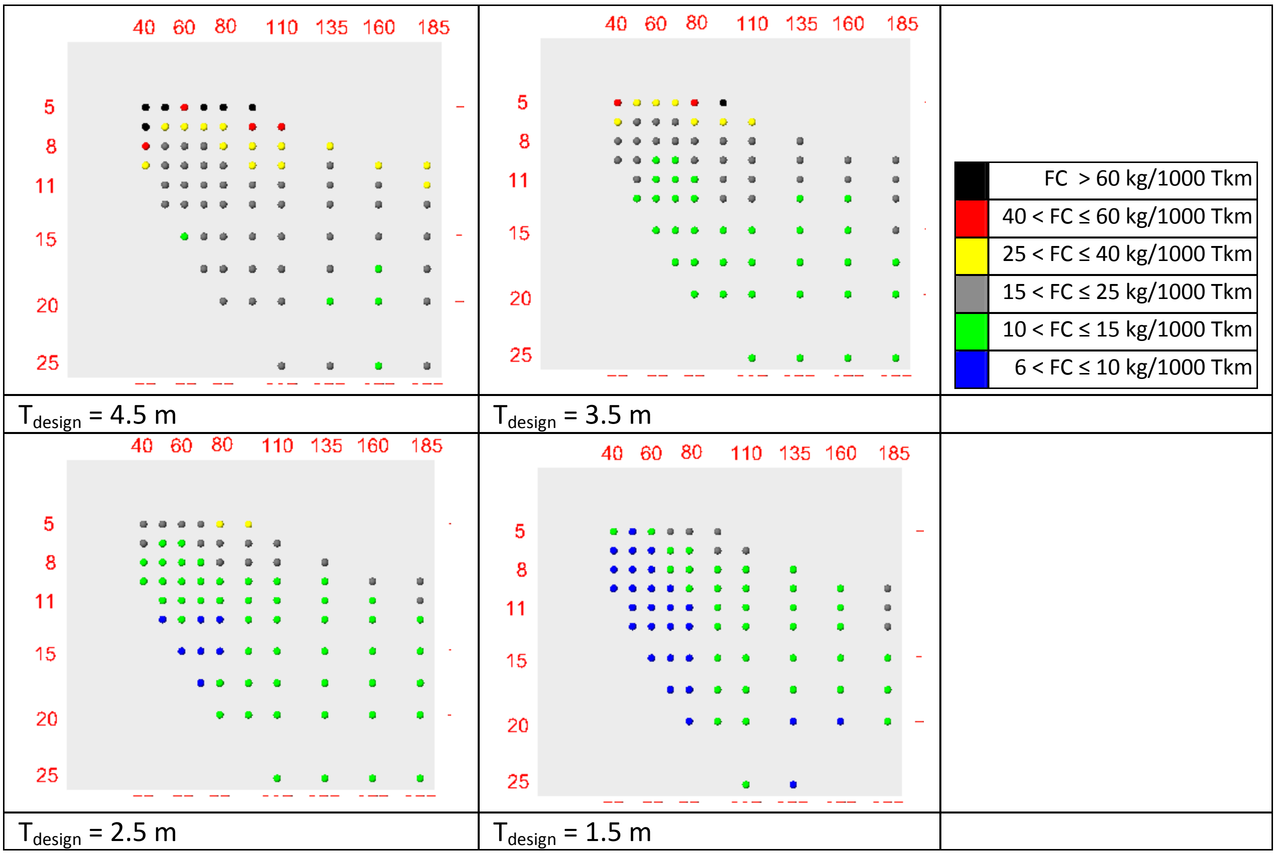


Figure 7-4: Fuel consumption in 2.0 m water depth

Since water depth so clearly has an impact on the fuel consumption of the ships, an intermediate water depth of 3 m is also reviewed. From Figure 7-5, it becomes clear that the 3.5 and 2.5 m draught vessels perform better than their high and low draught counterparts, which underlines the importance of matching design draught and water depth.

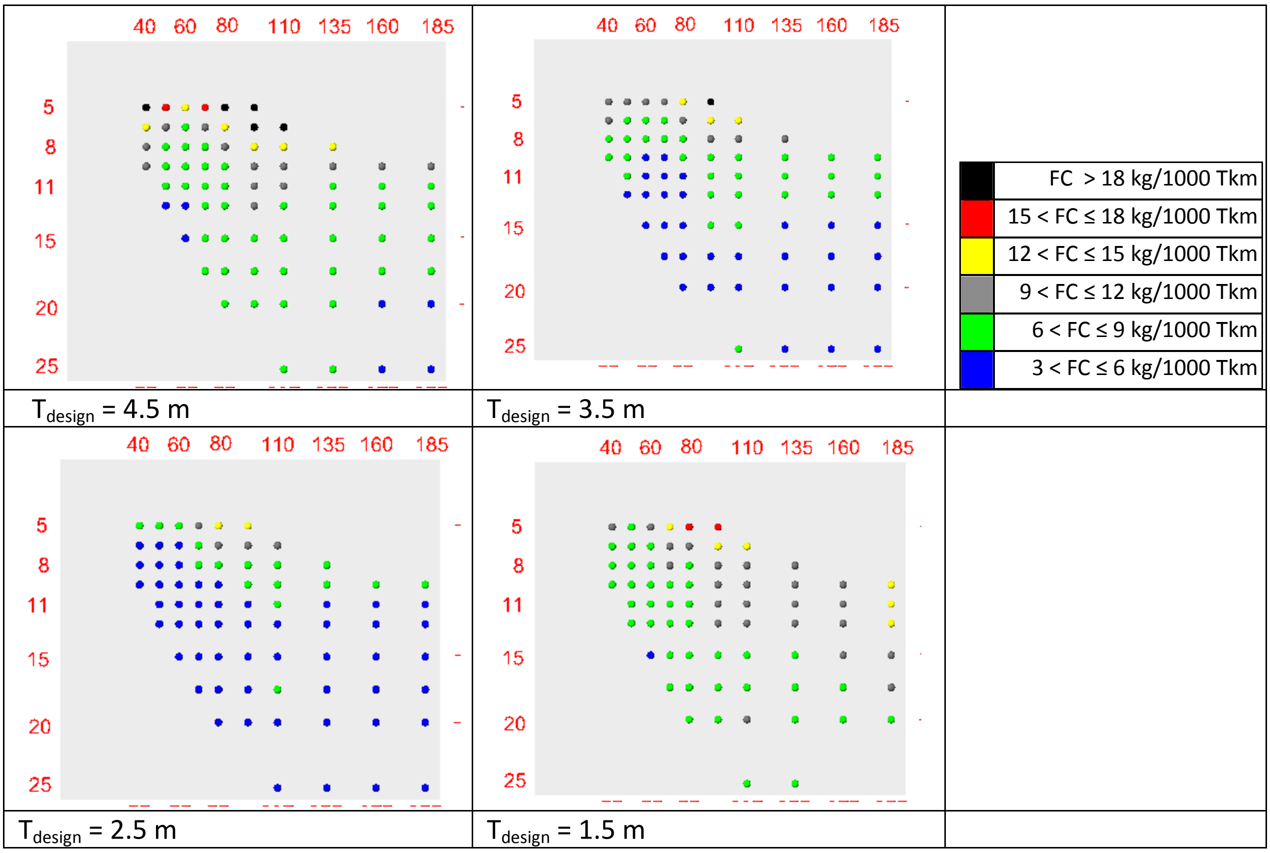


Figure 7-5: Fuel consumption at 3.0 m water depth

7.1.3 Time costs

Time costs are costs that are due to the passing of time and as such accumulate even if a vehicle is standing still [Blauwens et al., 2010, p. 99]. The time costs of inland ships consist mainly of the capital cost of the ship and the crew cost. Since the annual capital costs are fixed, the number of operational hours of the ship determines the capital cost per hour. The sailing regime (14, 18 or 24 hours per day), number of operational days per week and number of operational weeks per year determine the required number of crew members and their annual cost. In the following paragraphs, it is reviewed how these elements impact the cost per hour per ton of cargo carrying capacity for ships with various dimensions and sailing regimes.

Crew cost

The cost of crewing a ship depends on a large number of factors: the size and composition of the crew is dependent on vessel length and on sailing regime, [Central Commission for Navigation on the Rhine, 2007], while their wages depend on the number of hours they work, whether or not they receive irregularity allowances for working at night and on weekdays, the amount of overtime they put in, the nationality under which their company operates, their age and so on. Since there is currently (i.e. in 2011) no binding collective workers' agreement for the whole sector, there is little guidance regarding these issues. On top of the wages, the employers' cost needs to be paid. Furthermore, especially the single ship owner-operators of small ships often artificially lower wages by paying themselves and/or their partner a lower wage than they would pay employees [Beelen, 2011, p. 111].

In order to arrive at realistic estimates for labor costs, 4 scenarios are investigated:

- sailing regime A1 at full crew cost.
- sailing regime A1 at reduced crew cost.
- sailing regime B at full crew cost.
- sailing regime B at reduced crew cost.

In sailing regime A1 (day sailing), the ship is in operation 14 hours per day. This way of operating inland ships is common on short trips that can be completed in less than a day, allowing the crew to rest during times of waiting or during loading and unloading operations (during the latter only 1 crewmember needs to be on duty). This way, if the ship sails 5 days per week, it can be run by a single crew with a few temporary replacements during the vacation of a crewmember.

In sailing regime B (continuous service), the ship is in operation 24 hours per day, which is common on longer routes. The common way of manning ships with this sailing regime is by rotation of two crews, each of which spends X weeks on board and then has X weeks off (also known as system sailing). As a result, the ship is run by 2 crews and it can operate 7 days per week.

Within each regime, labor cost can still differ substantially, depending on whether the entire crew is paid normal wages or whether a captain-owner and his family members work on board at reduced wages. Labor costs may be as low as € 30.000 annually for a combined husband-wife crew, while no employers' cost like social security and holiday pay are incurred. As a result of this, labor costs may be reduced dramatically, especially for small ships in A1 operation.

As a result of the above, the scenarios under investigation are:

- A1 sailing, 5 days per week, 50 weeks per year (3500 operational hours annually)
  - With full crew cost.
  - With the cost of the first two crew members reduced to € 30.000,- annually.

- B sailing, 7 days per week, 50 weeks per year (8400 operational hours annually)
  - With full crew cost.
  - With the cost of the first two crew members reduced to € 30.000,- annually.

These scenarios result in crew costs as shown in Table 7-1. All values are 2011 values. In order to arrive at these values, the mandatory crew composition for Rhine navigation [Central Commission for Navigation on the Rhine, 2007] is used, together with wages according to the non-official collective workers' agreement for the Dutch inland shipping sector and Dutch rules for employers' cost.

Table 7-1: Annual crew cost

	A1		B	
Vessel length	Full cost	Reduced cost	Full cost	Reduced cost
L ≤ 70 m	€ 61197,-	€ 34533,-	€ 265366,-	€ 225977,-
70 m < L ≤ 86 m	€ 75036,-	€ 47660,-	€ 286784,-	€ 238705,-
L > 86 m	€ 91848,-	€ 48906,-	€ 377475,-	€ 311775,-

Table 7-2: Crew cost per operating hour

	A1		B	
Vessel length	Full cost	Reduced cost	Full cost	Reduced cost
L ≤ 70 m	€ 17.48	€ 9.87	€ 31.59	€ 26.90
70 m < L ≤ 86 m	€ 21.44	€ 13.62	€ 34.14	€ 28.42
L > 86 m	€ 26.24	€ 13.97	€ 44.94	€ 37.12

The stepwise increase in crew cost when certain length limits are exceeded that is shown in Table 7-1 and Table 7-2 has a significant impact on the scale advantages of inland ships. This impact is shown in Figure 7-6 below for a ship with a beam of 11.45 m and a design draught of 3.5 m. It shows that when lengths of 70 and 86 meters are exceeded, there is a jump in crew cost due to an additional required crew member.

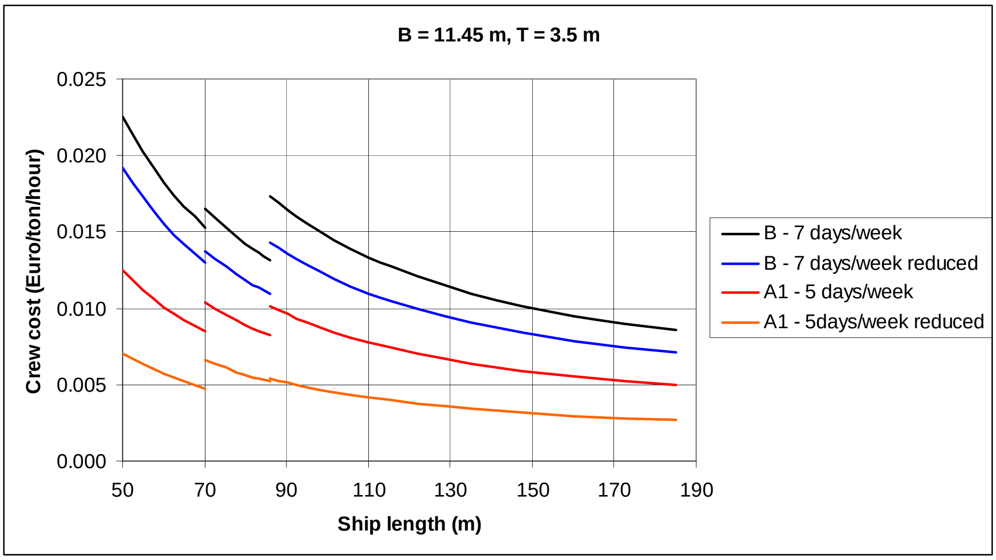


Figure 7-6: Crew cost as a function of ship length

<u>Capital costs</u>

The other main time cost elements that are directly related to the ship are capital costs: insurance, depreciation of the hull, depreciation of all equipment, machinery & outfitting and the cost of capital. Figure 7-7 shows these cost components at a weighted average cost of capital of 5%, hull depreciation time of 30 years, depreciation time of the rest of the ship ("other") of 15 years and sailing regime B. From this figure, a clear minimum can be observed at roughly 120 meters in length with regards to the depreciation cost of the hull insurance and required EBIT (i.e. required EBITDA minus depreciation, which is shown separately). Although the relative cost of equipment, machinery and outfitting keeps decreasing with increasing ship size, the cost of the hull reaches a minimum and then increases, due to a heavier structure that leads to higher absolute building costs as well as a relative decrease in carrying capacity.

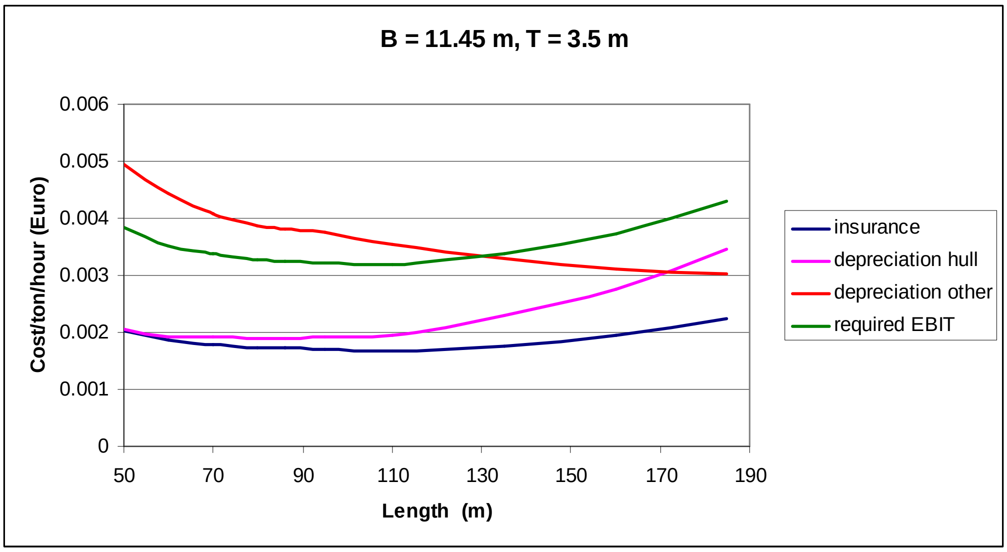


Figure 7-7: Capital cost per ton of cargo carrying capacity per hour as a function of length

When crew cost and capital cost are summed, like in Figure 7-8 below, two important conclusions can be drawn:

1) When the ships operates relatively few hours per year, the capital costs outweigh the crew cost to such an extent that a minimum time cost level occurs at a length that is close to the length at which the capital-related costs are lowest, i.e. in the case of Figure 7-8 at a length of roughly 130 meters.

2) When the ship operates many hours per year, crew cost outweighs capital-related costs and a minimum value for time cost is found at the upper end of the length range of investigated ships, i.e. in case of Figure 7-8 at a length of roughly 160 meters.

Apart from these two main conclusions, it becomes clear that due to the increase in the required number of crew members, there are negative scale effects for vessels that have dimensions that are just above the length at which more crew is required; at lengths of 70 and 86 meters, a slightly bigger ship suddenly becomes more expensive.

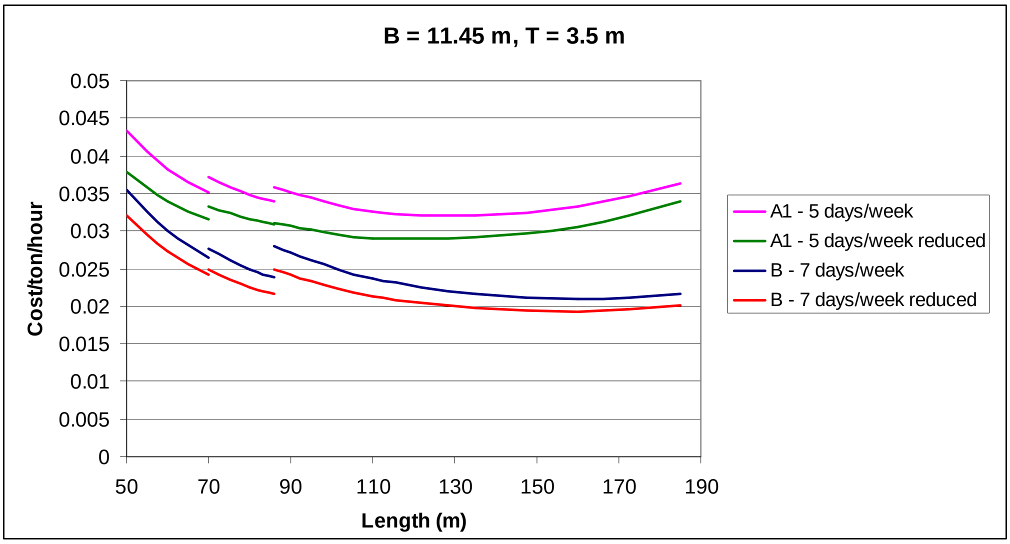


Figure 7-8: Time cost per hour as a function of length

7.1.4 The impact of time spent in port

The time costs as expressed in the previous paragraph are all based on the cargo carrying capacity of the ship, not on tons of cargo transported. In order to arrive at the actual cost per transported ton of cargo over a given period, it is also necessary to determine the actual amount of cargo that is transported. This amount is not only dependent on the level of utilization of the vessel but also on the time it spends in port, i.e. the time it can not actually transport any goods. This time spent in port will depend on the waiting time, the time required to load and unload the cargo and on the time spent sailing from terminal to terminal within a port (e.g. in case of collection and delivery of containers at multiple terminals in a major port).

To demonstrate the effect, a simple example is provided: Assume that a ship sails from Rotterdam to Duisburg (247 km), fully loaded both ways. It sails upstream at a speed of 15 km/h and downstream at a speed of 21 km/h. For argument's sake, the ship does not have to wait at a terminal and is handled as soon as it comes in.

Figure 7-9 shows how the percentage of a ship's operational time that is actually productive, i.e. spent sailing, changes as a function of handling speed and cargo weight.

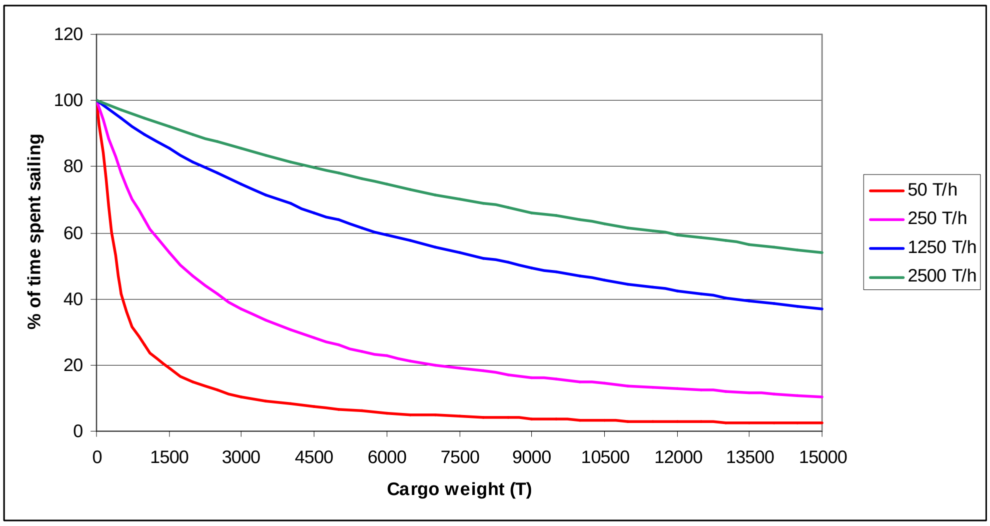


Figure 7-9: Effect of handling speed on percentage of time spent sailing

From Figure 7-9 above, it can be concluded that at low handling speeds, large vessels spend a (very) large part of their time at the quayside. Since the time cost of the vessel as described earlier will not change, the required ship rate per traveled kilometer will rise strongly for these vessels. As a result of these long waiting times and resulting low percentage of time that large ships actually spend sailing, they are unlikely to achieve economies of scale over much smaller ships which spend less time at the quayside.

Similar effects occur at a given handling speed (taken at 250 T/hour in Figure 7-10 below) when the distance between origin and destination changes: The longer the distance, the longer the ship can spend in port to maintain a given percentage of effective sailing time.

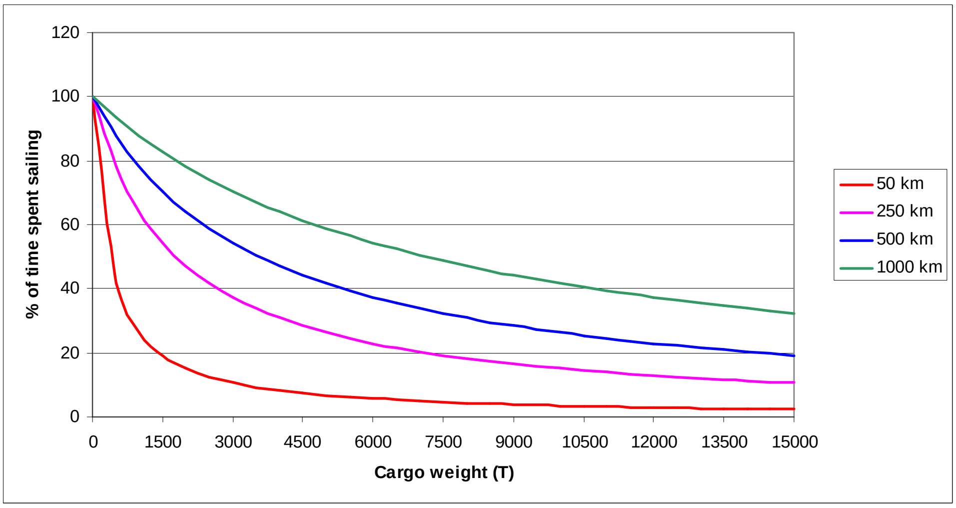


Figure 7-10: Effect of sailing distance on percentage of time spent sailing

The relationships as discussed above are roughly valid for containers, where vessels are given a time slot in which they can be loaded and unloaded. However, for bulk cargoes, the amount of time that a terminal can take to unload a ship is prescribed by law [Staatsblad, 2011].

When using these prescribed values to determine the amount of time that the ship spends at the quayside for loading & unloading and assuming that the vessel is either loaded or unloaded at a terminal, it can be seen in Figure 7-11 that the effect of sailing distance on the percentage of time that is spent sailing is much reduced due to the prescribed 1-day waiting time for all ships and the less-than-linear increase in time spent at the quayside per ton of increase of cargo capacity. As a result of this, the productivity reduction of large vessels compared to smaller vessels is much smaller than in case of the previously assumed constant handling speed and no waiting times.

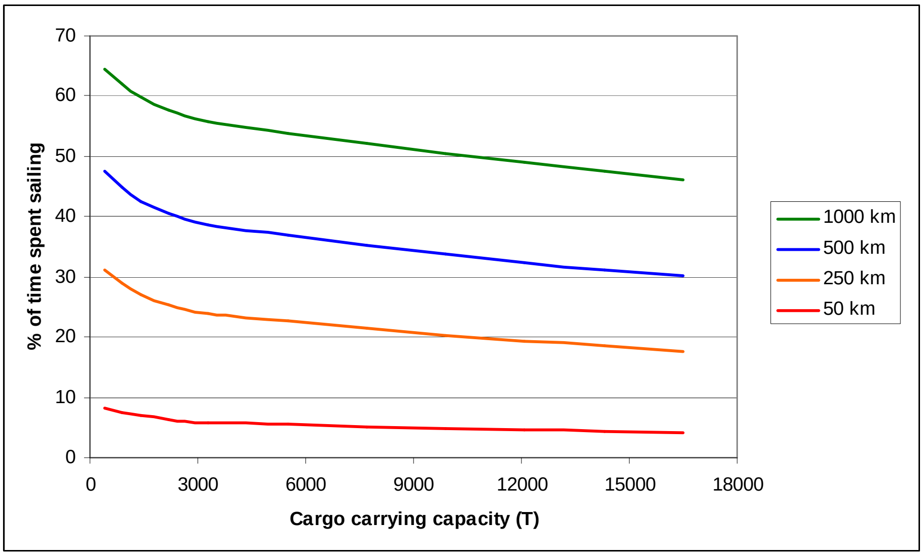


Figure 7-11: Effect of sailing distance on percentage of time spent sailing - corrected handling speed

7.2 Description of case studies

In the previous paragraph the time costs, distance costs and the factors that impact the productivity of inland ships have been treated in a generic way. It has been discussed that the required ship rate depends on the balance between time costs, distance costs and the time that a ship can be productive (i.e. actually sail). It has already been shown that the minimal capital cost per ton of deadweight is not found at maximum or minimum ship dimensions, but is somewhere inside the range of explored dimensions. It has also been shown that crew cost per ton deadweight decreases with increasing beam as well as with increasing length, with the exception of the points where lengths of 70 and 86 m are exceeded. These are the lengths at which the number of crew members needs to be increased and the resulting crew cost rises.

Regarding the time during which the vessel can be productive, chapter 7.1.4 has shown that time that is spent at the quayside increases as the amount of cargo that is carried increases. However, it has also been shown that for dry bulk and tank vessels, this increase is less than proportional to the amount of cargo that is carried. The impact of fuel consumption on the total cost of the vessel is not so easily judged, since it is the result of water levels, installed power, speed and design draught. Furthermore there are additional costs due to internalization of external costs, stock-in-transit and cycle stock, which might make a different ship than the one which can sail at the lowest ship rate the one that results in the lowest total logistical cost.

As a result of all these variables, which ship dimensions are optimal can only be determined if the assessment criteria, logistics chain characteristics and route are known. Here, it is important to realize that the main dimensions of a ship are not variables that a transport operator can change for every trip that a ship makes, but they are constants from the moment at which the ship is purchased until the moment it is sold or scrapped. In practice this means that a ship will usually transport goods for multiple shippers, will be used on a number of different routes and will encounter different water depths on these routes, since especially on the free-flowing rivers, water levels fluctuate over time.

This implies that the transport operator needs to make an assessment of the routes on which the ship will be used before he can identify the ship dimensions with which he can operate at the lowest required ship rate. This assessment should be based on the expected demand for transport and the physical limitations of the waterways, as well as on the expected water depths. Furthermore, since a ship's competitiveness is not only determined by the ship rate that it charges, but is in the end determined by the extent to which it can realize the lowest total logistical cost for a shipper, it is necessary to determine a typical commodity that will be transported as well as a typical annual demand for that commodity by the shipper. Only in this way can an assessment of the impact of ship dimensions on especially the cycle stock cost be made.

In order to create insight into the effect that the abovementioned variables have on the optimal ship dimensions, and thereby to assist a transport operator in his decision making process, a number of typical scenarios have been elaborated where sailing distance, water depth, transported commodity and annual demand by a single shipper are varied.

In chapter 7.2.1 the scenarios for the various routes along which the ship will sail are elaborated and in chapter 7.2.2 various scenarios for the logistics chain in which the ship operates are discussed.

7.2.1 Route scenarios

All route scenarios are defined around the busiest inland shipping route in Europe, the Rhine from and to Rotterdam. In all route scenarios, vessels sail fully loaded from the Dintelhaven port basin in Rotterdam and return there empty. This implies that they sail at an average utilization of 50%, which is a common value in the sector [NEA, 2004]. From Rotterdam, the vessel sails to one of four destinations per case in order to establish the effect of different sailing distances. These destinations are: Koblenz (430 km), Duisburg (247 km), Nijmegen (136 km) and Dordrecht (45 km).

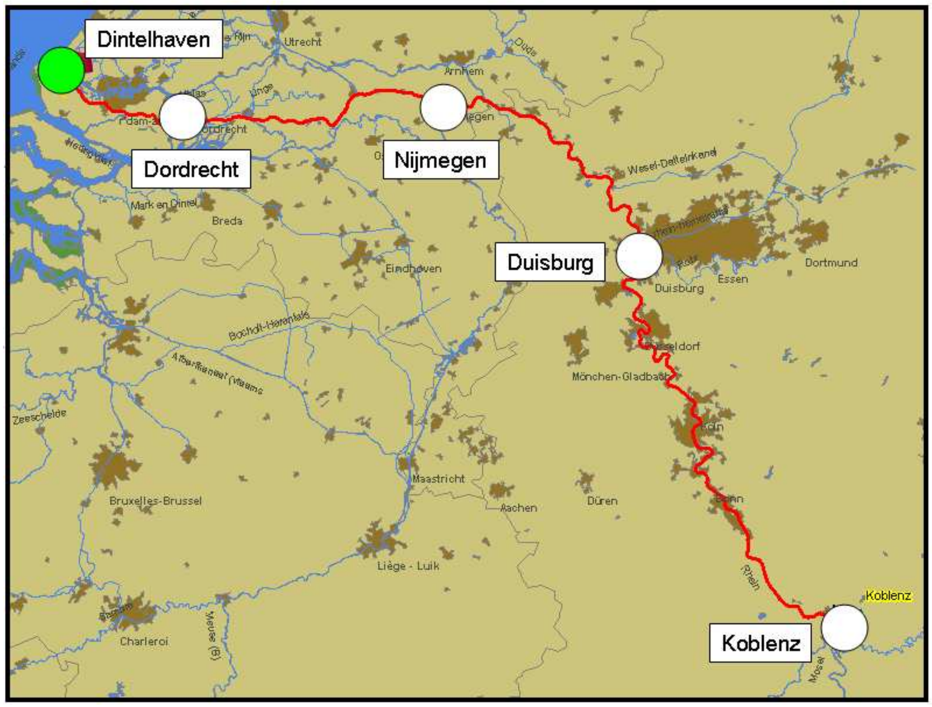


Figure 7-12: Origin and destinations of the route scenarios

The abovementioned ports are located on the Rhine, as a result of which the entire range of vessels in the generated dataset of ship designs can sail to each location. The ports are selected on the basis of their distance from the starting point rather than on the basis of a specific goods flow between Rotterdam and that port: e.g. Dordrecht is representative for ports that are positioned close to the point of origin while Koblenz represents a distance that is close to the longest distance that the largest ships can sail from the seaports in the Netherlands and Belgium. In the same way, the Dintelhaven port basin is representative of a number of terminals in the port of Rotterdam that are located in close vicinity of each other and handle various kinds of goods.

In order to establish the effects of water depth on the cost of operating each ship, the following vessel draughts are explored by setting the water depth of the waterway to a value that is equal to those draughts plus 50 cm under keel clearance:

T_{max}1) 4.5 m.
T_{max}2) minimum agreed water level: 2.8 m between Rotterdam and Duisburg, 2.5 m between Duisburg and Koblenz [Central commission for Navigation on the Rhine, 2011b].
T_{max}3) 1.75 m.

In a similar way as with the selection of the ports, the selected draughts are not chosen because they represent the 'normal' water levels on the selected route, but they are selected because they allow exploration of a scenario where all vessel designs can be loaded to their design draught, a scenario with a water depth at which ships should be able to sail the vast majority of days in a year and a very shallow water scenario.

These twelve combinations of water depth and sailing route are assessed for each of the three ship types that have been discussed before: dry bulk, container and tank vessels.

Throughout these 36 scenarios, a number of things have been kept constant or are explored in more depth for a given route:

- In all cases, the ship sails fully loaded in the upstream direction and returns empty. This reflects an average utilization of 50% that is common for most ship types. [NEA, 2004]
- In all cases, the current velocity is ±3 km/h.
- For the long distances (i.e. Rotterdam - Duisburg and Rotterdam – Koblenz), sailing regime B, 24/7 operation, is explored in most detail while for short distances (Rotterdam – Dordrecht and Rotterdam - Nijmegen) sailing regime A1 (14 hours per day) during 5 days per week is explored in most detail. This is done because the long waiting times in ports make B-type operation significantly more expensive than A1-type operations for short distances, while long distances complicate A1-type operations due to the need to find intermediate stopping places for the night.
- In all scenarios, reduced crewing cost (i.e. paying the captain-owner and his partner €30.000,- per year instead of the full wages), a fuel cost of 700 €/T and a depreciation period of 30 years for the hull and 15 years for the rest of the ship are taken as the base case.

Finally, as a sensitivity analysis, several cost elements of the ship are varied within each scenario for the first assessment criterion, lowest required ship rate. These cost elements are:

1) Crew cost (full or reduced)
2) Fuel cost (400, 700 and 1000 €/T)
3) Depreciation time (30 or 20 years for hull, 15 or 10 years for other elements)

7.2.2 Logistics chain scenarios

The route scenarios that were discussed in chapter 7.2.1 allow determination of the ship dimensions that result in the lowest required ship rate. However, they do not yet allow determination of which ship dimensions are optimal in the context of a given logistics chain. Therefore, the results from the route scenarios are assessed with regard to a number of logistics chain related assessment criteria:

1) Lowest required ship rate.
This assessment criterion is relevant in case a transport operator has no knowledge of the typical logistics chain in which his ship will operate throughout its life. If he does not know which cargo he is going to transport and/or does not know what the typical annual demand is of the shipper(s) that will hire him, he can only attempt to optimize his vessel by choosing the main dimensions such that his required ship rate is as low as possible. This is typical for tramp shipping and container shipping. In case of tramp shipping, the ship may operate for a different shipper from trip to trip and in case of container shipping, the ship even serves multiple shippers in a single trip.

2) Lowest required ship rate when external emission costs are internalized
This assessment criterion is identical to the previous criterion apart from the internalization of external cost. Therefore, this criterion is relevant for transport operators who do not know which cargo they will transport for whom but do expect that external emission costs will need to be internalized in the near future.

3) Lowest total logistical cost
In case a transport operator knows what the typical cargo is that he will be transporting in the foreseeable future and knows for whom he will be transporting this cargo, it becomes possible to optimize his ship in such a way that it results in the lowest logistical cost for the shipper. In this scenario, it is investigated what the optimal ship dimensions are when coal (55 €/T), iron ore (106 €/T) or gasoil (700 €/T) are transported for a single shipper with annual demands of 10.000, 25.000, 50.000 and 100.000 tons. These three cargo types represent low, medium and high value commodities. Containers are not included in this analysis, since container ships will never transport cargo for a single shipper for an extended period of time.

4) Lowest total logistical cost, including internalization of external emission costs
This assessment criterion is identical to criterion 3, apart from the internalization of external emission cost. Therefore, it is a relevant criterion for transport operators who know what they will be transporting for whom and expect that external emission cost will need to be internalized in the near future.

Paragraphs 7.3 to 7.6 each assess all route scenarios for one of the four abovementioned logistics chain scenarios.

7.3 Identification of optimal dimensions - lowest required ship rate

In this paragraph, the results for each of the 36 route scenarios and the variations in crew cost, fuel cost and depreciation time are discussed and it is concluded which ship can operate at the lowest required ship rate in each of the cases. In paragraph 7.3.1, the way in which results are presented is elaborated, while the results for dry bulk ships are discussed in paragraph 7.3.2 , results for container ships are treated in paragraph 7.3.3 and results for tank ships shown in paragraph 7.3.4.

7.3.1 Presentation of results

Based on the scenarios that were discussed above, it can be calculated for many different cases which ship dimensions result in the lowest required ship rate. Since this leads to large amounts of data, the results for all of these cases are shown in appendix F while the most important ones are discussed in this the body text of the thesis. As a typical example case, the scenarios for transport of dry bulk from Rotterdam to Duisburg at a maximum draught of 2.8 m are discussed in full detail once.

Table 7-4 shows the base case where the ship operates in sailing regime B, fuel cost is 700 €/T, the hull is depreciated in 30 years, the rest of the ship is depreciated in 15 years and crew is either fully paid or the crew cost are reduced by only paying a limited compensation to the captain-owner and his partner. Next to this base scenario, 4 variations are explored in order to establish the effect of changing the sailing regime to A1, changing fuel cost to 400 or 1000 €/T and changing the capital cost of the ship by depreciating the hull in 20 years and the rest of the ship in 10 years.

Apart from the main variables of each variation, Table 7-4 shows optimal main dimensions and the required ship rate in rows 5 and 6. In rows 7 to 10, the required ship rate of the optimal ship is compared to that of a standard 135 m ship (135 x 15 x 3.5 m), a standard 110 m ship (110 x 11.45 x 3.5 m) a standard 86 m ship (86 x 9.5 x 2.5 m) and in rows 11 to 16, it is compared to the designs surrounding the design with optimal main dimensions (rows 11-16).

For the determination of the main dimensions of these surrounding designs, an overview of lengths and beams for each ship design in the datasets that were created in chapter 5 is included in Table 7-3. The draught step is always 0.5 m (see chapter 5.1).

Table 7-3: Lengths and beams of vessels in the datasets of ship designs

Ship lengths	40 m	50 m	60 m	70 m	80 m	86 m	95 m	110 m	135 m	160 m	185 m
Ship beams	5 m	6.5 m	8 m	9.5 m	11 m	11.45 m	12.5 m	15 m	17.5 m	20 m	25 m

In order to assist in the evaluation of the comparisons in rows 7 to 16, values that deviate less than 10% from the optimal value are colored green, values that deviate between 10 and 25% are colored orange and values that deviate more than 25% are colored red.

Table 7-4: Results for route Rotterdam - Duisburg, Tmax = 2.8 m

		BASE CASE		Variation 1		Variation 2	
1	sailing regime	B		A1		B	
2	depreciation time	30/15 years		30/15 years		30/15 years	
3	fuel price (€/T)	700		700		400	
4	crew cost	full	reduced	full	reduced	full	reduced
5	optimal dimensions	160x20x3.5	135x17.5x3	135x17.5x3	135x17.5x3	135x17.5x3	135x17.5x3
6	required ship rate (€/T)	€ 4.77	€ 4.52	€ 4.41	€ 4.18	€ 4.27	€ 4.01
7	optimal	100%	100%	100%	100%	100%	100%
8	standard 135 m vessel	113%	112%	110%	110%	113%	112%
9	standard 110 m vessel	144%	141%	132%	129%	144%	141%
10	standard 86 m vessel	163%	159%	146%	143%	166%	162%
11	+ 1 length step	106%	103%	105%	106%	103%	103%
12	- 1 length step	102%	110%	112%	105%	111%	118%
13	+ 1 beam step	109%	103%	104%	105%	102%	102%
14	- 1 beam step	108%	107%	105%	104%	108%	108%
15	+ 1 draught step	110%	105%	105%	106%	105%	105%
16	- 1 draught step	102%	120%	120%	121%	121%	121%

	Variation 3		Variation 4	
sailing regime	B		B	
depreciation time (years)	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	160x20x3.5	135x17.5x3	135x17.5x3	135x17.5x3
required ship rate (€/T)	€ 5.26	€ 5.04	€ 5.20	€ 4.93
optimal	100%	100%	100%	100%
standard 135 m vessel	113%	112%	112%	112%
standard 110 m vessel	144%	141%	142%	140%
standard 86 m vessel	160%	156%	160%	157%
+ 1 length step	106%	102%	103%	103%
- 1 length step	103%	115%	110%	116%
+ 1 beam step	110%	103%	103%	103%
- 1 beam step	108%	107%	107%	107%
+ 1 draught step	110%	105%	105%	105%
- 1 draught step	102%	118%	120%	120%

From Table 7-4, a number of important conclusions can be drawn, which are valid for all cases in appendix F unless explicitly stated otherwise:

- The cost variations change the absolute value of the required ship rate considerably, but only occasionally result in a different set of optimal main dimensions; the optimal main dimensions are stable optimums that are relatively insensitive to changes in cost structure.

- The optimum that is found is usually not very distinct; the surrounding designs typically result in a required ship rate that is less than 10% higher than the optimum.

- The negative effect of a design draught that exceeds the actual draught is significantly smaller than the negative effect of a design draught that is smaller than the draught that is allowed by the water depth. This becomes apparent from the fact that all optimal vessels have a larger draught than the maximum draught that is possible on the route and the large increase in required ship rate for ships that have a draught that is 50 cm less (-1 draught step) than the optimal design.

After this discussion of the way in which results are presented, in the following paragraphs, these results are elaborated for all three ship types.

7.3.2 Dry bulk vessels

In this paragraph, the main dimensions that result in the lowest required ship rate for dry bulk vessels are discussed. Results are presented as a function of sailing distance and water depth for the base case of each route. Furthermore, comparison of the required ship rate with that of other designs is only done compared to standard designs. The results for variations in fuel price, sailing regime and depreciation time as well as the comparison of the required ship rate with that of surrounding designs can be found in appendix F.1. The results in appendix F.1 show that the variations lead to changes in the absolute value of the required ship rate, but that the optimal dimensions hardly change. Furthermore, the relative cost of the ship with optimal main dimensions compared to standard ships does not change significantly. As a result of this, it can be concluded that the results that are described here are stable solutions that are not drastically altered when one or more variables are changed. A more detailed analysis of how these variations affect ships of various dimensions is provided in chapter 7.9.

To assess how the distance of a trip and the water depth on the route affects the optimal ship dimensions, Table 7-5 presents the optimal dimensions for the four destinations and three water levels.

Table 7-5: Optimal dimensions as a function of route and maximum draught – dry bulk vessels

Rotterdam to:		Dordrecht	Nijmegen	Duisburg	Koblenz
Regime/crew cost		A1, reduced	A1, reduced	B, reduced	B, reduced
T_{max}	LxBxT (m)				
4.5 m		60x15x4.5 m	135x20x4.5 m	135x25x4.5 m	160x25x4.5 m
2.8/2.5 m		135x17.5x3 m	135x17.5x3 m	135x17.5x3 m	160x20x2.5 m
1.75 m		135x20x2 m	135x20x2 m	160x25x2 m	160x25x2 m

From Table 7-5 above, it becomes clear that there is a minor decrease in optimal length and beam as the sailing distance gets shorter. The only vessel that is considered to be small is the 60x15x4.5 m vessel on the route Rotterdam – Dordrecht, which in some cases results in a marginally lower required ship rate than a 135x15x4.5 m vessel. The reason for this is found in the long time that is spent at terminals. Due to these long handling times, the difference between the times that small and large vessels spend at the quayside is relatively small, as a result of which large vessels stay competitive on even the short routes. What also becomes apparent from Table 7-5 is that in all cases the design with the optimal main dimensions has a draught that is equal to or just above the maximum draught that is possible on the waterway. This indicates that it is less harmful to have a ship that is not fully loaded than a ship that is not able to fully utilize the available water depth.

To determine the advantages of these optimal designs compared to standard designs, in Table 7-6 and Table 7-7 below, the required ship rates of the optimal designs are compared to those of standard vessels. This is done for the routes Rotterdam – Dordrecht and Rotterdam Koblenz, to show the effect for both A1 and B-type operation. Table 7-6 shows that on short trips like Rotterdam – Dordrecht, a 10-15% reduction in required ship rate is possible compared to a 135 m vessel and that when the water is deep enough, the required ship rate per ton can be as low as just over half the required ship rate per ton of an 86 m vessel.

Table 7-6: Comparison of optimal ship with standard ships: Rotterdam - Dordrecht

Rotterdam - Dordrecht	Tmax = 4.5 m		Tmax = 2.8 m		Tmax = 1.75 m	
sailing regime	A1		A1		A1	
depreciation time (years)	30/15		30/15		30/15	
fuel price (€/T)	700		700		700	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	135x15x4.5 m	60x15x4.5 m	135x17.5x3 m	135x17.5x3 m	135x20x2 m	135x20x3 m
required ship rate (€/T)	€ 1.64	€ 1.53	€ 2.27	€ 2.12	€ 3.78	€ 3.54
optimal	100%	100%	100%	100%	100%	100%
standard 135 m vessel	113%	112%	111%	110%	116%	115%
standard 110 m vessel	136%	132%	127%	123%	131%	127%
standard 86 m vessel	194%	190%	144%	140%	129%	125%

On the longest route, Rotterdam – Koblenz, the reduction in required ship rate compared to standard ships can be even bigger than on short routes. This is due to the fact that the ship spends more time sailing than on short trips, since the time in port per trip does not change but the sailing time does increase on longer trips. In this case, the required ship rate per ton for the optimal vessel design may be as low as 40% of that of an 86 m vessel, while savings of 15 to 21% compared to standard 135 m vessels are possible.

Table 7-7: Comparison of optimal ship with standard ships: Rotterdam - Koblenz

Rotterdam - Koblenz	Tmax = 4.5 m		Tmax = 2.5 m		Tmax = 1.75 m	
sailing regime	B		B		B	
depreciation time (years)	30/15		30/15		30/15	
fuel price (€/T)	700		700		700	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	160x25x4.5 m	160x25x4.5 m	160x20x2.5 m	160x20x2.5 m	160x25x2 m	160x25x2 m
required ship rate (€/T)	€ 4.01	€ 3.89	€ 6.79	€ 6.52	€ 9.48	€ 9.09
optimal	100%	100%	100%	100%	100%	100%
standard 135 m vessel	127%	124%	119%	118%	127%	125%
standard 110 m vessel	168%	163%	148%	145%	162%	157%
standard 86 m vessel	240%	230%	152%	147%	168%	162%

From the above, important conclusions can be drawn with regard to the dry bulk ship that can operate at the lowest required ship rate:

- Its length is equal or slightly higher than the length of 135 m, which is the maximum length that is currently allowed. Lengthening the ship beyond 160 m does not improve its competitive edge.

- Wide vessels are efficient vessels; all optimal vessels have beams between 15 and 25 meters. The added advantage of increasing the ship's beam beyond 20 m is, however, limited.

- The draught of the ship should be equal to or higher than the maximum draught at which it can sail on a regular basis; the disadvantage of not being able to fully utilize the available draught is larger than the disadvantage of being unable to load the ship to its design draught.

It should be noted, however, that these results are quite strongly influenced by the time that the ships spend in port. For dry bulk vessels, the loading and unloading times as prescribed by Staatsblad [2011] are used. For container vessels, where it is assumed that the time spent in port is directly proportional to the number of containers that are on board, it will be shown that this alternative approach to loading and unloading the vessel will result in different optimal dimensions.

7.3.3 Container vessels

The optimal dimensions of container vessels can be determined in a similar way as the optimal dimensions of dry bulk vessels. However, there are two important differences. The first difference lies in the loading and unloading times. Since container ships typically operate within allocated time slots, their loading and unloading times are almost directly proportional to the number of containers that are loaded and/or unloaded. This results in very different handling times than the handling times of dry bulk vessels. The second difference lies in the loaded draught of container vessels: since containers are light cargo, it is often stability or maximum air draught that limits the number of containers that can be carried rather than the number of tons of cargo carrying capacity of the ship. In all analyses of container vessels, an average container weight of 14 ton per TEU and an air draught of 9.1 m is used [Central commission for Navigation on the Rhine, 2011].

For the designed container ships, these restrictions result in the ratios of loaded draught versus design draught as shown in Figure 7-13. From the figure it becomes clear that for the majority of container vessels, a design draught between 2.5 and 3.5 meters is sufficient, while in none of the cases a 4.5 m design draught is required. As a result of this, container ships are less sensitive to low water levels than dry bulk vessels, which in principle can always be loaded to their design draught.

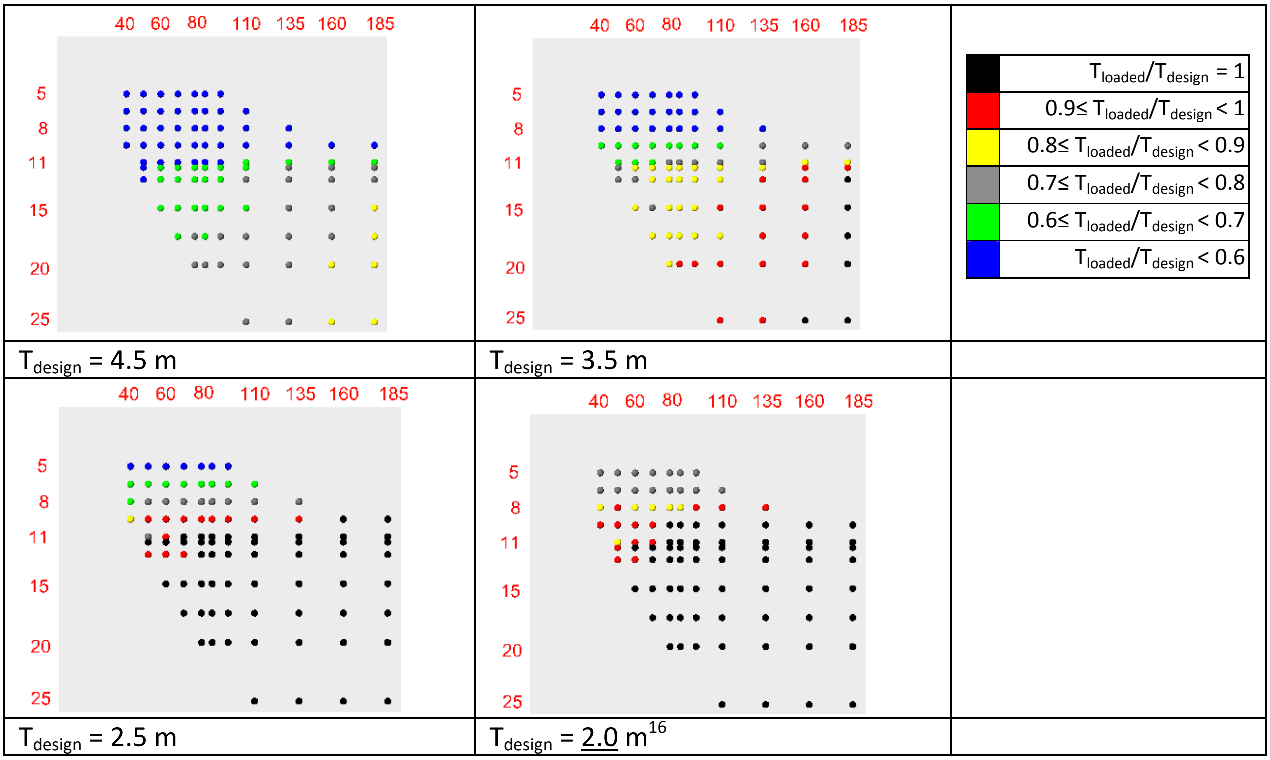


Figure 7-13: Design draught vs. maximum loaded draught for container vessels

In contrast with the results for dry bulk vessels, there is a clear relationship between the distance of a trip and optimal dimensions of a container ship, as is shown in Table 7-8: The longer the sailing distance, the larger the optimal ship dimensions are. This is explained by the fact that during short trips, large ships spend too much time loading and unloading to make good use of their scale advantage while sailing.

Table 7-8: Optimal dimensions as a function of route and maximum draught - container ships

Rotterdam to:		Dordrecht	Nijmegen	Duisburg	Koblenz
Regime/crew cost		A1, reduced	A1, reduced	B, reduced	B, reduced
Tmax	LxBxT (m)				
4.5 m		70x15x3 m	70x15x3 m	135x20x3.5 m	160x20x3.5 m
2.8/2.5 m		60x15x3 m	70x17.5x3 m	80x17.5x3 m	135x20x2.5 m
1.75 m		70x12.5x2 m	95x15x2 m	135x25x2 m	135x25x2 m

What also becomes apparent from Table 7-8 is that in none of the cases a design draught larger than 3.5 m results in an optimal ship.

In order to determine the advantage of the optimal main dimensions compared to existing ships, comparisons are made in Table 7-9 and Table 7-10 for the routes Rotterdam – Dordrecht (45 km) and Rotterdam – Koblenz (430 km). More elaborate results for all routes can be found in appendix F.2. Like in the previous paragraph, the results in appendix F.2 show that the variations that are analyzed lead to changes in the absolute value of the required ship rate, but that the optimal dimensions hardly change. Furthermore, the relative cost of the ship with optimal main dimensions compared to

16 Note that the displayed draught is 2.0 m rather than the usual 1.5 m. In all calculations a minimum draught of 1.5 m was used, so no vessels will show a draught smaller than that.

standard ships does not change significantly. As a result of this, it can be concluded that the results that are described here are stable solutions that are not drastically altered when one or more variables are changed.

Table 7-9: Comparison of optimal ship with standard ships: Rotterdam - Dordrecht

Rotterdam - Dordrecht	Tmax = 4.5 m		Tmax = 2.8 m		Tmax = 1.75 m	
sailing regime	A1		A1		A1	
depreciation time (years)	30/15		30/15		30/15	
fuel price (€/T)	700		700		700	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	70x15x3	70x15x3	60x15x3	60x15x3	70x15x2	70x12.5x2
required ship rate (€/T)	€ 1.11	€ 1.03	€ 1.24	€ 1.15	€ 1.90	€ 1.76
required ship rate (€/TEU)	€ 15.54	€ 14.42	€ 17.36	€ 16.10	€ 26.60	€ 24.64
optimal	100%	100%	100%	100%	100%	100%
standard 135 m vessel	141%	142%	141%	143%	129%	131%
standard 110 m vessel	129%	125%	123%	121%	143%	140%
standard 86 m vessel	130%	130%	123%	123%	115%	115%

From Table 7-9 above, it becomes apparent that on the route Rotterdam – Dordrecht, the optimal ship length is in all cases 70 meters or less and that for this short distance a small ship outperforms larger vessels due to the low crew cost and the fact that it spends less time per trip loading and unloading, resulting in a larger number of round trips per years. For long distance trips like Rotterdam – Koblenz, larger ships outperform smaller ships and the optimal dimensions are in fact quite close to those of a ‘standard’ 135 x 3.5 x 15 m container ship, as is shown in Table 7-10 below.

Table 7-10: Comparison of optimal ship with standard ships: Rotterdam - Koblenz

Rotterdam - Koblenz	Tmax = 4.5 m		Tmax = 2.5 m		Tmax = 1.75 m	
sailing regime	B		B		B	
depreciation time (years)	30/15		30/15		30/15	
fuel price (€/T)	700		700		700	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	160x20x3.5	160x20x3.5	135x20x2.5	135x20x2.5	135x25x2	135x25x2
required ship rate (€/T)	€ 3.48	€ 3.38	€ 4.99	€ 4.83	€ 6.82	€ 6.59
required ship rate (€/TEU)	€ 48.72	€ 47.32	€ 69.86	€ 67.62	€ 95.48	€ 92.26
optimal	100%	100%	100%	100%	100%	100%
standard 135 m vessel	112%	112%	113%	112%	124%	123%
standard 110 m vessel	140%	138%	135%	134%	146%	142%
standard 86 m vessel	176%	173%	136%	134%	154%	150%

The shift from small ships to larger ships as the optimal option occurs at a distance between that of Rotterdam – Dordrecht and Rotterdam - Koblenz. Since it is a good example, the results for Rotterdam – Duisburg at a maximum draught of 4.5 meters are shown below in more detail in Table 7-11.

Table 7-11: Comparison of optimal ship with other options: Rotterdam - Duisburg at 4.5 m maximum draught

Duisburg: Tmax = 4.5 m

sailing regime	B		A1		B	
depreciation time (years)	30/15		30/15		30/15	
fuel price (€/T)	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	160x20x3.5	135x20x3.5	70x15x3	70x15x3	86x20x3.5	80x17.5x3
required ship rate (€/T)	€ 2.37	€ 2.30	€ 3.12	€ 2.94	€ 1.96	€ 1.88
required ship rate (€/TEU)	€ 33.18	€ 32.2	€ 43.68	€ 41.16	€ 27.44	€ 26.32
optimal	100%	100%	100%	100%	100%	100%
standard 135 m vessel	107%	106%	110%	111%	107%	105%
standard 110 m vessel	129%	127%	120%	120%	126%	123%
standard 86 m vessel	158%	155%	146%	147%	156%	153%
+ 1 length step	110%	103%	105%	106%	109%	101%
- 1 length step	101%	106%	111%	110%	103%	107%
+ 1 beam step	113%	105%	105%	105%	no data	102%
- 1 beam step	104%	108%	107%	106%	102%	106%
+ 1 draught step	104%	107%	113%	114%	114%	104%
- 1 draught step	115%	107%	114%	114%	103%	120%

From Table 7-11 it becomes clear how close the various options are together: depending on the details of the analysis, ships ranging from 70 to 160 m in length can be the solution that results in the lowest required ship rate, but in all cases the standard 135 m container ship is close to the optimal solution. Like for dry bulk ships, the optimal ship dimensions for all variations in sailing regime, fuel cost, depreciation time and sailing regime can be found in appendix F.2. The effects of these variations on ships of all dimensions are discussed in paragraph 7.9.

7.3.4 Tank vessels

The optimal dimensions of tank vessels, i.e. those dimensions that result in the lowest required ship rate, are determined in a similar way as those of dry bulk vessels. Since tank vessels are more expensive than dry bulk vessels with the same cargo carrying capacity, the optimal main dimensions will be situated closer to those dimensions that result in the lowest capital cost. This leads to optimum lengths that are somewhat shorter than those of dry bulk ships, as shown in Table 7-12 below: In the majority of cases the optimal ship is 135 m long, 25 m wide and has a design draught that approximates the maximum possible draught. These ships only perform worse than slightly smaller ships on short trips like Rotterdam – Dordrecht. The savings that these ships can achieve is typically between 13 and 33% compared to a standard 135 m vessel.

Table 7-12: Optimal dimensions as a function of route and maximum draught - tank vessels

Rotterdam to:		Dordrecht	Nijmegen	Duisburg	Koblenz
Regime/crew cost		A1, reduced	A1, reduced	B, reduced	B, reduced
Tmax					
4.5 m		110x20x4.5	135x20x4.5	135x25x4.5	135x25x4.5
2.8/2.5 m		135x17.5x3	135x25x3	135x25x3	135x25x2.5
1.75 m		135x25x2	135x25x2	135x25x2	135x25x2

When comparing these results to cases where the crew is fully paid and to ships with common main dimensions for the route Rotterdam – Dordrecht in Table 7-13, it is demonstrated that the use of a ship with optimized main dimensions may reduce the required ship rate by 12% (100/114) to 43% (100/175) compared to the use of standard ships. It also shows only a minor influence of changing to full crew costs on the relative performance of the various ships. Cases in which the optimal dimensions at full crew cost deviate from those at reduced crew cost are marked in yellow.

Table 7-13: Comparison of optimal ship with standard ships: Rotterdam - Dordrecht

Dordrecht	Tmax = 4.5 m		Tmax = 2.8 m		Tmax = 1.75 m	
sailing regime	A1		A1		A1	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		700	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	110x20x4.5	110x20x4.5	110x25x3	135x17.5x3	135x25x2	135x25x2
Required ship rate (€/T)	€ 2.32	€ 2.22	€ 3.12	€ 2.97	€ 4.62	€ 4.41
optimal	100%	100%	100%	100%	100%	100%
standard 135 m vessel	114%	114%	118%	118%	150%	149%
standard 110 m vessel	130%	127%	135%	132%	175%	170%
standard 86 m vessel	169%	165%	129%	126%	147%	143%

As shown in Table 7-14 below, in a similar way as for dry bulk ships, on the long Rotterdam – Koblenz route potential savings are bigger than on the short routes due to the fact that the ship spends more time sailing rather than spending time in port to for the handling of cargo. In contrast with container ships, there is little to no increase in the optimal dimensions as the route gets longer.

Table 7-14: Comparison of optimal ship with standard ship: Rotterdam - Koblenz

Koblenz	Tmax = 4.5 m		Tmax = 2.5 m		Tmax = 1.75 m	
sailing regime	B		B		B	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		700	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	135x25x4.5	135x25x4.5	135x25x2.5	135x25x2.5	135x25x2	135x25x2
Required ship rate (€/T)	€ 4.95	€ 4.81	€ 7.52	€ 7.25	€ 10.78	€ 10.32
optimal	100%	100%	100%	100%	100%	100%
standard 135 m vessel	126%	124%	133%	132%	154%	153%
standard 110 m vessel	160%	156%	170%	167%	200%	196%
standard 86 m vessel	220%	212%	156%	152%	183%	178%

More elaborate results for all routes can be found in appendix F.3. Like in the previous paragraphs, the results in appendix F.3 show that the variations that are analyzed lead to changes in the absolute value of the required ship rate, but that the optimal dimensions hardly change. Furthermore, the relative cost of the ship with optimal main dimensions compared to standard ships does not change significantly. As a result of this, it can be concluded that the results that are described here are stable solutions that are not drastically altered when one or more variables are changed.

The effect that the most important variations from appendix F have on the required ship rate of ships with all dimensions is discussed in chapter 7.9.

7.4 *Identification of optimal dimensions – lowest required ship rate with internalization of external emission costs*

To determine the effect that internalization of external emission costs has on the ship dimensions that result in the lowest required ship rate, the external costs of emissions, as discussed in chapter 6.2.3, are included in the required ship rate. The internalization of external costs results in an increase of the required ship rate of roughly 0.0018 to 0.016 €/Tkm, as is shown in Figure 7-14 for a dry bulk ship sailing fully loaded in one direction and returning empty, in both cases in a water depth of 5.0 m.

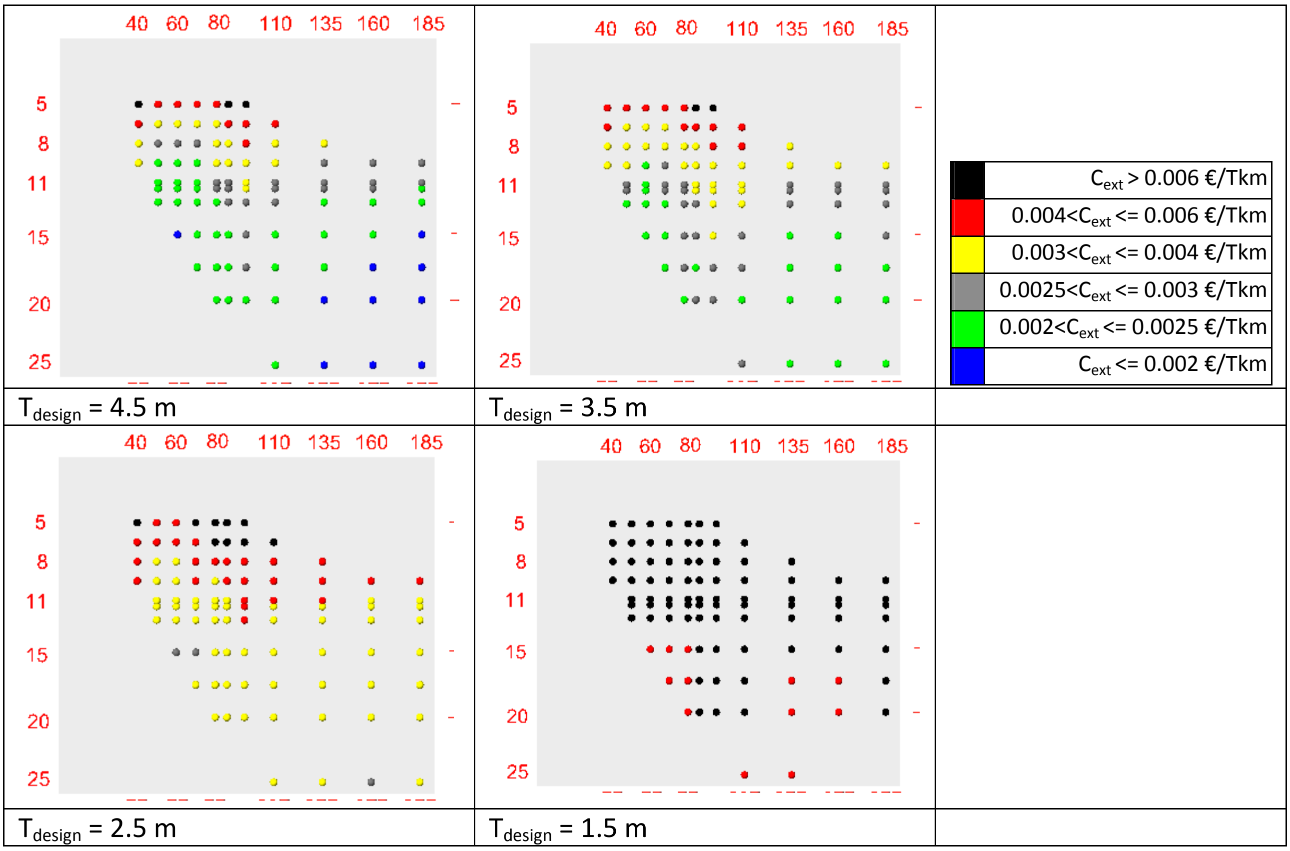


Figure 7-14: Impact of internalization of external costs on required ship rate – dry bulk

The added cost of internalizing external emission costs shows the roughly same behavior as that of capital cost and crew cost, i.e. the larger the amount of cargo that can be carried, the smaller its impact. As a result, it is to be expected that internalization of external emission costs will not change the optimal ship dimensions significantly, especially when the optimal ship was already large. That this is in fact the case becomes apparent from Table 7-15 in which the change in required ship rate and optimal ship dimensions are shown for the four routes, three water depths and the base case scenario with reduced crew cost. In all tables in this paragraph, cases where the new optimum deviates from the old optimum from paragraph 7.3 are marked in yellow.

7.4.1 Dry bulk ships

Table 7-15 below shows the required ship rate for the reference case from paragraph 7.3 and the required ship rate in case the external emission costs are internalized (column "intl. ext") as well as a comparison with standard ship types for all routes and water depths. From the table, it can be seen that internalization of external costs only in two cases results in a slight change in optimal dimensions (i.e. Rotterdam-Duisburg at Tmax = 4.5 m and Rotterdam Koblenz at Tmax = 2.5 m). From the comparison with standard ships, which is also shown in Table 7-15, it can be concluded that the internalization of external emission costs only marginally improves or reduces the relative performance of the optimal ship compared to the standard 86, 110 and 135 m vessels. Since more fuel is consumed on longer trips while ships also spend a larger percentage of their time sailing, both the absolute and the relative increase in the required ship rate due to internalization of emission costs get larger as the sailing distance increases.

When the maximum draught decreases from 4.5 to 2.8 meters and the optimal vessel dimensions change accordingly, the absolute value of the additional cost of internalization increases by about 50% per ton. However, the relative contribution of the internalization of external emission costs to the required ship rate decreases substantially due to the high reference value for the required ship rate as a result of the low cargo carrying capacity of low draught ships.

Table 7-15: Change of optimal dimensions due to internalization of external costs – dry bulk ships

Tmax = 4.5 m	Dordrecht		Nijmegen		Duisburg		Koblenz	
sailing regime	A1		A1		B		B	
depreciation time	30/15		30/15		30/15		30/15	
fuel price	700		700		700		700	
crew cost	reduced		reduced		reduced		reduced	
case	reference	intl. ext	reference	intl. ext	reference	intl. ext	reference	intl. ext
optimal dimensions	60x15x4.5	60x15x4.5	135x20x4.5	135x20x4.5	135x25x4.5	160x25x4.5	160x25x4.5	160x25x4.5
req. ship rate (€/T)	€ 1.53	€ 1.62	€ 2.16	€ 2.43	€ 2.99	€ 3.48	€ 3.89	€ 4.71
optimal	100%	100%	100%	100%	100%	100%	100%	100%
st. 135 m vessel	113%	113%	112%	113%	122%	123%	124%	125%
st. 110 m vessel	136%	134%	133%	136%	161%	161%	163%	163%
st. 86 m vessel	194%	191%	190%	191%	229%	226%	230%	226%

Tmax=2.8/2.5 m	Dordrecht		Nijmegen		Duisburg		Koblenz	
sailing regime	A1		A1		B		B	
dep. time	30/15		30/15		30/15		30/15	
fuel price	700		700		700		700	
crew cost	reduced		reduced		reduced		reduced	
case	reference	intl. ext	reference	intl. ext	reference	intl. ext	reference	intl. ext
optimal dims	135x17.5x3	135x17.5x3	135x17.5x3	135x17.5x3	135x17.5x3	135x17.5x3	160x20x2.5	160x25x2.5
req. ship rate (€/T)	€ 2.12	€ 2.26	€ 3.05	€ 3.47	€ 4.52	€ 5.29	€ 6.52	€ 7.88
optimal	100%	100%	100%	100%	100%	100%	100%	100%
st. 135 m vessel	110%	111%	110%	110%	112%	112%	118%	118%
st. 110 m vessel	123%	125%	127%	129%	141%	142%	145%	145%
st. 86 m vessel	140%	140%	142%	141%	159%	155%	147%	145%

Tmax = 1.75 m	Dordrecht		Nijmegen		Duisburg		Koblenz	
sailing regime	A1		A1		B		B	
depreciation time	30/15		30/15		30/15		30/15	
fuel price	700		700		700		700	
crew cost	reduced		reduced		reduced		reduced	
case	reference	intl. ext	reference	intl. ext	reference	intl. ext	reference	intl. ext
optimal dimensions	135x20x3	135x20x3	135x20x2	135x20x2	160x25x2	160x25x2	160x25x2	160x25x2
req. ship rate (€/T)	€3.54	€3.69	€ 5.06	€ 5.52	€ 6.94	€7.71	€ 9.09	€ 10.44
optimal	100%	100%	100%	100%	100%	100%	100%	100%
st. 135 m vessel	115%	115%	116%	116%	123%	123%	125%	124%
st. 110 m vessel	127%	127%	131%	131%	154%	153%	157%	155%
st. 86 m vessel	125%	127%	133%	135%	157%	159%	162%	162%

7.4.2 Container ships

For container ships, similar results and trends can be observed as for dry bulk ships: internalization of external costs does not change optimal dimensions significantly. As is shown in Table 7-16 below, a shift in optimal main dimensions occurs in only three cases and the internalization of external costs does not change the relative advantage of the optimal ship compared to standard ships by much.

Table 7-16: Change of optimal dimensions due to internalization of external costs – container ships

Tmax = 4.5 m	Dordrecht		Nijmegen		Duisburg		Koblenz	
sailing regime	A1		A1		B		B	
depreciation time	30/15		30/15		30/15		30/15	
fuel price	700		700		700		700	
crew cost	reduced		reduced		reduced		reduced	
case	reference	intl. ext	reference	intl. ext	reference	intl. ext	reference	intl. ext
optimal dimensions	70x15x3	70x15x3	70x15x3	70x15x3	135x20x3.5	160x20x3.5	160x20x3.5	160x20x3.5
req. ship rate (€/T)	€ 1.03	€ 1.14	€ 1.89	€ 2.21	€ 2.30	€ 2.85	€ 3.38	€ 4.34
required ship rate (€/TEU)	€ 14.42	€ 15.96	€ 26.46	€ 30.94	€ 32.20	€ 39.90	€ 47.32	€ 60.76
optimal	100%	100%	100%	100%	100%	100%	100%	100%
st. 135 m vessel	142%	139%	120%	120%	106%	109%	112%	114%
st. 110 m vessel	125%	125%	121%	126%	127%	134%	138%	144%
st. 86 m vessel	130%	134%	142%	147%	155%	161%	173%	176%

Tmax =2.8/2.5 m	Dordrecht		Nijmegen		Duisburg		Koblenz	
sailing regime	A1		A1		B		B	
depreciation time	30/15		30/15		30/15		30/15	
fuel price	700		700		700		700	
crew cost	reduced		reduced		reduced		reduced	
case	reference	intl. ext	reference	intl. ext	reference	intl. ext	reference	intl. ext
optimal dimensions	60x15x3	60x15x3	70x15x3	70x15x3	80x17.5x3	70x17.5x3	135x20x2.5	160x25x2.5
required ship rate (€/T)	€ 1.15	€ 1.29	€ 2.25	€ 2.67	€ 2.79	€ 3.56	€ 4.83	€ 6.23
required ship rate (€/TEU)	€ 16.10	€ 18.06	€ 31.50	€ 37.38	€ 39.06	€ 49.84	€ 67.62	€ 87.22
optimal	100%	100%	100%	100%	100%	100%	100%	100%
st. 135 m vessel	143%	140%	123%	121%	111%	112%	112%	114%
st. 110 m vessel	121%	122%	122%	125%	129%	131%	134%	136%
st. 86 m vessel	123%	125%	128%	130%	138%	138%	134%	134%

Tmax = 1.75 m	Dordrecht		Nijmegen		Duisburg		Koblenz	
sailing regime	A1		A1		B		B	
depreciation time	30/15		30/15		30/15		30/15	
fuel price	700		700		700		700	
crew cost	reduced		reduced		reduced		reduced	
case	reference	intl. ext	reference	intl. ext	reference	intl. ext	reference	intl. ext
optimal dimensions	70x12.5x2	70x12.5x2	95x15x2	95x15x2	135x25x2	135x25x2	135x25x2	135x25x2
required ship rate (€/T)	€ 1.76	€ 2.01	€ 3.69	€ 4.27	€ 4.15	€ 5.02	€ 6.59	€ 8.10
required ship rate (€/TEU)	€ 24.64	€ 28.14	€ 51.66	€ 59.78	€ 58.10	€ 70.28	€ 92.26	€ 113.40
optimal	100%	100%	100%	100%	100%	100%	100%	100%
st. 135 m vessel	131%	124%	119%	116%	120%	119%	123%	121%
st. 110 m vessel	140%	141%	120%	118%	137%	135%	142%	140%
st. 86 m vessel	115%	113%	121%	121%	143%	144%	150%	150%

7.4.3 Tank ships

For tank ships the impact of internalization of external emission costs on the total cost is even more limited than for dry bulk and container vessels, due to the higher capital cost of the ship. From Table 7-17 below, it can be seen that internalization of external emission costs does not result in any changes in the optimal dimensions, nor does it result in major changes in the relative advantage of the optimal ship compared to standard ships. The trends of increasing impact of internalization of external emission cost on the total cost as the sailing distance increase can again be observed, like with the other ship types. The increase in required ship rate when the maximum draught is reduced also shows a trend that highly similar to the trend for the other ship types.

Table 7-17: Change of optimal dimensions due to internalization of external costs – tank ships

Tmax = 4.5 m	Dordrecht		Nijmegen		Duisburg		Koblenz	
sailing regime	A1		A1		B		B	
depreciation time	30/15		30/15		30/15		30/15	
fuel price	700		700		700		700	
crew cost	reduced		reduced		reduced		reduced	
case	reference	intl. ext	reference	intl. ext	reference	intl. ext	reference	intl. ext
opt. dims	110x20x4.5	110x20x4.5	135x20x4.5	135x20x4.5	135x25x4.5	135x25x4.5	135x25x4.5	135x25x4.5
required ship rate (€/T)	€ 2.22	€ 2.33	€ 2.99	€ 3.27	€ 3.77	€ 4.29	€ 4.81	€ 5.70
optimal	100%	100%	100%	100%	100%	100%	100%	100%
st. 135 m vessel	114%	113%	113%	115%	123%	123%	124%	125%
st. 110 m vessel	127%	127%	130%	133%	153%	154%	156%	158%
st. 86 m vessel	165%	166%	172%	175%	208%	207%	212%	211%

Tmax =2.8/2.5 m	Dordrecht		Nijmegen		Duisburg		Koblenz	
sailing regime	A1		A1		B		B	
depreciation time	30/15		30/15		30/15		30/15	
fuel price	700		700		700		700	
crew cost	reduced		reduced		reduced		reduced	
case	reference	intl. ext	reference	intl. ext	reference	intl. ext	reference	intl. ext
opt. dims	135x17.5x3	135x17.5x3	135x25x3	135x25x3	135x25x3	135x25x3	135x25x2.5	135x25x2.5
required ship rate (€/T)	€ 2.97	€ 3.12	€ 4.09	€ 4.51	€ 5.26	€ 6.03	€ 7.25	€ 8.66
optimal	100%	100%	100%	100%	100%	100%	100%	100%
st. 135 m vessel	118%	117%	118%	118%	125%	124%	132%	130%
st. 110 m vessel	132%	133%	136%	138%	156%	156%	167%	165%
st. 86 m vessel	126%	127%	133%	133%	156%	154%	152%	149%

Tmax = 1.75 m	Dordrecht		Nijmegen		Duisburg		Koblenz	
sailing regime	A1		A1		B		B	
depreciation time	30/15		30/15		30/15		30/15	
fuel price	700		700		700		700	
crew cost	reduced		reduced		reduced		reduced	
case	reference	intl. ext	reference	intl. ext	reference	intl. ext	reference	intl. ext
opt. dims	135x25x2	135x25x2	135x25x2	135x25x2	135x25x2	135x25x2	135x25x2	135x25x2
req ship rate (€/T)	€ 4.41	€ 4.57	€ 6.12	€ 6.58	€ 7.93	€ 8.77	10.32	€ 11.78
optimal	100%	100%	100%	100%	100%	100%	100%	100%
st. 135 m vessel	149%	148%	151%	150%	153%	150%	153%	150%
st. 110 m vessel	170%	170%	177%	176%	194%	191%	196%	191%
st. 86 m vessel	143%	144%	152%	154%	174%	174%	178%	177%

7.5 Identification of optimal dimensions - lowest total logistical cost

In the previous paragraphs, the focus was on determination of the ship dimensions that result in the lowest required ship rate. However, as was discussed in chapter 6, the costs for a shipper consist of more than just the out of pocket cost of transport; it also includes the cost of cycle stock, safety stock and stock in transit. For completeness, equation 6-35 from chapter 6.2.4 is iterated below.

$$TLC = TC + \left(\frac{1}{R_g}\cdot\frac{Q}{2}\cdot v\cdot hc\right) + \left(Lt\cdot v\cdot\frac{hc}{365}\right) + \left(\frac{1}{R_g}\cdot v\cdot hc\cdot K\cdot\sqrt{(L\cdot d_g)+(D_g{}^2\cdot l)}\right) \quad \text{Eq. 7-1}$$

Where:

TLC = total logistic costs (€/unit)
TC = transport cost (€/unit)
R_g = annual volume (units)
Q = loading capacity/shipment size (units)
v = value of the goods (€/unit)
h = holding cost (fraction of value/year)
Lt = average lead-time / travel time (days)
l = variance of lead times (days^2)
K = safety factor
D_g = average daily demand (units/day)
D_g = variance of daily demand (units^2/day)

In the previous paragraphs, the 'optimal' ship, i.e. the ship that can operate at the lowest required ship rate, is usually a large ship, resulting in relatively few large shipments in case of a fixed demand from a shipper. Blauwens et al. [2010, p. 238], however, indicate that the lowest total logistical cost may be found at a larger number of smaller shipments with higher order (shipment) costs, as is also expressed in Figure 7-15 below.

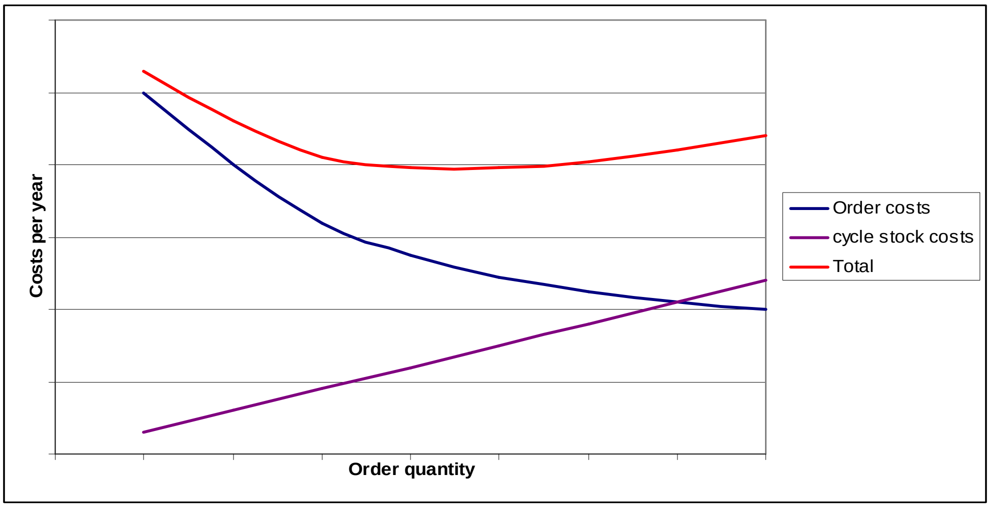


Figure 7-15: Cycle stock cost and order costs. Source: own representation of Blauwens et al. [2010, p. 238]

When attempting to identify which ship dimensions result in the lowest total logistical cost, it is important to assess which effect ship dimensions have on each of the elements in the total logistical cost equation.

The effect that ship dimensions have on transport cost has been discussed elaborately in this thesis. Since no investigations are made regarding the variance of lead time and daily demand, safety stock is set at 0, as was discussed in chapter 6.2.4. To determine the cost of cycle stock, it is necessary to estimate the annual volume of goods that a shipper needs as well as the shipment size and the holding cost. The determination of the cost of stock-in-transit requires knowledge of shipment size, lead time and holding cost. For the scenarios that are analyzed, shipment size is considered as equal to the amount of cargo a ship can carry on a given water depth on a given route, and the lead time is equal to the travel time from port to final destination.

The final item, holding cost or inventory cost, is composed of the following elements [Blauwens et al. 2010, p. 208]:

1) Interest cost
2) Insurance cost or risk cost
3) Depreciation of goods
4) Warehousing cost

Of these elements, Interest cost, the cost of interest related to capital tied up in the goods is around 4% of the cost of the goods, looking at the financial market in western countries over a number of years [Blauwens et al. 2010, p. 209].

Insurance costs, i.e. the costs to ensure goods against fire or theft are usually insignificant [Blauwens et al. 2010, p. 209]. This is especially the case for low value bulk goods. Therefore, they are neglected in this analysis.

Depreciation of goods relates to the loss of value of goods over time. For common bulk goods, this may be assumed to be 0, since they do not become obsolete. For items that are sensitive to becoming obsolete, e.g. computers, Blauwens et al. advise a lifetime of an item of about 3 years. [Blauwens et al. 2010, p. 209].

Warehousing costs per unit, especially at a customer's site, are highly dependent on the extent to which the existing warehousing capacity is used. Blauwens et al. [2010] advise "*In order to arrive at the cost of storage per unit, a working rule is to divide the annual cost of the warehouse by the average level of stock*". In practice, shippers will make a one-time decision to build storage space rather than to build or demolish storage facilities every time a new choice is made with regard to the vessel or vehicle with which goods are supplied. Furthermore, some of the major clients of the inland shipping sector, such as the steel industry in Germany, are already supplied by several ship types and sizes simultaneously. As a result of this, for the purpose of this thesis it is assumed that the storage capacity of a customer is not decided on the basis of the size of individual shipments. Therefore, it is assumed to be equal for all ship sizes.

As a result of this, the only variables that are affected by the shipment size are interest cost and depreciation. The latter is only assumed to be larger than zero for containerized goods since they can become obsolete within a short time span, in contrast to bulk goods.

However, in contrast with bulk goods, shipments of containers are hardly ever intended for a single customer: liner services of container ships will typically serve multiple shippers in on a single trip. As a result, the depreciation cost of the cycle stock of a single shipper can not be linked to the dimensions of an inland ship. Since the length of the ship can influence its design speed, the only direct link between the dimensions of a ship and the depreciation cost of stock (in-transit) lies in the differences in sailing time. Since sailing distances and speed differences are small and containers that are shipped by inland waterways rather than by road may be assumed to be relatively insensitive to loss of value as a result of a slightly longer travel time, the effect of different sailing speeds is assumed to be negligible.

As a result, for containerized goods, the relationship between total logistical cost and ship dimensions solely lies in the direct transport cost. For dry bulk and liquid bulk, however, the interest costs of cycle stock also have an impact. Due to the previously discussed short sailing distances, small differences in sailing times and the low value of the goods, the interest cost of stock in transit is neglected. In the following calculations, interest is taken as 4% of the value of the goods per year.

For the assessment of the holding cost, the following goods and values are used:

Table 7-18: Value of various commodities

Ship type	Commodity	Value (2011 values)
Dry bulk	Coal	55 €/T
Dry bulk	Iron ore	106 €/T
Tanker	Gasoil/fuel oil for industry	700 €/T

When plotting the holding cost of cycle stock per ton as a function of annual demand and the size of single shipments, results are as shown in Figure 7-16 below. For low value goods like coal, the impact of receiving a small number of large shipments is relatively small, but for a much more expensive commodity like gasoil, the holding cost can easily exceed the transport cost, especially when using large ships on short distances and in case of low annual demand.

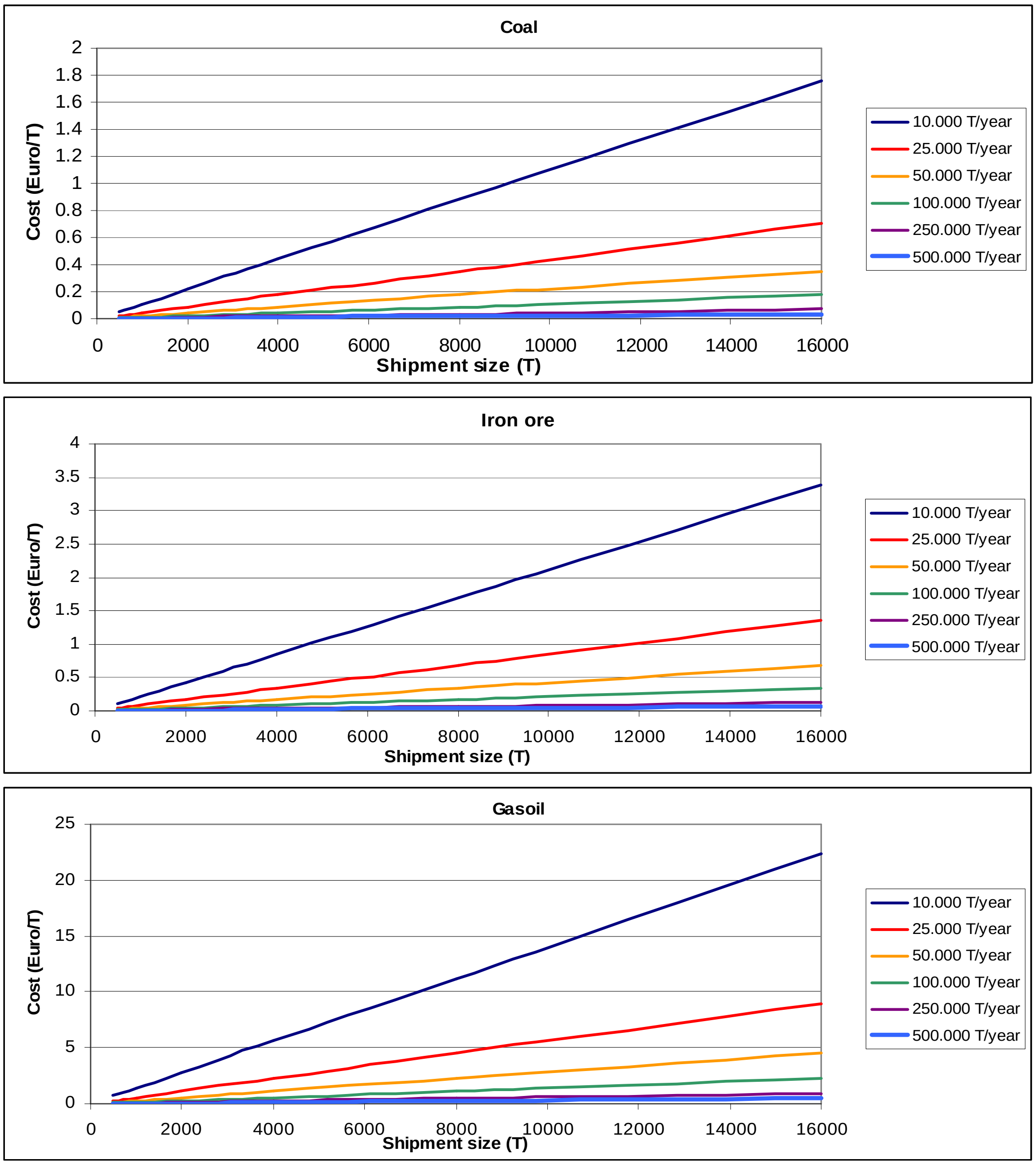


Figure 7-16: Cost of cycle stock vs. shipment size

In the following paragraphs, it is investigated how the inclusion of the holding cost changes the optimal vessel dimensions if the shipper has an annual demand of 10.000, 25.000, 50.000 or 100.000 tons of goods, which are values ranging from the same order of magnitude of a single shipment in a large ship to a much larger cargo volume.

7.5.1 Iron ore

When transporting iron ore, it becomes apparent from Table 7-19 below that inclusion of the cost of cycle stock in the assessment leads to a strong reduction in the optimal dimensions of a vessel. On the route Rotterdam – Dordrecht, a comparison between the optimal dimensions from a lowest-ship-rate-perspective (the ‘original optimum’) and the optimal dimensions from a total-logistical-cost-perspective reveals that the optimal dimensions shift from 135 m to 70 m in length, implying that it is favorable for the shipper to accept higher direct transport cost in exchange for lower holding cost. From the table, it can also be seen that including holding cost in the cost calculation can increase the transport cost of the original optimum (i.e. the ship with the lowest required ship rate) by almost 50% in the worst case.

Table 7-19: Impact of holding cost on optimal dimensions: iron ore, Rotterdam - Dordrecht

Rotterdam - Dordrecht			annual demand 10.000 T		annual demand 25.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	60x15x4.5	€ 1.53	€ 0.65	same	€ 0.26	same
T_{max} = 2.8 m	135x17.5x3	€ 2.12	€ 1.03	70x15x3	€ 0.41	70x15x3
T_{max} =1.75 m	135x20x2	€ 3.54	€ 0.61	70x17.5x2	€ 0.24	70x17.5x2

			annual demand 50.000 T		annual demand 100.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	60x15x4.5	€ 1.53	€ 0.13	same	€ 0.07	same
T_{max} = 2.8 m	135x17.5x3	€ 2.12	€ 0.21	70x15x3	€ 0.10	70x15x3
T_{max} =1.75 m	135x20x2	€ 3.54	€ 0.12	70x17.5x2	€ 0.06	70x17.5x2

On the route Rotterdam – Nijmegen (Table 7-20), the tradeoff between low transport cost and low holding cost becomes visible: in case of a maximum draught of 4.5 m, the cargo carrying capacity most ships is so large that the holding cost due to the small number of large shipments leads to such high costs that the original optimum is no longer optimal but loses from a much smaller vessel. In case of low water depth and/or annual demands of 50.000 T or more, the ship with the lowest required ship rate is still optimal. In these cases, it can be seen that the increase in the total cost due to the holding cost is only a couple of cents.

Table 7-20: Impact of holding cost on optimal dimensions: iron ore, Rotterdam - Nijmegen

Rotterdam - Nijmegen			annual demand 10.000 T		annual demand 25.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	135x20x4.5	€ 2.16	€ 2.03	60x15x4.5	€ 0.81	60x15x4.5
T_{max} = 2.8 m	135x17.5x3	€ 3.05	€ 1.03	70x15x3	€ 0.41	70x17.5x3
T_{max} = 1.75 m	135x20x2	€ 5.06	€ 0.61	110x17.5x2	€ 0.24	same

			annual demand 50.000 T		annual demand 100.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	135x20x4.5	€ 2.16	€ 0.41	60x15x4.5	€ 0.20	60x15x4.5
T_{max} = 2.8 m	135x17.5x3	€ 3.05	€ 0.21	same	€ 0.10	same
T_{max} =1.75 m	135x20x2	€ 5.06	€ 0.12	same	€ 0.06	same

From Table 7-21 below, which shows the results for the route Rotterdam – Duisburg, it can be observed that as the sailing distance, and thereby the transport cost, increases, the optimal ship dimensions start to increase and in the majority of cases the ship with the lowest required ship rate is still the optimal solution when the total logistical costs are taken into account.

Table 7-21: Impact of holding cost on optimal dimensions: iron ore, Rotterdam - Duisburg

Rotterdam - Duisburg			annual demand 10.000 T		annual demand 25.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	135x25x4.5	€ 2.99	€ 2.51	60x15x4.5	€ 1.00	86x20x4.5
T_{max} = 2.8 m	135x17.5x3	€ 4.52	€ 1.03	86x17.5x3	€ 0.41	same
T_{max} = 1.75 m	160x25x2	€ 6.94	€ 0.86	135x20x2	€ 0.35	same

			annual demand 50.000 T		annual demand 100.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	135x25x4.5	€ 2.99	€ 0.50	135x20x4.5	€ 0.25	135x20x4.5
T_{max} = 2.8 m	135x17.5x3	€ 4.52	€ 0.21	same	€ 0.10	same
T_{max} = 1.75 m	160x25x2	€ 6.94	€ 0.17	same	€ 0.09	same

Finally, on the route Rotterdam - Koblenz (Table 7-22), a further increase occurs in optimal ship dimensions. However, the original optimum dimensions had also increased on this distance. From Table 7-21 above and Table 7-22 below, it can be concluded that on long distances, the existing 135 m ships are quite close to the optimal ship dimensions, but that widening them to 20-25 meters may further improve their competitiveness. 160 m long vessels now seem to be too large to be able to operate effectively, at least on distances up to 430 km when the maximum draught is 2.5 m or more.

Table 7-22: Impact of holding cost on optimal dimensions: iron ore, Rotterdam - Koblenz

Rotterdam - Koblenz			annual demand 10.000 T		annual demand 25.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	160x25x4.5	€ 3.89	€ 2.96	60x15x4.5	€ 1.19	135x20x4.5
T_{max} = 2.8 m	160x20x2.5	€ 6.52	€ 1.16	135x20x2.5	€ 0.46	135x20x2.5
T_{max} = 1.75 m	160x25x2	€ 9.09	€ 0.86	same	€ 0.35	same

			annual demand 50.000 T		annual demand 100.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	160x25x4.5	€ 3.89	€ 0.59	135x20x4.5	€ 0.30	135x25x4.5
T_{max} = 2.5 m	160x20x2.5	€ 6.52	€ 0.23	135x20x2.5	€ 0.12	135x20x2.5
T_{max} =1.75 m	160x25x2	€ 9.09	€ 0.17	same	€ 0.09	same

7.5.2 Coal

Coal is a much less valuable commodity than iron ore, and as such the effects of including the holding cost in cost calculations has a much smaller impact than in case of iron ore. From Table 7-23 to Table 7-26, it can be concluded that only for the shortest distance and for the lowest demand, vessels with a length smaller than 135 m are considered the optimal solution. It can also be observed that 160 m long vessels are competitive again on the route Rotterdam – Koblenz, which they were not when transporting iron ore. This clearly demonstrates the link between the value of goods and the optimal dimensions of a ship: The lower the value of the goods, the more dominant the out-of-pocket cost of transport are, and as a result the larger the benefits are of large ships that can operate at a low required ship rate. Especially in the case of high annual demand, the holding cost in the tables below is only a couple of cents, while especially at low water levels, the out-of-pocket transport cost (the 'original cost' in the tables) is many times higher.

Table 7-23: Impact of holding cost on optimal dimensions: coal, Rotterdam - Dordrecht

Rotterdam - Dordrecht			annual demand 10.000 T		annual demand 25.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	60x15x4.5	€ 1.53	€ 0.34	same	€ 0.14	same
T_{max} = 2.8 m	135x17.5x3	€ 2.12	€ 0.53	70x15x3	€ 0.21	70x15x3
T_{max} =1.75 m	135x20x2	€ 3.54	€ 0.31	70x17.5x2	€ 0.13	70x17.5x2

			annual demand 50.000 T		annual demand 100.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	60x15x4.5	€ 1.53	€ 0.07	same	€ 0.03	same
T_{max} = 2.8 m	135x17.5x3	€ 2.12	€ 0.11	70x15x3	€ 0.05	same
T_{max} =1.75 m	135x20x2	€ 3.54	€ 0.06	70x17.5x2	€ 0.03	same

Table 7-24: Impact of holding cost on optimal dimensions: coal, Rotterdam - Nijmegen

Rotterdam - Nijmegen			annual demand 10.000 T		annual demand 25.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	135x20x4.5	€ 2.16	€ 1.05	60x15x4.5	€ 0.42	60x15x4.5
T_{max} = 2.8 m	135x17.5x3	€ 3.05	€ 0.53	70x15x3	€ 0.21	same
T_{max} = 1.75 m	135x20x2	€ 5.06	€ 0.31	same	€ 0.13	same

			annual demand 50.000 T		annual demand 100.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	135x20x4.5	€ 2.16	€ 0.21	60x15x4.5	€ 0.11	60x15x4.5
T_{max} = 2.8 m	135x17.5x3	€ 3.05	€ 0.11	same	€ 0.05	same
T_{max} = 1.75 m	135x20x2	€ 5.06	€ 0.06	same	€ 0.03	same

Table 7-25: Impact of holding cost on optimal dimensions: coal, Rotterdam - Duisburg

Rotterdam - Duisburg			annual demand 10.000 T		annual demand 25.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	135x25x4.5	€ 2.99	€ 1.30	70x17.5x4.5	€ 0.52	135x20x4.5
T_{max} = 2.8 m	135x17.5x3	€ 4.52	€ 0.53	same	€ 0.21	same
T_{max} =1.75 m	160x25x2	€ 6.94	€ 0.45	same	€ 0.18	same

			annual demand 50.000 T		annual demand 100.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	135x25x4.5	€ 2.99	€ 0.26	135x20x4.5	€ 0.13	same
T_{max} = 2.8 m	135x17.5x3	€ 4.52	€ 0.11	same	€ 0.05	same
T_{max} =1.75 m	160x25x2	€ 6.94	€ 0.09	same	€ 0.04	same

Table 7-26: Impact of holding cost on optimal dimensions: coal, Rotterdam - Koblenz

Rotterdam - Koblenz			annual demand 10.000 T		annual demand 25.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	160x25x4.5	€ 3.89	€ 1.54	86x20x4.5	€ 0.61	135x20x4.5
T_{max} = 2.8 m	160x20x2.5	€ 6.52	€ 0.60	135x20x2.5	€ 0.24	135x20x2.5
T_{max} =1.75 m	160x25x2	€ 9.09	€ 0.45	same	€ 0.18	same

			annual demand 50.000 T		annual demand 100.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	160x25x4.5	€ 3.89	€ 0.31	135x25x4.5	€ 0.15	same
T_{max} = 2.8 m	160x20x2.5	€ 6.52	€ 0.12	135x20x2.5	€ 0.06	same
T_{max} =1.75 m	160x25x2	€ 9.09	€ 0.09	same	€ 0.04	same

7.5.3 Gasoil

For tankers that transport gasoil or fuel oil for industry, the impact of including holding cost on the optimal ship dimensions is considerable. For the route Rotterdam – Dordrecht, in all but a few scenarios the optimal ship is a small one with a length of 80 m or less. Furthermore, at small annual demands and short sailing distances, even the maximum possible draught is not used. What also becomes apparent from this table is that the increase in cost due to holding cost may be several times as large as the original direct transport cost, thus signifying the importance of optimization on the basis of total logistical cost rather than the lowest required ship rate for valuable goods.

Table 7-27: Impact of holding cost on optimal dimensions – gasoil, Rotterdam - Dordrecht

Rotterdam – Dordrecht			annual demand 10.000 T		annual demand 25.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	110x20x4.5	€ 2.22	€ 10.71	50x9.5x3	€ 4.28	70x12.5x3.5
T_{max} = 2.8 m	135x17.5x3	€ 2.97	€ 6.51	70x9.5x2	€ 2.61	70x12.5x2.5
T_{max} =1.75 m	135x25x2	€ 4.41	€ 4.88	70x9.5x2	€ 1.95	80x17.5x2

			annual demand 50.000 T		annual demand 100.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	110x20x4.5	€ 2.22	€ 2.14	60x11.45x4.5	€ 1.07	70x12.5x4.5
T_{max} = 2.8 m	135x17.5x3	€ 2.97	€ 1.30	110x11x2.5	€ 0.65	110x11x2.5
T_{max} =1.75 m	135x25x2	€ 4.41	€ 0.98	80x17.5x2	€ 0.49	110x17.5x2

On the route Rotterdam – Nijmegen, the picture is very similar to that on the route Rotterdam - Dordrecht: The overview is dominated by small vessels and only in case of very low water depth and very high demand is the original optimum still the optimum. From Table 7-27 to Table 7-30 it also becomes clear why so many tank vessels that operate today are 86 m long and 9.6 to 11.45 m wide. These ship dimensions fit well with the typical optimal dimensions that are identified in these tables.

Table 7-28: Impact of holding cost on optimal dimensions – gasoil, Rotterdam - Nijmegen

Rotterdam – Nijmegen			annual demand 10.000 T		annual demand 25.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	110x20x4.5	€ 2.99	€ 10.71	60x9.5x3.5	€ 4.28	70x12.5x3.5
T_{max} = 2.8 m	135x25x3	€ 4.09	€ 9.34	70x12.5x2.5	€ 3.73	110x11x2.5
T_{max} =1.75 m	135x25x2	€ 6.12	€ 4.88	70x12.5x2	€ 1.95	110x15x2

			annual demand 50.000 T		annual demand 100.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	110x20x4.5	€ 2.99	€ 2.14	70x12.5x4.5	€ 1.07	80x20x4.5
T_{max} = 2.8 m	135x25x3	€ 4.09	€ 1.87	110x11x2.5	€ 0.93	110x11x2.5
T_{max} =1.75 m	135x25x2	€ 6.12	€ 0.98	110x15x2	€ 0.49	same

Due to the increased transport distance, the required ship rate on the route Rotterdam – Duisburg is higher than on the route Rotterdam – Dordrecht. As a result, the impact the of the ship rate on the total logistical cost is larger, as becomes apparent in Table 7-29 below: in case of low water depth and/or high demand, the original optimal dimensions do not change due to the inclusion of holding cost, while in the other cases small vessels are favored over large ones due to the lower holding cost.

Table 7-29: Impact of holding cost on optimal dimensions – gasoil, Rotterdam - Duisburg

Rotterdam - Duisburg			annual demand 10.000 T		annual demand 25.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	135x25x4.5	€ 3.77	€ 16.23	70x12.5x3.5	€ 6.49	60x15x4.5
T_{max} = 2.8 m	135x25x3	€ 5.26	€ 9.34	60x15x2.5	€ 3.73	80x17.5x3
T_{max} =1.75 m	135x25x2	€ 7.93	€ 4.88	80x17.5x2	€ 1.95	same

			annual demand 50.000 T		annual demand 100.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	135x25x4.5	€ 3.77	€ 3.25	80x20x4.5	€ 1.62	80x20x4.5
T_{max} = 2.8 m	135x25x3	€ 5.26	€ 1.87	135x17.5x3	€ 0.93	same
T_{max} =1.75 m	135x25x2	€ 7.93	€ 0.98	same	€ 0.49	same

On the longest route, Rotterdam – Koblenz (Table 7-30 below), the increase in scale continues, but the most important thing to note is that in case of deep water or demands of 25.000 T per year or less, small ships with a length of 86 m or less are still a more cost-effective means of transporting goods than the much larger ships with a low required ship rate.

Table 7-30: Impact of holding cost on optimal dimensions – gasoil, Rotterdam - Koblenz

Rotterdam - Koblenz			annual demand 10.000 T		annual demand 25.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	135x25x4.5	€ 4.81	€ 16.23	70x12.5x3.5	€ 6.49	60x15x4.5
T_{max} = 2.8 m	135x25x2.5	€ 7.25	€ 8.10	70x15x2.5	€ 3.24	86x15x2.5
T_{max} =1.75 m	135x25x2	€ 10.32	€ 4.88	135x15x2	€ 1.95	same

			annual demand 50.000 T		annual demand 100.000 T	
	original optimum	original cost	increase in cost	new optimum	increase in cost	new optimum
T_{max} = 4.5 m	135x25x4.5	€ 4.81	€ 3.25	80x20x4.5	€ 1.62	80x20x4.5
T_{max} = 2.8 m	135x25x2.5	€ 7.25	€ 1.62	same	€ 0.81	same
T_{max} =1.75 m	135x25x2	€ 10.32	€ 0.98	same	€ 0.49	same

7.6 Identification of optimal dimensions - lowest total logistical cost with internalization of external emission costs

The fourth and final cost study is the determination of the optimal ship dimensions when the cost of internalizing the external emission costs is added to the total logistical cost. The following tables show a comparison between the original optimal main dimensions on the basis of the required ship rate (paragraph 7.3), optimal dimensions from paragraph 7.5 (column 'w/o intl ext') and the optimal dimensions in case external costs are internalized (column 'w intl ext').

While inclusion of holding cost into the cost comparison of paragraph 7.5 has led to a reduction of the optimal ship dimensions, internalization of external emission costs should tip the balance back towards larger, more fuel efficient ships again. The extent to which this effect actually leads to different optimal dimensions is discussed in the following paragraphs.

7.6.1 Iron ore

In case of the transport of iron ore, Table 7-31 shows that internalization of external costs only changes the optimal dimensions in several of cases: especially on the long routes and in case of low water levels, i.e. those cases where fuel consumption per unit of transported cargo is high, a shift towards larger ships can be observed (yellow cells). In one case on the route Rotterdam – Duisburg a shift towards a shorter (and as a result, slower and more fuel efficient) ship occurs.

Table 7-31: Impact of internalization of external costs on optimal ship dimensions – iron ore

Rotterdam - Dordrecht		annual demand 10.000 T		annual demand 25.000 T	
	original optimum	w/o intl ext	w intl ext	w/o intl ext	w intl ext
T_{max} = 4.5 m	60x15x4.5	same	same	same	same
T_{max} = 2.8 m	135x17.5x3	70x15x3	70x15x3	70x15x3	70x15x3
T_{max} =1.75 m	135x20x2	70x17.5x2	70x17.5x2	70x17.5x2	110x17.5x2

		annual demand 50.000 T		annual demand 100.000 T	
	original optimum	w/o intl ext	w intl ext	w/o intl ext	w intl ext
T_{max} = 4.5 m	60x15x4.5	same	same	same	same
T_{max} = 2.8 m	135x17.5x3	70x15x3	70x15x3	70x15x3	70x15x3
T_{max} =1.75 m	135x20x2	70x17.5x2	same	70x17.5x2	same

Rotterdam - Nijmegen		annual demand 10.000 T		annual demand 25.000 T	
	original optimum	w/o intl ext	w intl ext	w/o intl ext	w intl ext
T_{max} = 4.5 m	135x20x4.5	60x15x4.5	60x15x4.5	60x15x4.5	60x15x4.5
T_{max} = 2.8 m	135x17.5x3	70x15x3	70x15x3	70x17.5x3	70x15x3
T_{max} =1.75 m	135x20x2	110x17.5x2	same	same	same

		annual demand 50.000 T		annual demand 100.000 T	
	original optimum	w/o intl ext	w intl ext	w/o intl ext	w intl ext
T_{max} = 4.5 m	135x20x4.5	60x15x4.5	60x15x4.5	60x15x4.5	60x15x4.5
T_{max} = 2.8 m	135x17.5x3	same	same	same	same
T_{max} =1.75 m	135x20x2	same	same	same	same

Rotterdam - Duisburg		annual demand 10.000 T		annual demand 25.000 T	
	original optimum	w/o intl ext	w intl ext	w/o intl ext	w intl ext
T_{max} = 4.5 m	135x25x4.5	60x15x4.5	60x15x4.5	86x20x4.5	70x17.5x4.5
T_{max} = 2.8 m	135x17.5x3	86x17.5x3	80x17.5x3	same	same
T_{max} =1.75 m	160x25x2	135x20x2	same	same	same

		annual demand 50.000 T		annual demand 100.000 T	
	original optimum	w/o intl ext	w intl ext	w/o intl ext	w intl ext
T_{max} = 4.5 m	135x25x4.5	135x20x4.5	135x20x4.5	135x20x4.5	135x20x4.5
T_{max} = 2.8 m	135x17.5x3	same	same	same	same
T_{max} =1.75 m	160x25x2	same	same	same	same

Rotterdam - Koblenz		annual demand 10.000 T		annual demand 25.000 T	
	original optimum	w/o intl ext	w intl ext	w/o intl ext	w intl ext
T_{max} = 4.5 m	160x25x4.5	60x15x4.5	70x17.5x4.5	135x20x4.5	135x20x4.5
T_{max} = 2.8 m	160x20x2.5	135x20x2.5	135x20x2.5	135x20x2.5	same
T_{max} =1.75 m	160x25x2	same	same	same	same

		annual demand 50.000 T		annual demand 100.000 T	
	original optimum	w/o intl ext	w intl ext	w/o intl ext	w intl ext
T_{max} = 4.5 m	160x25x4.5	135x20x4.5	same	135x25x4.5	same
T_{max} = 2.8 m	160x20x2.5	135x20x2.5	same	135x20x2.5	same
T_{max} =1.75 m	160x25x2	same	same	same	same

7.6.2 Coal

For the transport of coal, the results are very similar to those of iron ore. Changes mainly occur at low water depth and long distances, where fuel consumption is relatively high. From this and the results for iron ore, it can be concluded that for a significant part of all dry bulk commodities, the internalization of external emission costs has only a limited impact on the optimal ship dimensions.

Table 7-32: Impact of internalization of external costs on optimal ship dimensions - coal

Rotterdam - Dordrecht		annual demand 10.000 T		annual demand 25.000 T	
	original optimum	w/o intl ext	w intl ext	w/o intl ext	w intl ext
T_{max} = 4.5 m	60x15x4.5	same	same	same	same
T_{max} = 2.8 m	135x17.5x3	70x15x3	70x15x3	70x15x3	70x15x3
T_{max} =1.75 m	135x20x2	70x17.5x2	110x17.5x2	70x17.5x2	same

		annual demand 50.000 T		annual demand 100.000 T	
	original optimum	w/o intl ext	w intl ext	w/o intl ext	w intl ext
T_{max} = 4.5 m	60x15x4.5	same	same	same	same
T_{max} = 2.8 m	135x17.5x3	70x15x3	70x15x3	same	same
T_{max} =1.75 m	135x20x2	70x17.5x2	same	same	same

Rotterdam - Nijmegen		annual demand 10.000 T		annual demand 25.000 T	
	original optimum	w/o intl ext	w intl ext	w/o intl ext	w intl ext
T_{max} = 4.5 m	135x20x4.5	60x15x4.5	60x15x4.5	60x15x4.5	60x15x4.5
T_{max} = 2.8 m	135x17.5x3	70x15x3	70x17.5x3	same	same
T_{max} =1.75 m	135x20x2	same	same	same	same

		annual demand 50.000 T		annual demand 100.000 T	
	original optimum	w/o intl ext	w intl ext	w/o intl ext	w intl ext
T_{max} = 4.5 m	135x20x4.5	60x15x4.5	60x15x4.5	60x15x4.5	60x15x4.5
T_{max} = 2.8 m	135x17.5x3	same	same	same	same
T_{max} =1.75 m	135x20x2	same	same	same	same

Rotterdam - Duisburg		annual demand 10.000 T		annual demand 25.000 T	
	original optimum	w/o intl ext	w intl ext	w/o intl ext	w intl ext
T_{max} = 4.5 m	135x25x4.5	70x17.5x4.5	70x17.5x4.5	135x20x4.5	135x20x4.5
T_{max} = 2.8 m	135x17.5x3	same	same	same	same
T_{max} =1.75 m	160x25x2	same	same	same	same

		annual demand 50.000 T		ann. demand 100.000 T	
	original optimum	w/o intl ext	w intl ext	w/o intl ext	w intl ext
T_{max} = 4.5 m	135x25x4.5	135x20x4.5	135x20x4.5	same	same
T_{max} = 2.8 m	135x17.5x3	same	same	same	same
T_{max} =1.75 m	160x25x2	same	same	same	same

Rotterdam - Koblenz		annual demand 10.000 T		annual demand 25.000 T	
	original optimum	w/o intl ext	w intl ext	w/o intl ext	w intl ext
T_{max} = 4.5 m	160x25x4.5	86x20x4.5	60x15x4.5	135x20x4.5	135x20x4.5
T_{max} = 2.8 m	160x20x2.5	135x20x2.5	135x20x2.5	135x20x2.5	same
T_{max} =1.75 m	160x25x2	same	same	same	same

		annual demand 50.000 T		annual demand 100.000 T	
	original optimum	w/o intl ext	w intl ext	w/o intl ext	w intl ext
T_{max} = 4.5 m	160x25x4.5	135x25x4.5	135x20x4.5	same	same
T_{max} = 2.8 m	160x20x2.5	135x20x2.5	same	same	same
T_{max} =1.75 m	160x25x2	same	same	same	same

7.6.3 Gasoil

The high value of gasoil typically results in small optimal dimensions for tank ships, as was discussed in chapter 7.5. For such small ships, which consume more fuel per ton of cargo than large ships, internalization of external costs has a relatively large impact on the total cost. This also becomes apparent from Table 7-33, where internalization of external costs leads to different optimal dimensions in 14 cases. These changes are mainly a shift to vessels with a length of 60 m, since the 60 meter vessel is slow and, as a result, more fuel-efficient than the longer and faster vessels. In a limited number of cases, there is a shift towards larger ships that benefit from economies of scale in powering. This is the same effect that was observed in Figure 7-3: small ships benefit from low fuel consumption due to low speeds, while large ships benefit from the ability to spread the cost of relatively high fuel consumption over a large number of transported tons.

Table 7-33: Impact of internalization of external costs on optimal dimensions - gasoil

Rotterdam - Dordrecht		annual demand 10.000 T		annual demand 25.000 T	
	original optimum	w/o intl	w intl	w/o intl	w intl
T_{max} = 4.5 m	110x20x4.5	50x9.5x3	50x9.5x3	70x12.5x3.5	60x12.5x3.5
T_{max} = 2.8 m	135x17.5x3	70x9.5x2	70x9.5x2	70x12.5x2.5	60x15x2.5
T_{max} =1.75 m	135x25x2	70x9.5x2	70x9.5x2	80x17.5x2	80x17.5x2

		annual demand 50.000 T		annual demand 100.000 T	
	original optimum	w/o intl	w intl	w/o intl	w intl
T_{max} = 4.5 m	110x20x4.5	60x11.45x4.5	60x11.45x4.5	70x12.5x4.5	70x12.5x4.5
T_{max} = 2.8 m	135x17.5x3	110x11x2.5	110x11x2.5	110x11x2.5	110x11x 2.5
T_{max} =1.75 m	135x25x2	80x17.5x2	80x17.5x2	110x17.5x2	110x17.5x2

Rotterdam - Nijmegen		annual demand 10.000 T		annual demand 25.000 T	
	original optimum	w/o intl	w intl	w/o intl	w intl
T_{max} = 4.5 m	110x20x4.5	60x9.5x3.5	60x9.5x3.5	70x12.5x3.5	70x12.5x3.5
T_{max} = 2.8 m	135x25x3	70x12.5x2.5	60x15x2.5	110x11x2.5	60x15x2.5
T_{max} =1.75 m	135x25x2	70x12.5x2	110x11x2.5	110x15x2	110x17.5x2

		annual demand 50.000 T		annual demand 100.000 T	
	original optimum	w/o intl	w intl	w/o intl	w intl
T_{max} = 4.5 m	110x20x4.5	70x12.5x4.5	70x12.5x4.5	80x20x4.5	80x20x4.5
T_{max} = 2.8 m	135x25x3	110x11x2.5	110x11x2.5	110x11x2.5	135x17.5x3
T_{max} =1.75 m	135x25x2	110x15x2	same	same	same

Rotterdam - Duisburg		annual demand 10.000 T		annual demand 25.000 T	
	original optimum	w/o intl	w intl	w/o intl	w intl
T_{max} = 4.5 m	135x25x4.5	70x12.5x3.5	60x15x3.5	60x15x4.5	60x15x4.5
T_{max} = 2.8 m	135x25x3	60x15x2.5	60x15x2.5	80x17.5x3	80x17.5x3
T_{max} =1.75 m	135x25x2	80x17.5x2	same	same	same

		annual demand 50.000 T		annual demand 100.000 T	
	original optimum	w/o intl	w intl	w/o intl	w intl
T_{max} = 4.5 m	135x25x4.5	80x20x4.5	80x20x4.5	80x20x4.5	80x20x4.5
T_{max} = 2.8 m	135x25x3	135x17.5x3	135x17.5x3	same	same
T_{max} =1.75 m	135x25x2	same	same	same	same

Rotterdam - Koblenz		annual demand 10.000 T		annual demand 25.000 T	
	original optimum	w/o intl	w intl	w/o intl	w intl
T_{max} = 4.5 m	135x25x4.5	70x12.5x3.5	60x15x3.5	60x15x4.5	60x15x4.5
T_{max} = 2.8 m	135x25x2.5	70x15x2.5	70x15x2.5	86x15x2.5	80x15x2.5
T_{max} =1.75 m	135x25x2	135x15x2	135x15x1.5	same	same

		annual demand 50.000 T		annual demand 100.000 T	
	original optimum	w/o intl	w intl	w/o intl	w intl
T_{max} = 4.5 m	135x25x4.5	80x20x4.5	80x20x4.5	80x20x4.5	same
T_{max} = 2.8 m	135x25x2.5	same	same	same	same
T_{max} =1.75 m	135x25x2	same	same	same	same

7.7 Flow charts for the determination of optimal ship dimensions

In the previous paragraphs, it was found that the optimal dimensions of inland ships are highly dependent on the characteristics of the route, the value of the transported goods and the annual demand of the shipper. It was also found that the optimal ship dimensions are not very sensitive to changes in the ship's cost structure and that internalization of external costs only has a limited impact on the relative performance of ships of various main dimensions.

In order to make the results of the previous paragraphs more easy to use, they are placed in a number of flow charts, on the basis of which the optimal ship dimensions can be estimated as a function of route, water depth and annual demand for the three investigated ship types. This is done under the assumption that the value of the transported goods is linked to vessel type: low to medium value goods are transported by dry bulk ship and high value goods by tank ship.

The flow charts start with the identification of the navigation area of the ship: If it is intended for class III canals, the ship dimensions should be maximized for the relevant waterway. If not, it needs to be decided consecutively what the typical sailing distance is and if optimization of vessel dimensions should be done from a lowest required ship rate point-of-view or from a lowest total logistical cost point-of-view. Whenever it has an impact on the optimal ship dimensions, the flowchart also requires definition of the expected typical water depth and expected typical annual demand for goods by a shipper before a conclusion about the optimal dimensions can be reached.

Figure 7-17 shows the flow chart for dry bulk vessels, while Figure 7-18 shows the flow chart for tank vessels. Figure 7-19, which shows the flow chart for container ships, is simpler than the other two figures since container ship dimensions can only be optimized from a required ship rate point-of-view because a container ship will never transport goods for a single shipper.

Optimal dimensions of dry bulk ships

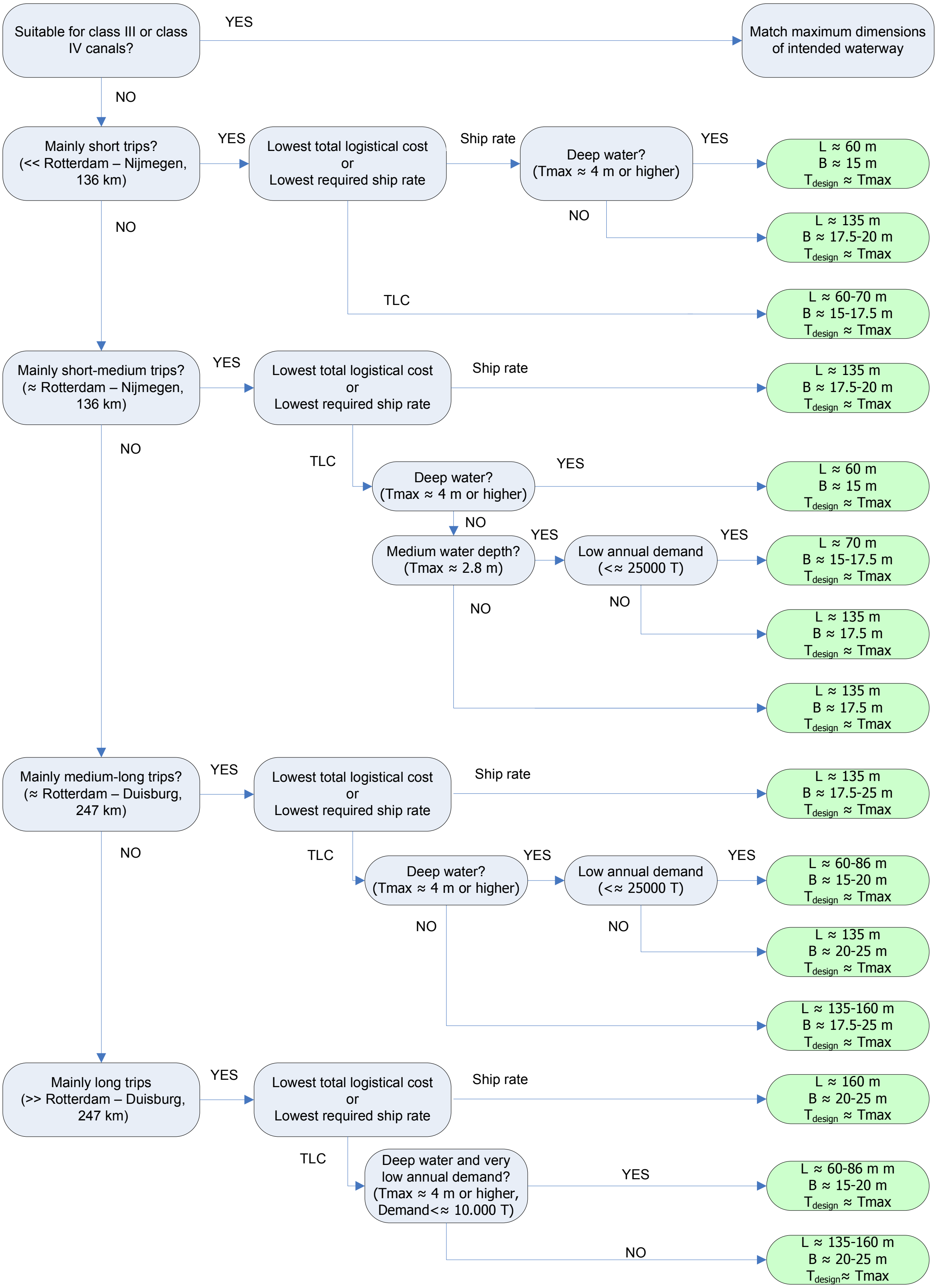
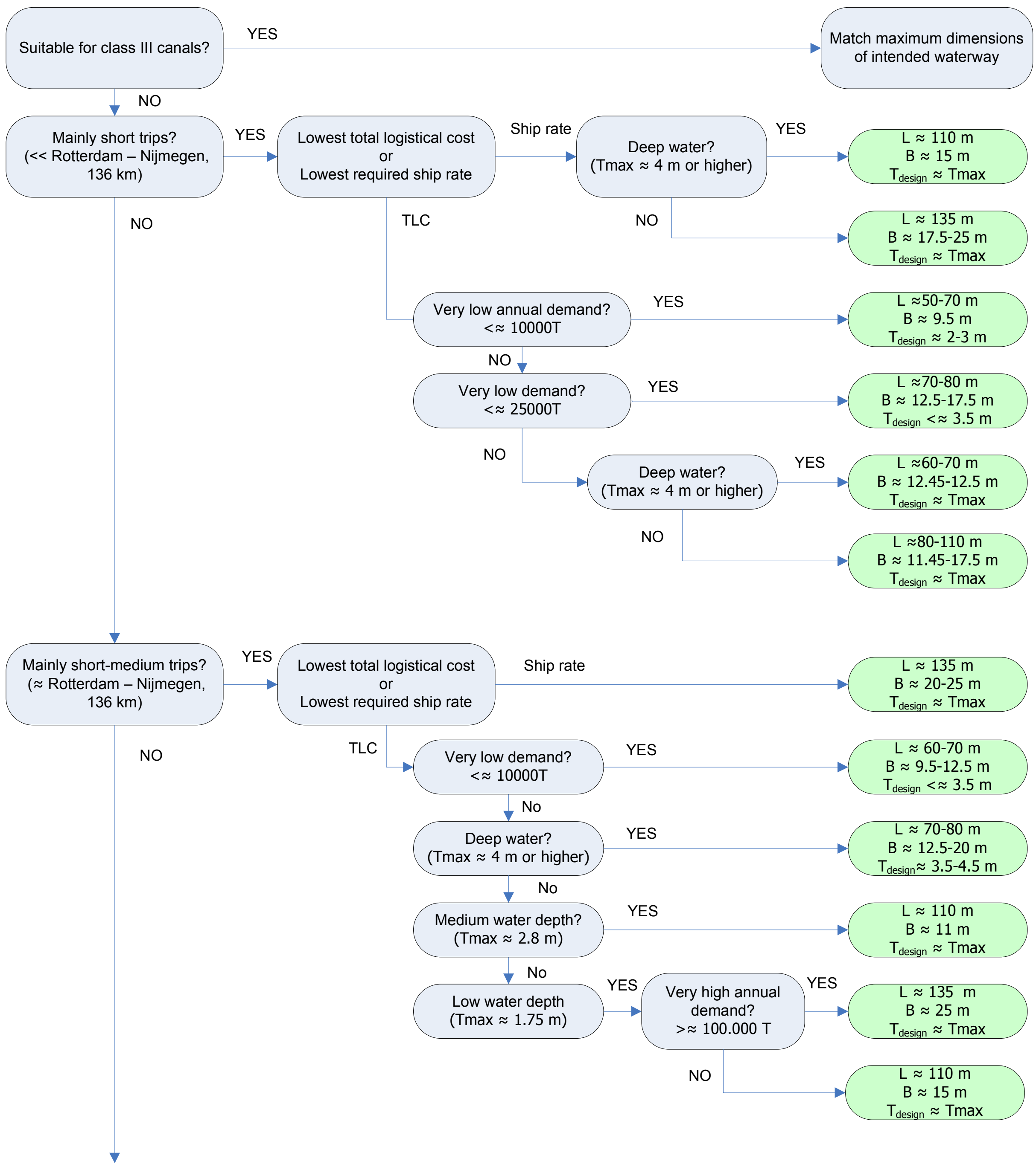


Figure 7-17: Flow chart for the determination of the optimal dimensions of dry bulk vessels

Optimal dimensions of tank ships



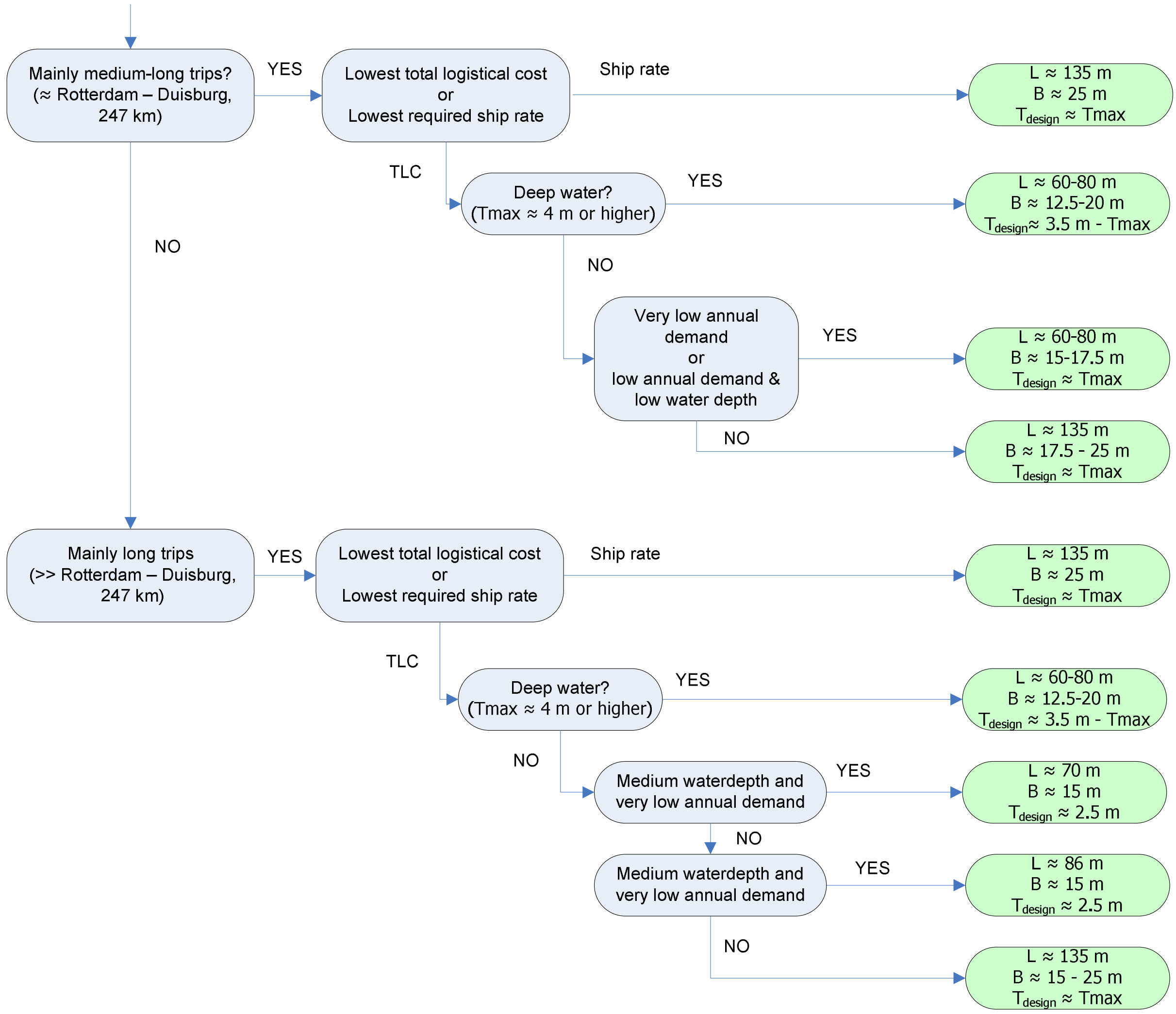


Figure 7-18: Flow chart for the determination of the optimal dimensions of tank ships

Optimal dimensions of container ships

Since container ships typically transport goods for multiple shippers in a single trip, it is not possible to link the total logistical costs of the shipper directly to the size of the ship. As a result, only a scheme for the determination of the main dimensions that allows determination of the lowest required ship rate is provided.

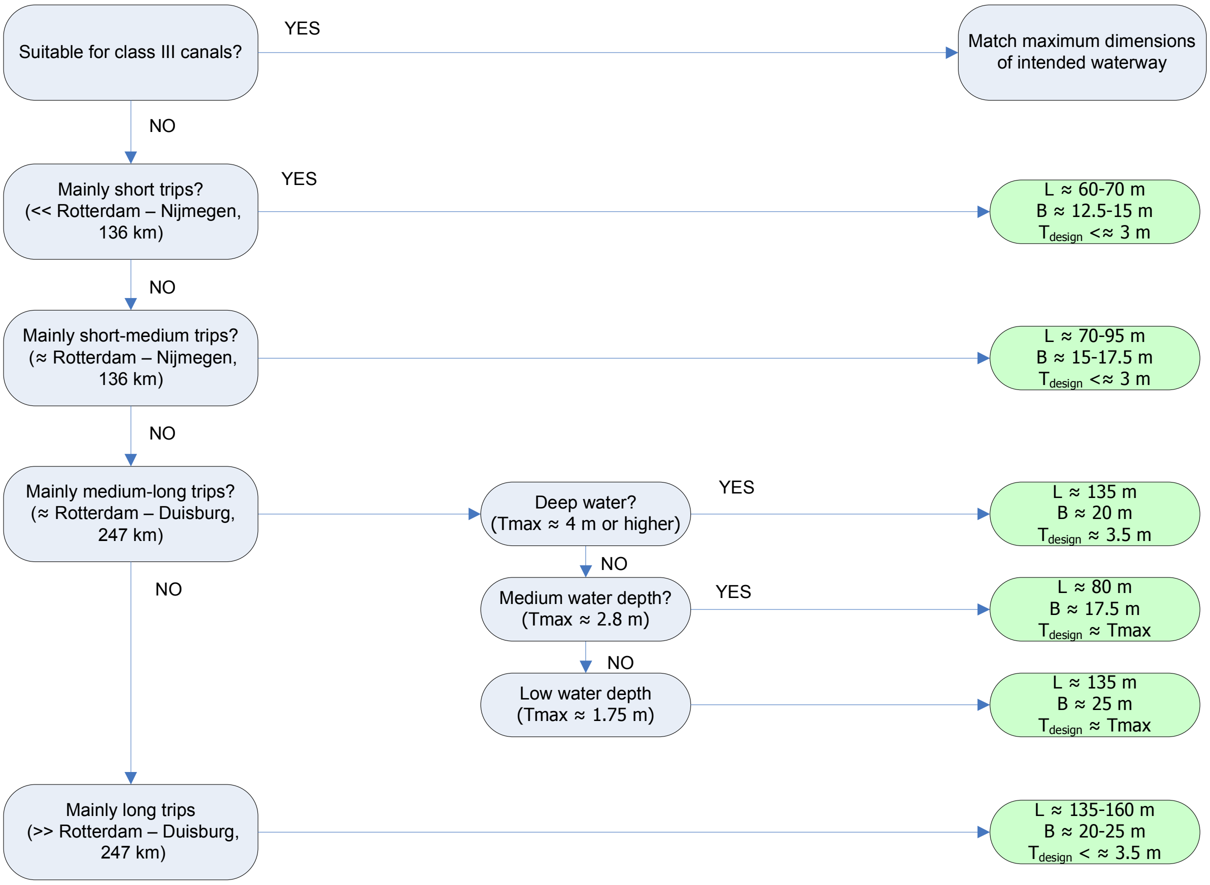


Figure 7-19: Flow chart for the determination of the optimal dimensions of container ships

7.8 Comparison of competitiveness between waterborne, road and rail transport

In the previous paragraphs, it was identified which ship dimensions are optimal for a number of assessment criteria in various transport scenarios. However, this has been a selection of the most competitive ship rather than a selection of the best transport mode. Since it is still possible that the optimal ship performs worse than a truck or train, in this paragraph an assessment of the competitiveness of waterborne transport versus road transport and rail transport is made, both in terms of transport cost and in terms of external costs that result from emissions.

The comparison with road transport is made for two scenarios: the first scenarios is a pure comparison between road and water without pre or end haulage and in the second scenario the ship is assumed to be part of an intermodal chain that consists of the waterborne leg, handling in one inland port and 10 kilometers of pre/end haulage. Handling cost at the sea port and final destination are assumed to be identical for all modes. Therefore, it is excluded from the calculation. The comparison with rail is made under the assumption that both modes require the same amount of handling and end haulage at equal cost and that handling and end haulage can, therefore, be left out of the comparison.

For dry bulk a handling cost of 2.8 €/T per move is used and for containers a handling cost of 28.5 €/TEU (all 2011 values) is used, based on Lundoluka et al. [2005], indexed according to the OECD's producers price index [OECD, 2012]. The costs of road and rail transport are determined according to the formulas that are described in chapter 6.2.2.

7.8.1 Dry bulk

To determine in which cases ships can compete with road transport, it is assessed on how many of the four routes (Rotterdam to Dordrecht, Nijmegen, Duisburg or Koblenz) ships can compete with road transport when the out-of-pocket cost of transport is the assessment criterion. This is done for a water depth that is equal to the lowest agreed water depth, i.e. 2.8 m draught between Rotterdam and Duisburg and 2.5 m between Duisburg and Koblenz. In all figures in this paragraph, n indicates on how many of the four routes the performance of waterborne or intermodal transport is better than that of pure road transport.

Figure 7-20 below shows the basic comparison between waterborne and road transport, without any pre or end haulage. It shows that when no pre or end haulage is required, almost all ships can compete with road transport in all cases, except for the smallest ships and some of the big ships with a very low design draught of 1.5 m.

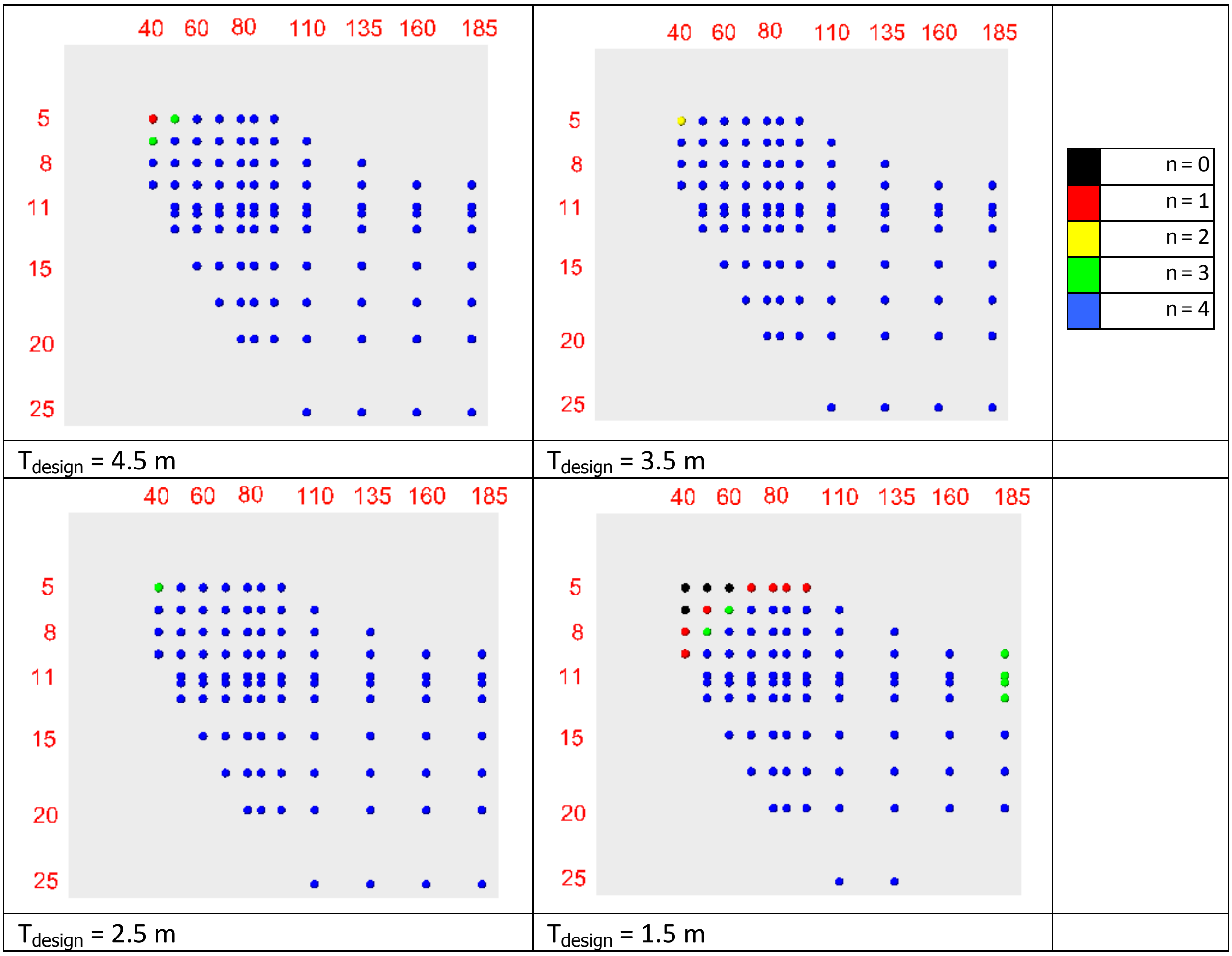


Figure 7-20: Competitiveness of dry bulk vessels compared to road - no end haulage

When pre or end haulage is required, the image changes substantially, as becomes apparent from Figure 7-21 below. None of the dry bulk vessels can now compete on all routes because of the high cost of handling and end haulage, while a significant number of the small and very low draught vessels can not compete on any of the routes.

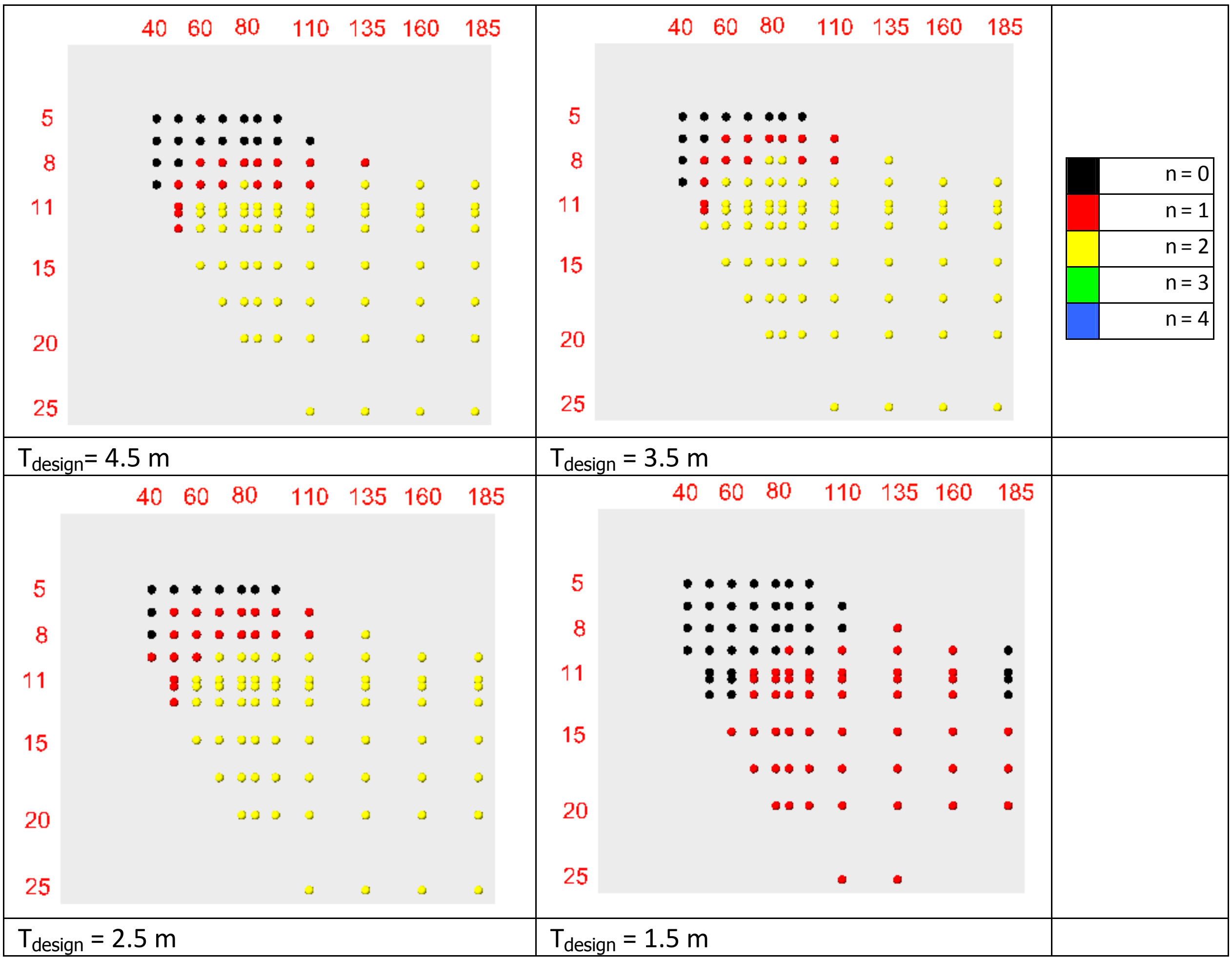


Figure 7-21: Competitiveness of dry bulk vessels compared to road- with end haulage

One of the important conclusions to be drawn from Figure 7-21 above is that especially for those smaller vessels that are intended for transport on canals, their continued viability strongly depends on the presence of shippers that are located directly at the waterfront. The figure also explains why inland shipping plays such a small role in continental transport: Handling and pre- and/or end haulage severely reduce a vessel's ability to compete with road transport.

A comparison with rail is also made, which is shown in Figure 7-22. Since the rail track from Rotterdam to the various destinations along the Rhine follows the river closely, the comparison is made on the basis of the same travelled distance, whereas the comparison between water and road took into account that the distance from origin to destination is smaller by road than it is by water.

A comparison between Figure 7-20 and Figure 7-22 shows that it is harder for small ships to compete with rail than it is with road when no pre or end haulage is required. This is due to the scale advantages that rail has over road. In case end haulage is required, a comparison between Figure 7-21 and Figure 7-22 shows that road still is the main competitor for inland waterway transport. Figure 7-22 also shows that ships with a draught of 1.5 meters will only seldom be able to compete with rail.

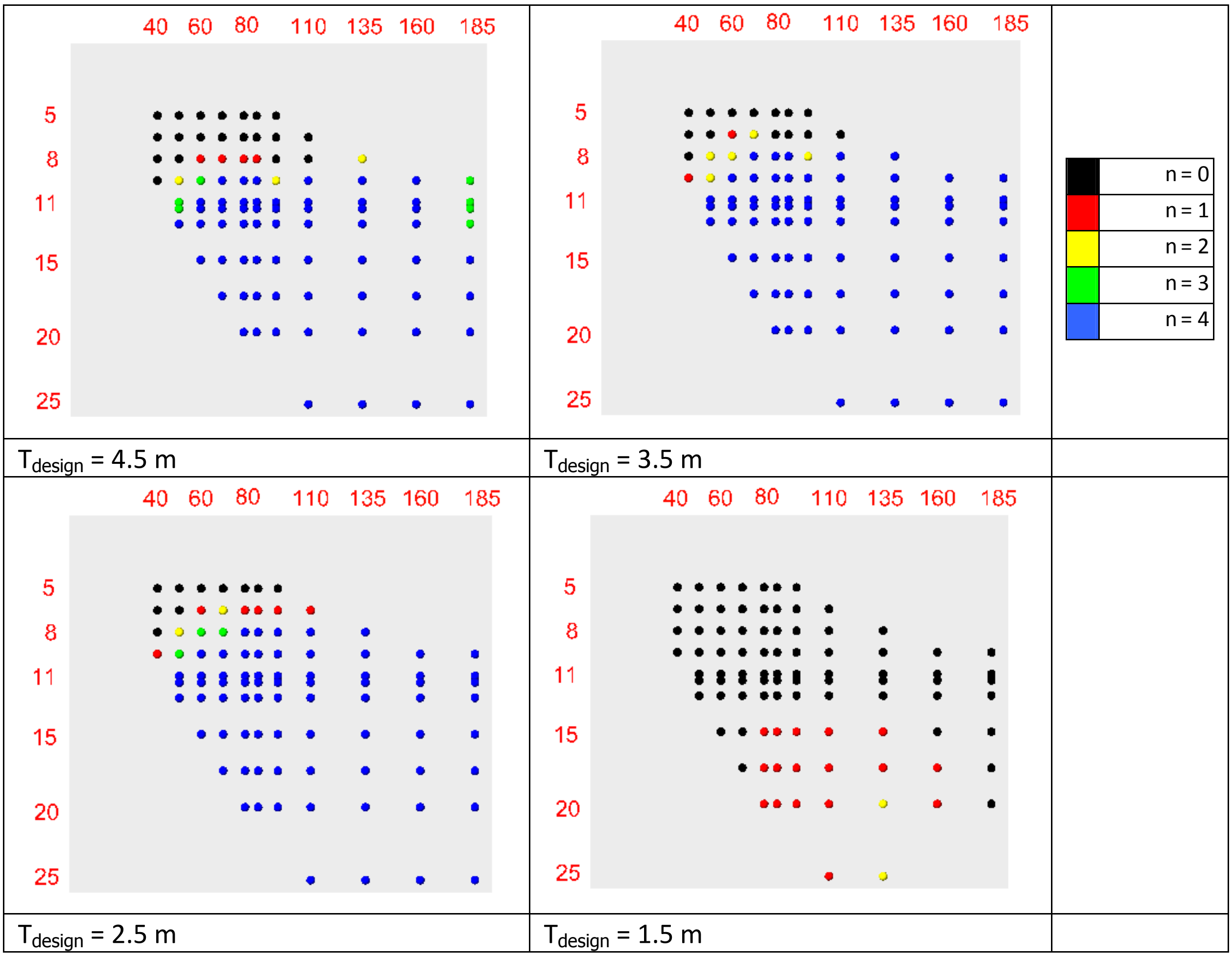


Figure 7-22: Competitiveness of dry vessels with rail – independent of need for end haulage

7.8.2 Containers

Since the final destination of a container is typically not located directly at the waterfront, there is a need for end haulage in almost all cases. Because of this, Figure 7-23 includes end haulage, while transport without end haulage is not explored. Due to the fact that handling a 20 foot container with a weight of 14 tons is often cheaper than handling 14 tons of bulk goods and the assumption that waiting times for container ships are lower than those for dry bulk vessels (see chapter 6.2.1), the competitiveness of container vessels is better than that of dry bulk vessels. Still, in none of the cases intermodal transport is able to compete with road transport on the short Rotterdam – Dordrecht route while especially narrow vessels also have difficulty competing on the route Rotterdam – Nijmegen on the basis of out-of-pocket transport cost alone. It should be noted that trucking costs are very sensitive to time spent at the terminal for such short distances: as soon as delays occur at the seaport or congestion slows the truck down, the competitiveness of waterborne transport quickly improves. However, this works both ways: in case ships have to call at multiple terminals within one port to load and unload containers, this will increase roundtrip times and decrease the competitiveness of inland ships.

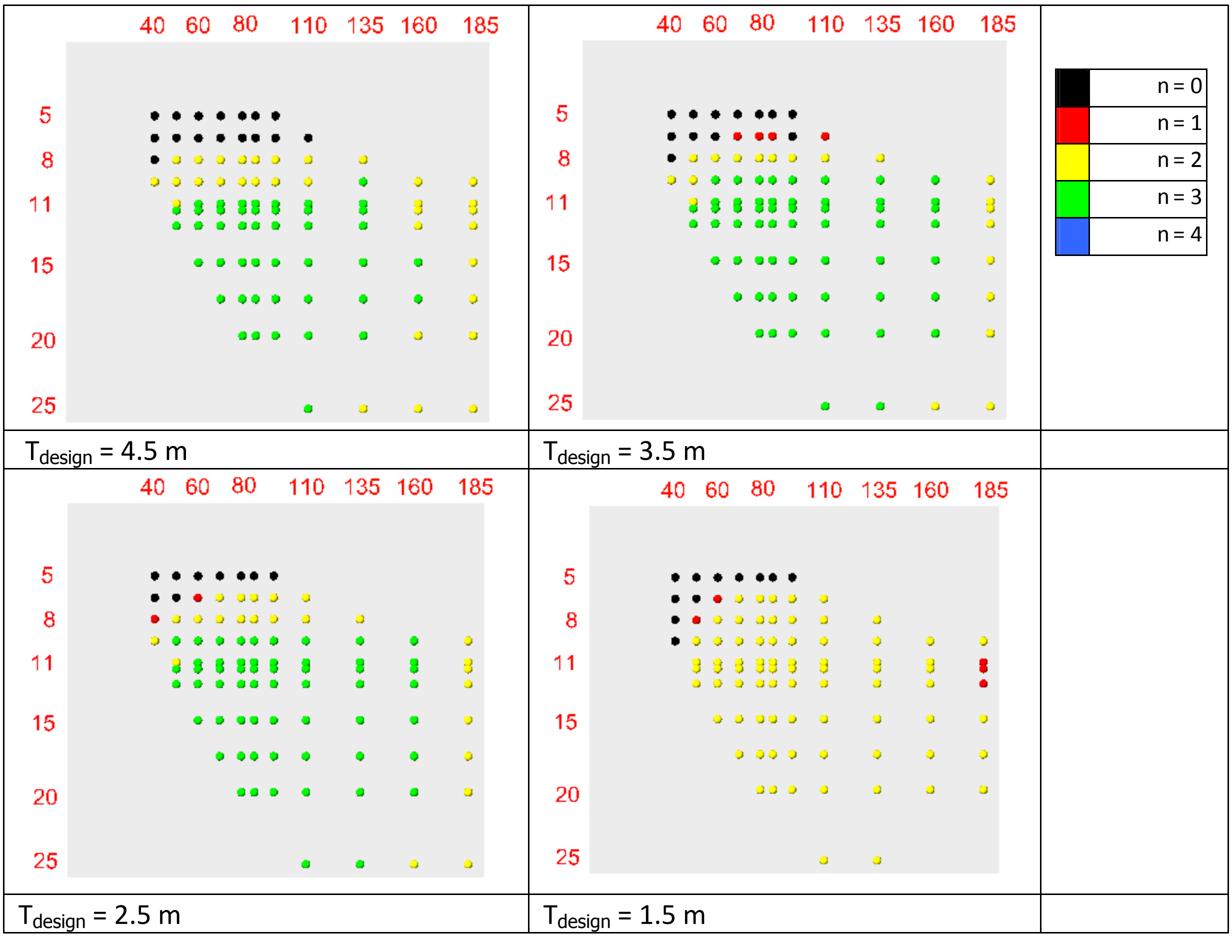
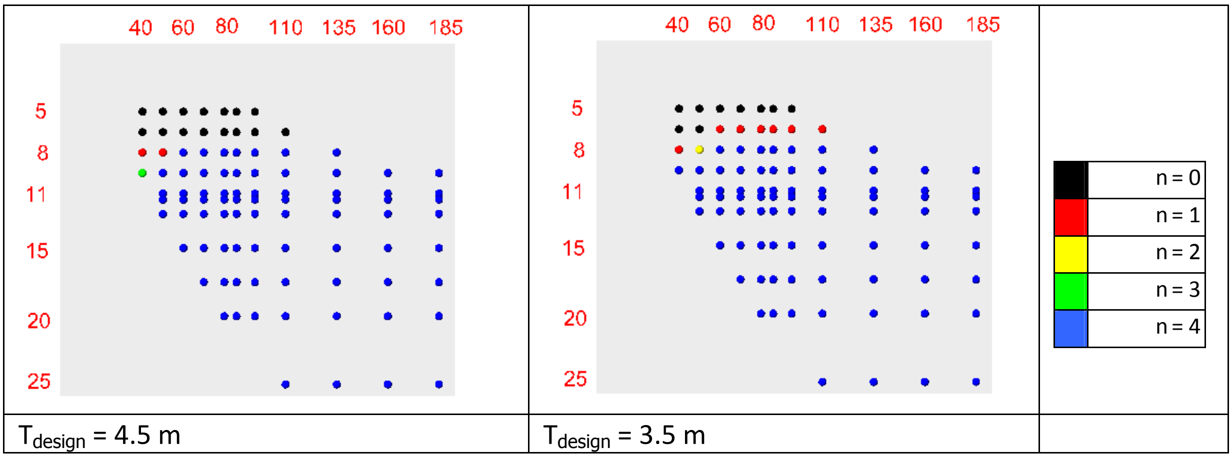


Figure 7-23: Competitiveness of container ships with road - with end haulage

When a comparison with rail is made in Figure 7-24, it becomes clear that most vessels can compete with rail on all routes. A comparison between Figure 7-21 and Figure 7-23 also shows that the competitiveness of shallow draught container vessels with road is much better than that of shallow draught dry bulk vessels due to the fact that they spend less time in port (see chapter 6.2.1). In the same way as in the comparison with road transport, this time in port will become longer in case the ship needs to visit several terminals in one port to load and unload containers.



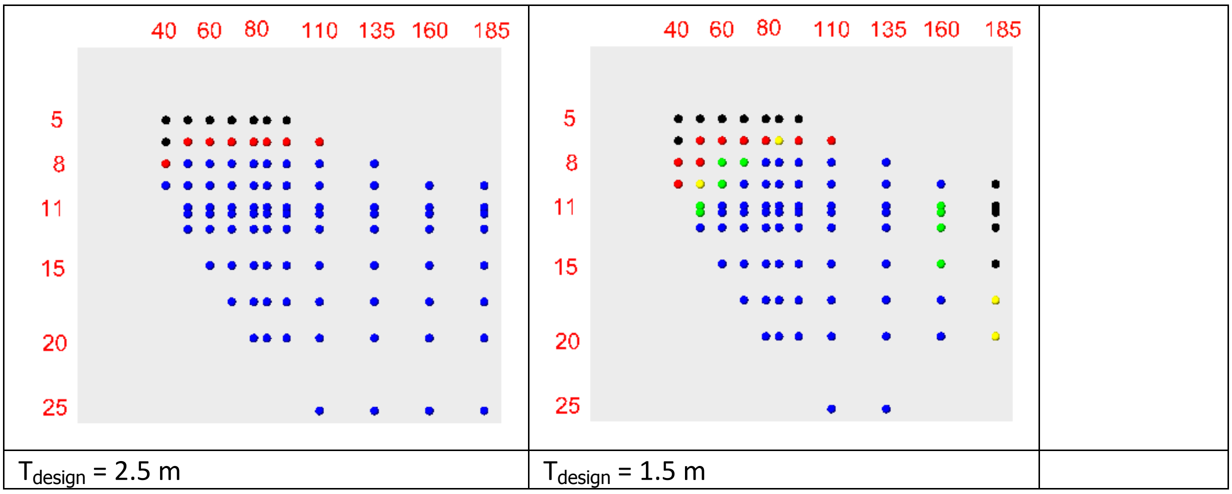


Figure 7-24: Competitiveness of container ships with rail – independent of need for end haulage

7.8.3 Liquid bulk

When the competitiveness of tank ships is compared to road transport, a similar image appears as for dry bulk: when no end haulage is required, the vast majority of vessels can compete with road transport on the vast majority of routes, and in case end haulage is required, this number is greatly reduced. What is important to note in Figure 7-25 compared to Figure 7-20 is that more of the narrow deep draught vessels are unable to compete with road transport since their design is such that they cannot be loaded to their design draught for stability reasons and as a result, they can carry very little cargo. For the vessels with a very low draught, it can also be seen that several of them can not compete on all routes. In this case that is due to the fact that the tank ships are heavier and more expensive than dry bulk ships, thus resulting in higher transport cost per transported unit of cargo.

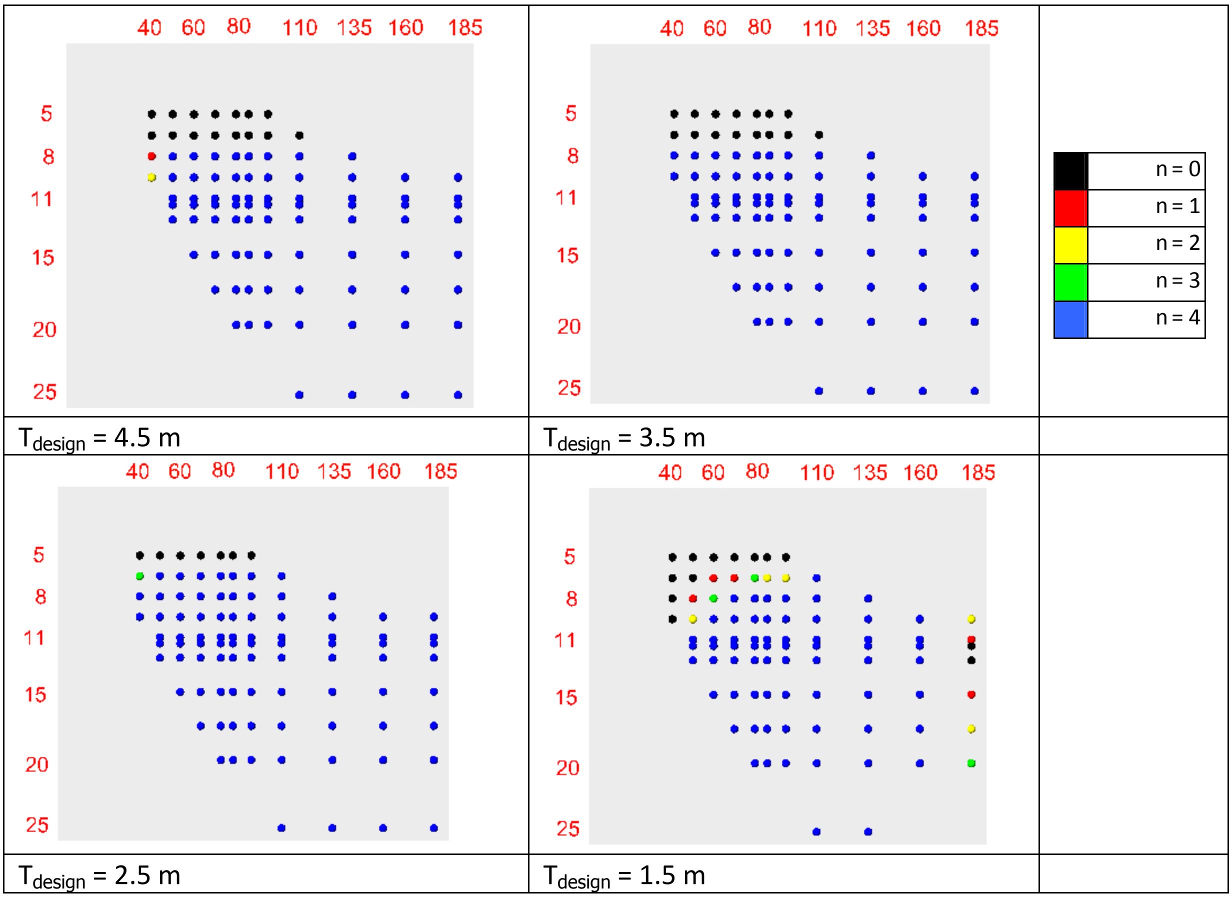


Figure 7-25: Competitiveness of tank ships with road - no end haulage

The effects that become apparent from a comparison of Figure 7-20 with Figure 7-25 also become apparent when Figure 7-26 below is compared to its dry bulk counterpart: across the board, the ability of tank vessels to compete with road transport is less than that of dry bulk vessels because of the fact that tank vessels are heavier and more expensive to build.

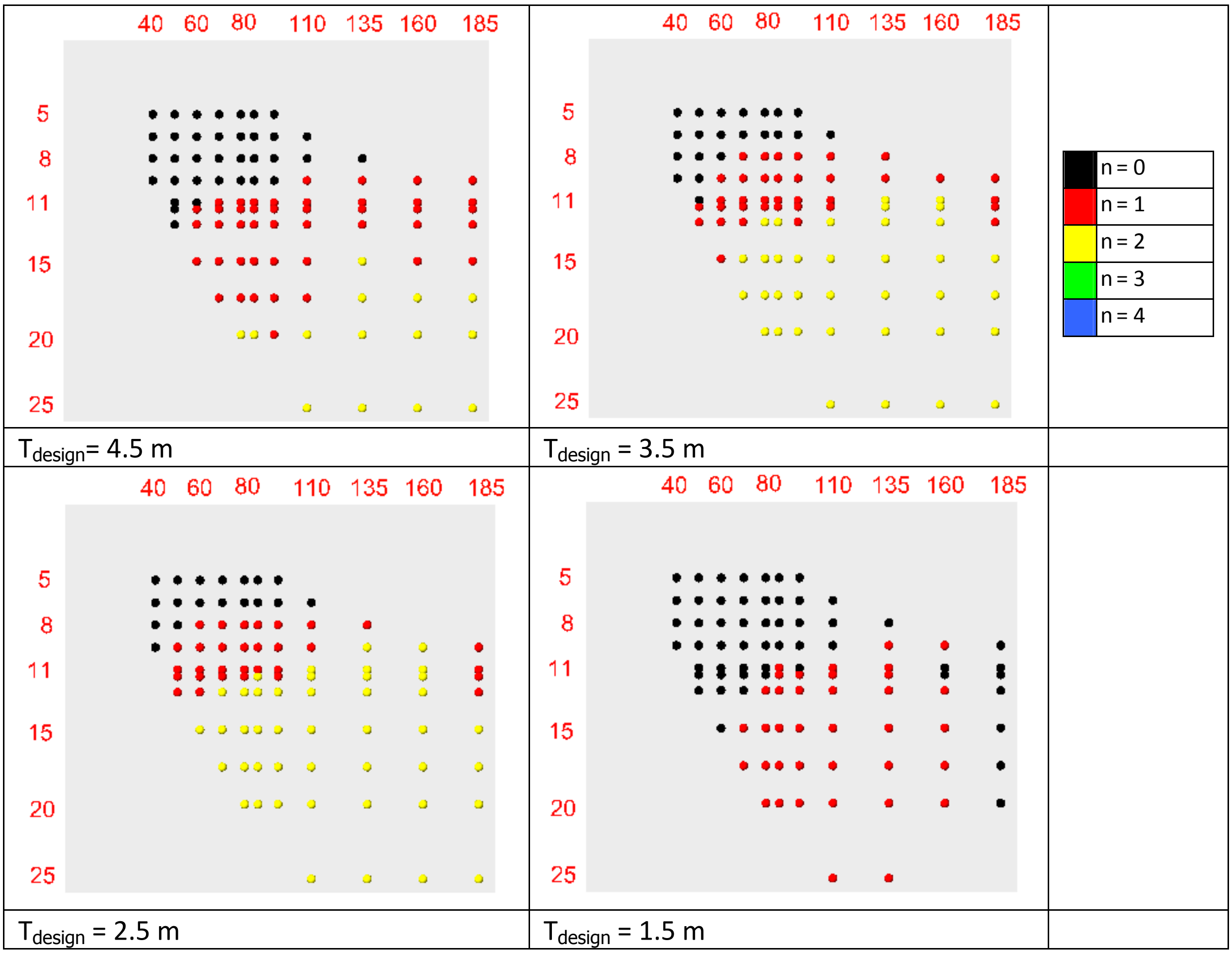


Figure 7-26: Competitiveness of tank ships with road - with end haulage

The effect of the increase in transport cost due to the use of tank vessels, that are heavier and more expensive than dry bulk vessels, also becomes apparent from Figure 7-27. At water depths that are equal to the minimum agreed water level, especially the ships with the largest design draughts, which can not be loaded completely under these circumstances, have difficulty to compete with rail. Most of the vessels with a medium design draught can compete with rail on a substantial number of routes, while vessels with a low design draught can not compete with rail.

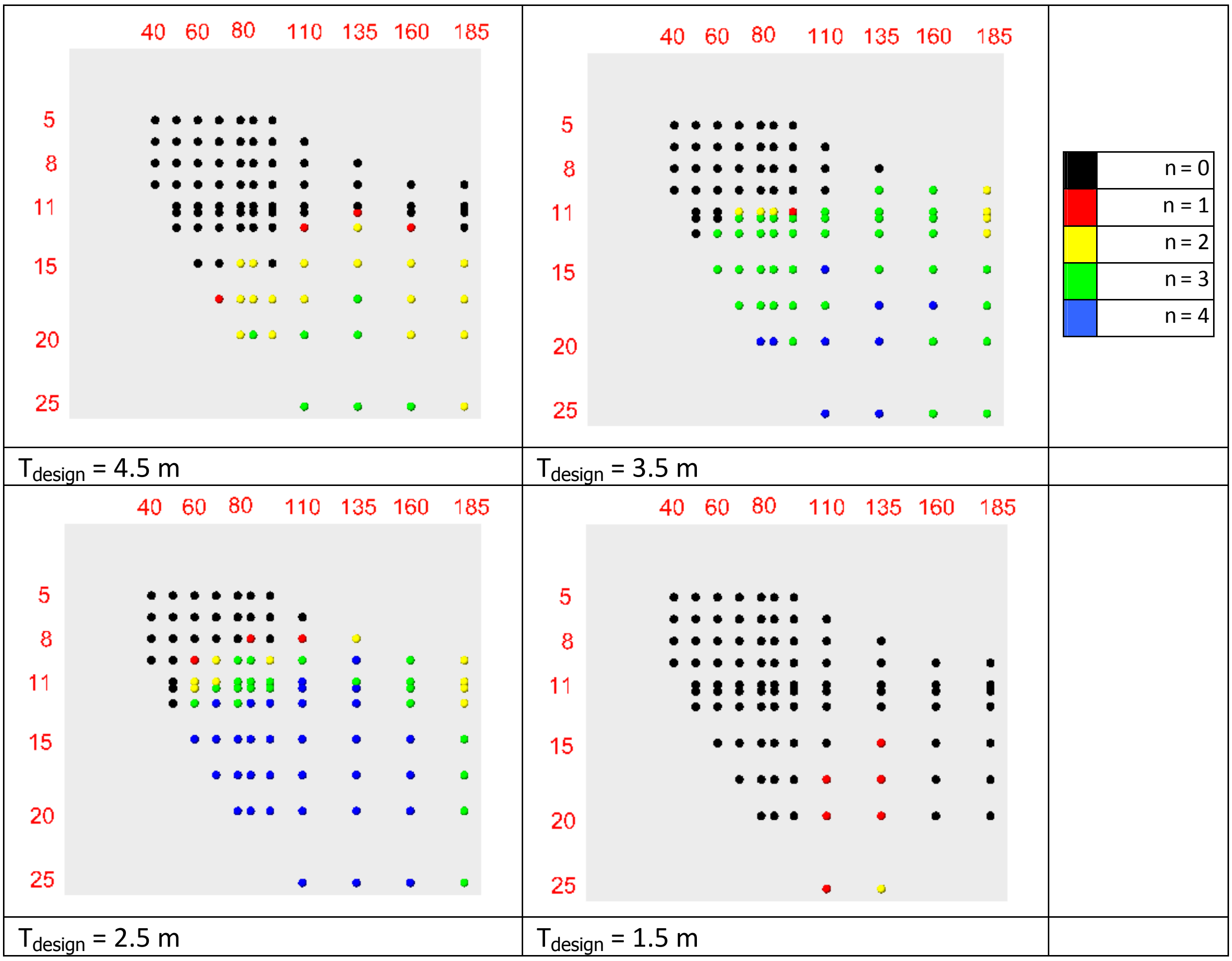


Figure 7-27: competitiveness of tank ships with rail – independent of need for end haulage

7.8.4 External emission costs

As a final comparison between the three modes of transport, the effect of internalization of external emission costs on competitiveness is assessed. In Figure 7-28 below, it is shown to which extent internalization of emission costs improves or worsens the competitive edge of (dry bulk) inland waterway transport compared to road. In this figure, negative values for ΔC_{ext} represent a cost advantage for inland waterway transport and positive values represent a cost advantage for road. In both cases, modern engines are assumed: EURO V engines for trucks and CCNR II engines for ships. All ship-related calculations are based on the assumption that the water depth is 5 meters, i.e. sufficient to load all ships to their design capacity, and that the average utilization of the ships is 50%, like in all previous assessments.

From Figure 7-28 it can be concluded how internalization of external emission costs leads to changes in the competitive position of inland ships compared to road. Only for the large deep draught (3.5 – 4.5 m) vessels does internalization of external emission costs lead to a clear improvement of their competitive position, but for draughts of around 2.5 meters this improvement is reduced or even reversed. At a maximum draught of 1.5 meters, internalization of external costs results in a loss of competitiveness for all ships.

That internalization of external emission costs does not result in improvement of the competitive edge for many inland ships is not mainly due to their fuel consumption, but due to the much higher

NO_x emissions per kilowatt-hour of CCNR II engines compared to EURO V engines. This negates the advantages in fuel consumption and the related CO_2 emission cost.

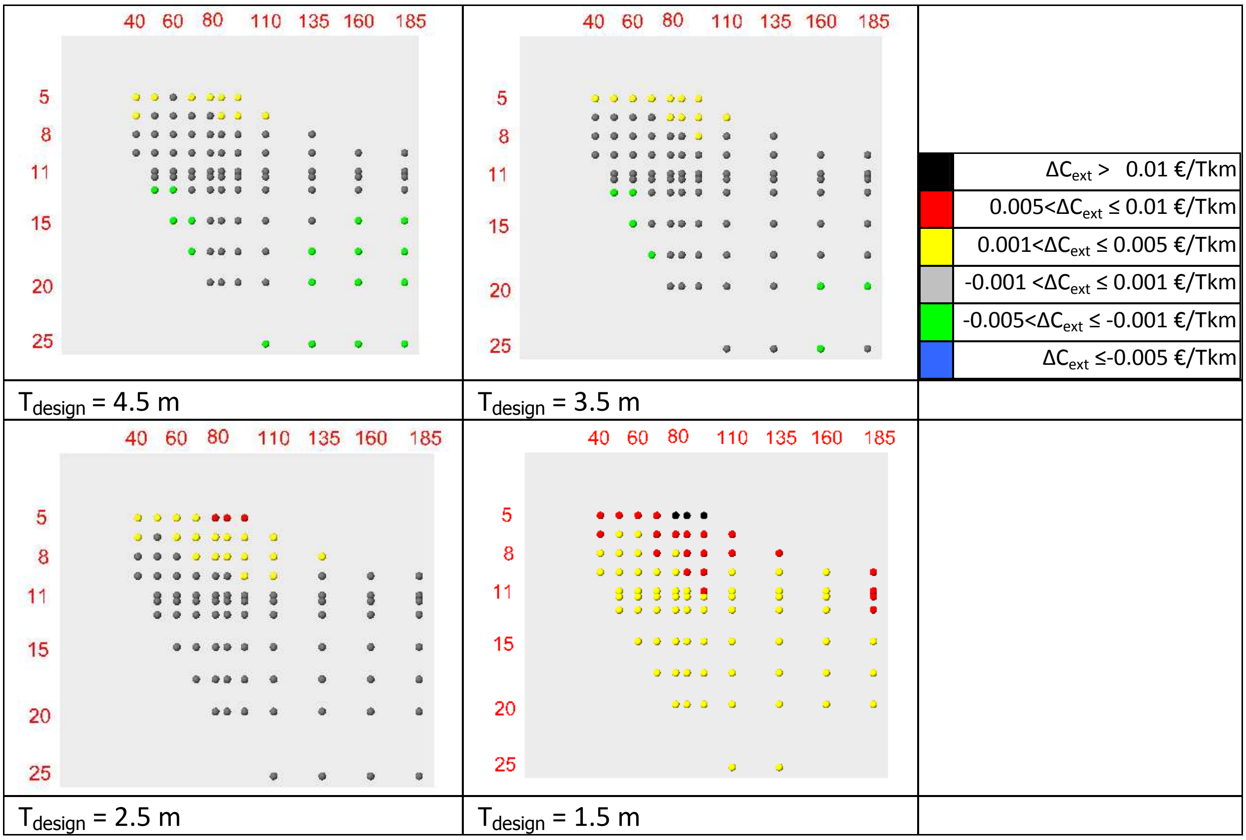
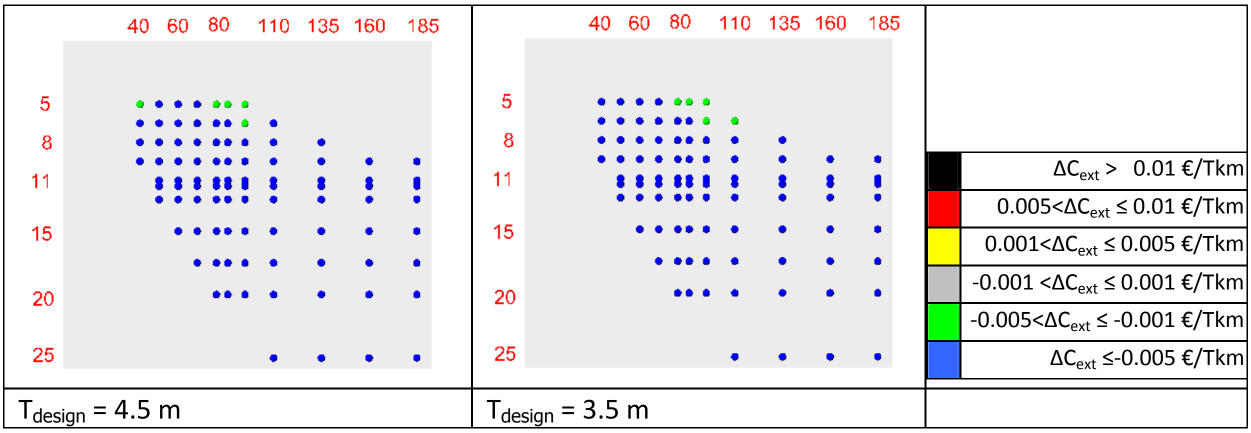


Figure 7-28: Impact of internalization of external emission costs on competitiveness - dry bulk ships vs. road

A comparison of the change in competitiveness between water and rail leads to very different results. As was discussed in chapter 6.2.3, no external costs due to emissions are attributed to electric trains in the *Handbook on estimation of external costs in the transport sector* [CE Delft et al., 2008b]. Therefore, no comparison is made. However, a comparison between waterborne transport and transport by diesel train can be made. This comparison is shown in Figure 7-29.



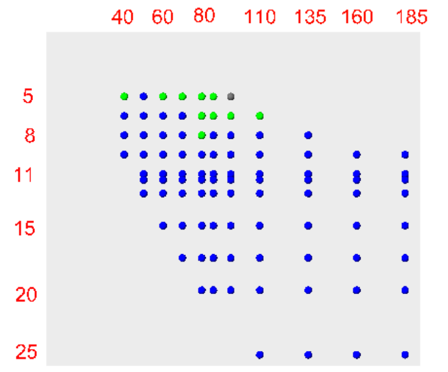
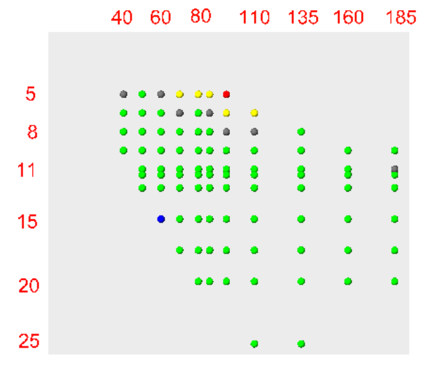
		
T_{design} = 2.5 m	T_{design} = 1.5 m	

Figure 7-29: Impact of internalization of external emission costs on competitiveness - dry bulk ships vs. rail (diesel)

Figure 7-29 reveals a very different image compared to Figure 7-28. In nearly all cases, internalization of external emission costs leads to an improvement in the competitive position of waterborne transport compared to diesel trains. The maximum change is -0.0083 €/Tkm. Even for the ships with the lowest draughts, internalization of their external emission costs will lead to an improvement of their competitive position compared to rail.

7.9 The effect of parameter variations on the required ship rate

In order to determine the ship dimensions that result in the lowest required ship rate and in order to establish that these dimensions are stable solutions, several cost variants were calculated for each route, water depth and ship type. Fuel price and depreciation time were varied as well as the sailing regime of the ship and the crew cost. These variants are all presented in appendix F.

As was discussed in chapter 7.3, the ship dimensions that lead to the lowest required ship rate have proven to be relatively insensitive to these variations since the optimal dimensions are identical for nearly all variants that were assessed. As a result, it was concluded that the solutions that were found are very stable, despite the fact that the absolute value of the required ship rate does change significantly as a result of the different variations.

Although it is not the purpose of this thesis to optimize the operation of a ship with given main dimensions but only to find the optimal dimensions of a ship, significant additional insight can be gained into how the parameter variations that were performed in chapter 7.3 affect the required ship rate of a ship. Therefore, they are discussed in the next paragraphs.

7.9.1 Effect of changes in the operational schedule

In the analyses of chapter 7.3, the sailing regime of the ships was differentiated as a function of the sailing distance. For the long distances (i.e. Rotterdam - Duisburg and Rotterdam – Koblenz), sailing regime B, 24/7 operation, is the assumed standard mode of exploitation. For short distances (Rotterdam – Dordrecht and Rotterdam - Nijmegen) sailing regime A1 (14 hours per day) during 5 days per week is assumed. This is done because the long waiting times in ports make B-type operation significantly more expensive than A1-type operations for short distances, while the need to moor the ship at night is a complicating factor for A1-type operation on longer trips.

The effect of paying the crew during waiting times becomes clear in Figure 7-30 and Figure 7-31 that show the cost reduction that is achieved by switching from B-operation to A1-operation for the route

Rotterdam - Nijmegen and Rotterdam – Duisburg for dry bulk, in both cases at reduced crew cost and a maximum draught of 2.8 m. For liquid bulk, effects are similar.

On the route Rotterdam – Nijmegen (Figure 7-30), B-operation is more expensive than A1-operation, but this effect is far more distinct for small ships than for large ships. On the route to Duisburg (Figure 7-31), the advantage of A1-operation over B-operation is much less distinct and for the largest ships, B-operation even becomes the cheapest option.

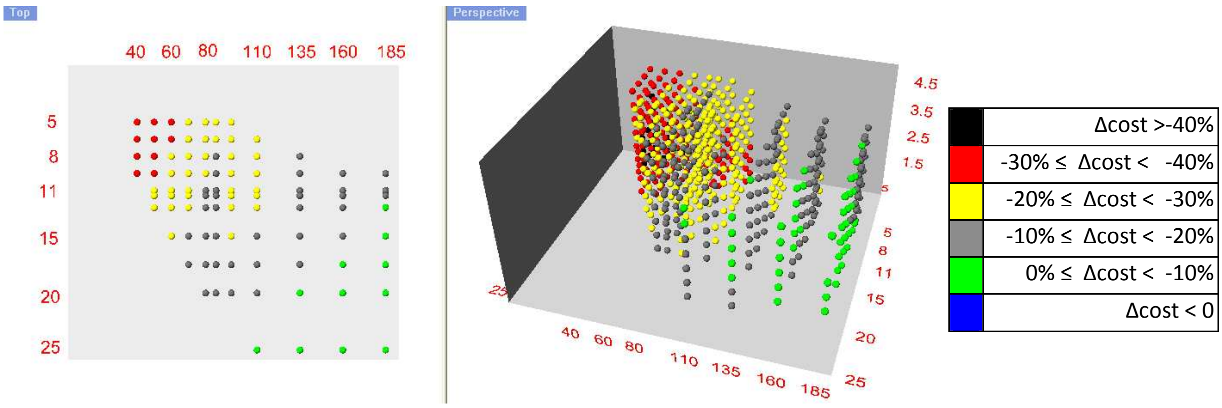


Figure 7-30: Cost reduction due to a switch from B to A1-operation: Rotterdam – Nijmegen, dry bulk

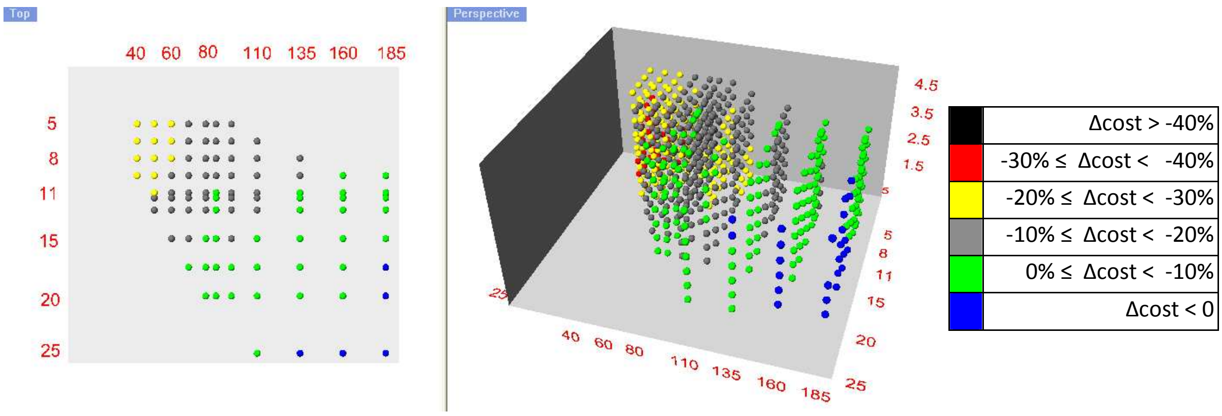


Figure 7-31: Cost reduction due to a switch from B to A1-operation: Rotterdam – Duisburg, dry bulk

The reason behind the fact that especially on short routes, A1-operation is cheaper than B-operation is that ships spend a long time in port, see chapter 6.2.2. When the crew is paid 24 hours per day, 7 days per week, the waiting in port becomes very expensive because the crew still needs to be paid, even if the ship is not active. When the ship is only operational for 14 hours per day during 5 days per week, the waiting time in ports becomes much cheaper since the crew does not need to be paid during the entire waiting time.

In case of container liner services, where ships have assigned slots and as a result do not have long waiting times, switching from B to A1-operation has a very different effect: due to the lower number of operational hours of the A1-schedule, the number of containers that can be transported per year is significantly reduced, as a result of which the price per container is increased. This effect becomes apparent from Figure 7-32 which shows the cost increase due to a switch from B to A1-operations on the route Rotterdam - Duisburg.

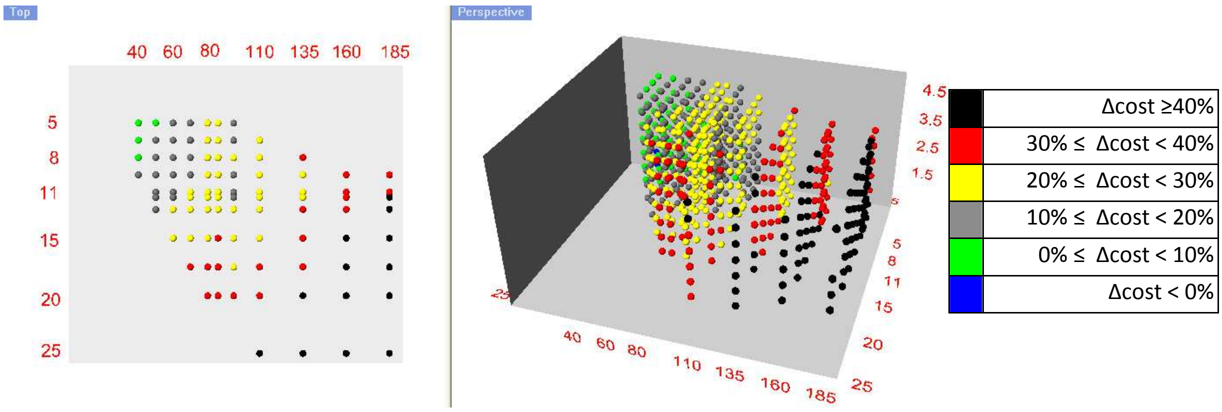


Figure 7-32: Cost increase due to a switch from B to A1-operation: Rotterdam – Duisburg, containers

From Figure 7-32, it becomes apparent that especially in case of large ships, where the impact of the crew cost on the total cost is most limited, switching from B to A1 operation increases the cost per unit by well over 40%. For small ships, where the crew cost forms a major share in the total cost of operation, the cost increase due to this switch of schedules is much smaller.

7.9.2 Effect of changes in various cost elements

Changes in the cost structure of the ship are easier to assess than changes in the operational schedule of the ship, since they do not affect the operation of the ship itself. In Figure 7-33 to Figure 7-36, the effects of increasing the fuel price from €700 to €1000 per ton, switching from reduced to full crew cost and reducing the depreciation time of the ship by 33% are shown.

The effect of an increase in fuel price from €700 to €1000 ton is shown in Figure 7-33 for a dry bulk ship on the route Rotterdam-Koblenz at a maximum draught of 2.5 meters. Koblenz is chosen because it represents the furthest destination and as a result the share of fuel cost on the total cost is higher than on the shorter routes, although all routes show similar trends.

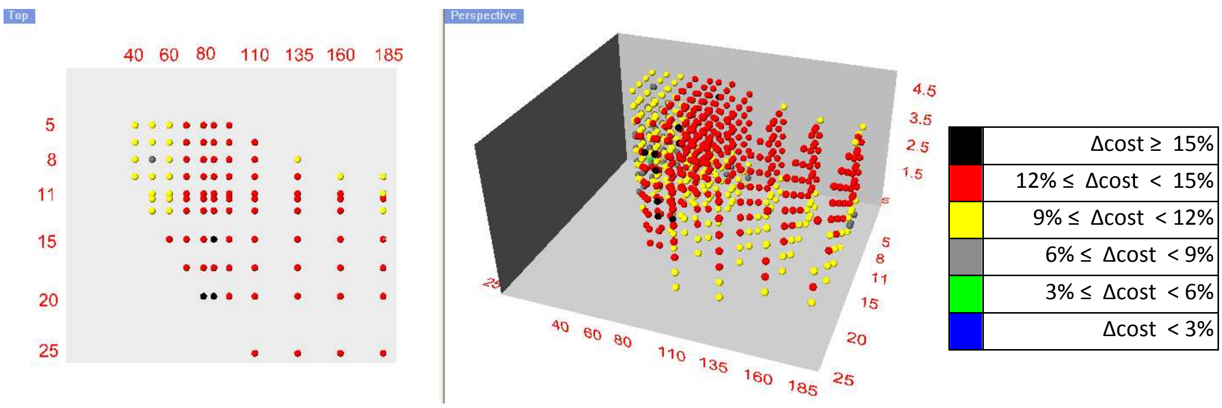


Figure 7-33: Increase in cost due to an increase in fuel price: Rotterdam – Koblenz, dry bulk

Figure 7-33 shows an increase in cost of between 9% and 15% for nearly all ships. As a result, changing fuel prices do affect the cost of inland waterway transport, but do not lead to a major shift of the relative competitive positions of ships of various dimensions.

In all previous analyses, it was assumed that the ship operates at reduced crew cost, i.e. the captain-owner and his partner pay themselves a compensation of € 30.000,- in stead of the normal salary of the two most expensive crew members. In Figure 7-34 below, it is shown to which extent the transport operator's cost increases when the ship sails in B-operation and the two most expensive crew members are paid conventional salaries.

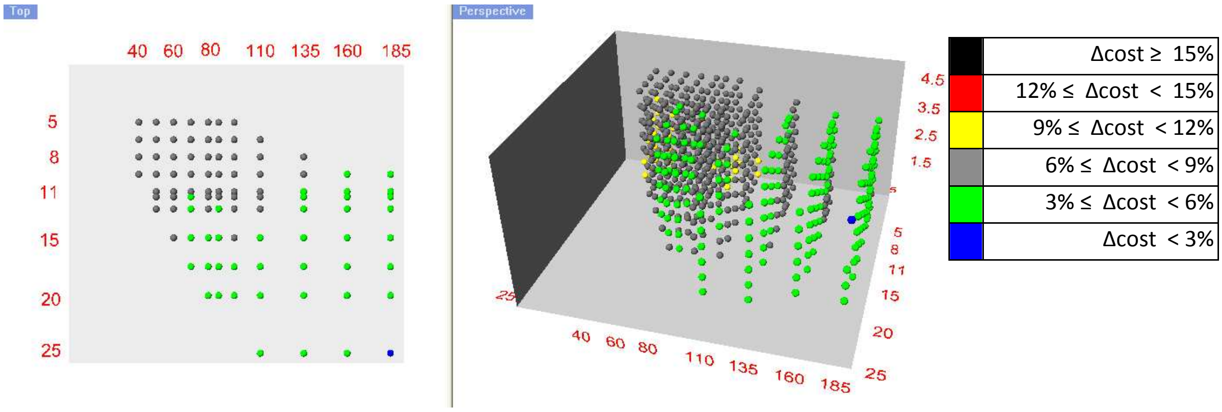


Figure 7-34: Increase in cost due to full crew cost, Rotterdam – Duisburg, B-operation

The increase in cost is higher for small ships than for large ships, since the share of crew cost in the total cost is higher for these ships. In nearly all cases the cost increase is between three and nine percent. When the ship sails in A1-operation, the impact of paying all crew members conventional salaries is slightly bigger, as becomes apparent from Figure 7-35, which shows a cost increase from about three to over twelve percent.

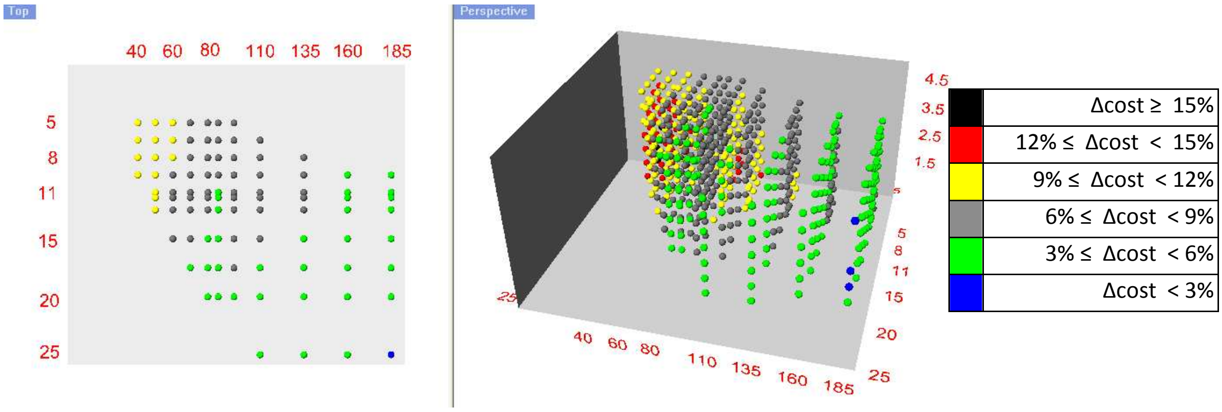


Figure 7-35: Increase in cost due to full crew cost, Rotterdam – Nijmegen, A1-operation

The final cost variant that was discussed in chapter 7.2 is the increase in capital costs due to a reduction of the depreciation period from 30 years for the hull and 15 years for the rest of the ship to 20 years for the hull and 10 years for the rest of the ship. Figure 7-36 below shows the impact that this has on cost.

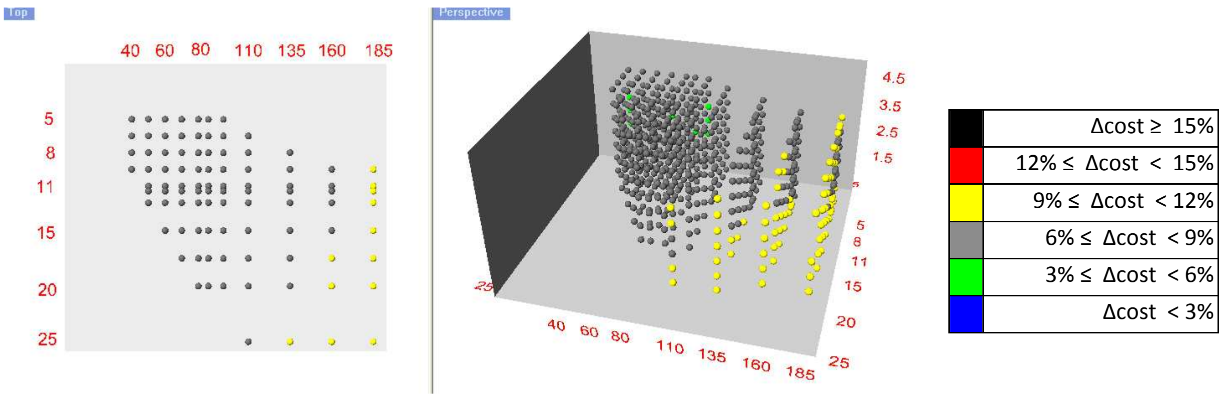


Figure 7-36: Increase in cost due to a reduced depreciation time

From Figure 7-36, it becomes apparent that this reduction of the depreciation period leads to a cost increase of roughly 3 to 12%. Since capital cost has a higher share in the total cost of large ships than in the total cost of small ships, the impact of a reduced depreciation period is larger for large ships.

7.10 Further considerations regarding the optimal dimensions of inland ships

In the previous paragraphs, the optimal dimensions of inland ships have been determined on the basis of four cost-related criteria. However, there are other considerations to take into account when selecting the main dimensions of a new ship which are not assessed quantitatively in this thesis. Some of the important ones are discussed qualitatively in this paragraph.

<u>Geographic flexibility</u>
Many of the ‘optimal’ ships that were found have a large beam and/or length, as a result of which they only fit through few locks. This harms their flexibility to some extent: they are limited to operation on only the largest waterways. Smaller ships that do fit through more locks can also enter the market of a number of connected smaller waterway systems, thus having access to a wider market and being less vulnerable to overcapacity in the market for large ships such as has occurred at the end of the first decade of the 21st century. Such considerations might lead to the choice for a standard vessel rather than one that is optimal from a cost point of view, despite the fact that these cost-optimal ships can still serve a very significant portion of the market, see chapter 2.3.

<u>Customer flexibility</u>
It has been shown that large ships have a cost advantage over small ships especially when a customer has large annual throughput and sailing distances are large. However, this also means that many smaller customers and customers close to the cargo’s point of origin will have no need for such a large vessel, thus making it dependent on a smaller customer base. This is why it is important to prevent a mismatch between the capacity of the ship and the required batch size of customers. As a result, a study of the demand distribution of shippers along the Rhine corridor would allow for more well founded decisions regarding the optimal dimensions of a ship.

<u>Sensitivity to water levels</u>
Throughout this chapter, it has been established on various occasions that matching vessel draught to the maximum draught that is allowed by the waterway results in cost advantages. However, on several occasions it could also be seen that in case of (temporary) low water levels, such ships may lose much of their competitiveness. Since low water levels are frequent on European free-flowing rivers, it is important to find the right design draught, based on the balance between high and low water levels and any low water surcharges that may influence market prices.

<u>Bridge & container heights</u>
Especially for container vessels, the height of bridges is a crucial factor in the extent to which the ship can be loaded. In this chapter a high bridge height of 9.1 m, typical for the lower Rhine, was used in all assessments. However, on other waterways like the river Danube and the German canals, bridge heights are lower and as a result, fewer tiers of containers can be carried on board of a ship. Furthermore, the containers that were used in this chapter are standard containers. When high-cube containers, which are higher than standard containers, are transported, this may also mean a reduction in the number of tiers of containers that can be carried, thus reducing the carrying capacity of a ship and resulting in different optimal dimensions.

Terminal characteristics

Within the context of this thesis, no research was done on the maximum ship dimensions that terminals can handle nor was the speed at which terminals will actually load or unload a ship in individual cases reviewed. These considerations may lead to rejection of a ship with 'optimal' dimensions since it cannot call at a port or it may result in a change in the optimal dimensions themselves due to changed boundary conditions compared to the calculations executed in this thesis.

In all cases, it needs to be stressed that it is important to properly analyze a logistics chain and transport route before deciding on the optimum vessel dimensions for that chain. The variables of this logistics chain have too much influence to directly transfer the results of this thesis to any other logistics chain or waterway system.

Port congestion and waiting times

Throughout this chapter, it has been discussed that the time that a ship spends in port has a large impact on its competitiveness. It has been assumed that for non-liner services, these waiting and handling times in ports match the values that are prescribed by Dutch law [Staatsblad, 2011], while for liner services no waiting times are included. However, in practice the actual time that is spent in port may differ from these values, e.g. due to congestion or faster handling. For container services there is the additional complication of 'terminal hopping' i.e. the need to call at several terminals within the same (sea) port in order to fill the ship. This may increase the time that is spent in port considerably.

7.11 Synthesis

In this chapter, it was assessed what the optimal main dimensions of dry bulk, container and tank ships are, dependent on the primary characteristics of the transport chain in which they operate. These primary characteristics are sailing distance, water depth, type of transported goods and a shipper's annual demand for transport of these goods.

After a generic review of the way in which ship dimensions influence time and distance costs, it was established what the optimal ship dimensions are as a function of specific routes and various water depths. The explored routes all start in the 'Dintelhaven' port basin in Rotterdam and end at Dordrecht, Nijmegen, Duisburg or Koblenz, thus providing a good spread in sailing distances. For all routes it is explored what the optimum ship dimensions are in case water levels are very high (maximum draught ≥ 4.5 m), very low (maximum draught = 1.75 m) or match the lowest agreed water depth, i.e. a maximum draught = 2.8 m between Rotterdam and Duisburg and 2.5 m between Duisburg and Koblenz, as is shown in Table 7-34 below.

Table 7-34: Analyzed scenarios

Route	Distance	Max draught	Lowest agreed draught	Min draught
Rotterdam – Dordrecht	45 km	4.5 m	2.8 m	1.75 m
Rotterdam – Nijmegen	136 km	4.5 m	2.8 m	1.75 m
Rotterdam – Duisburg	247 km	4.5 m	2.8 m	1.75 m
Rotterdam - Koblenz	430 km	4.5 m	2.5 m	1.75 m

For each of these scenarios, it was determined which ship dimensions result in:

1) The lowest required ship rate.
2) The lowest required ship rate in case external emission costs are internalized.
3) The lowest total logistical cost.
4) The lowest total logistical cost in case external emission costs are internalized.

Since the determination of total logistical cost requires knowledge of a customer's annual demand for goods and the value of the goods that are transported, 12 scenarios for this were investigated with demands of 10.000, 25.000, 50.000 and 100.000 tons annually for coal, iron ore and gasoil. For each scenario on each route at each water depth, costs were calculated on the basis of a standard case as shown in Table 7-35 below, which is deemed the most representative of inland waterway transport in the Rhine area in 2011.

Table 7-35: Cost parameters

Depreciation time	Hull: 30 years, rest of ship:15 years
Sailing regime	Dordrecht & Nijmegen: A1; Duisburg & Koblenz: B
Crew cost	Reduced; Total remuneration of € 30.000,- p/a for the first two crew members
Fuel price	€ 700 per ton

To determine the sensitivity of the optimal ship dimensions to these parameters, the required ship rate was also calculated for other sailing regimes, depreciation in 20/10 years, full crew cost, a fuel price of € 400 per ton and a fuel price of € 1000 per ton.

It was shown that optimal ship dimensions are not very sensitive to the cost parameters of the ship itself or to internalization of external emission costs, despite the fact that these elements do strongly affect the absolute value of the required ship rate. They are however strongly dependent on sailing distance, waiting time in port, annual demand of a shipper and water depth. Flow charts that allow the determination of optimal ship dimensions as a function of these criteria are provided in chapter 7.7.

Furthermore, the competitiveness of waterborne transport with road and rail were investigated and it was analyzed to which extent internalization of external emission cost improved or worsened the competitive position of inland waterway transport compared to road and rail transport. It was shown that competition with road transport is most difficult in case end haulage is required, while competition with rail is most difficult for tank vessels due to their high weight and cost.

8 Conclusions & recommendations

The aim of this thesis is to assess which length, beam and draught of an inland ship lead to the best competitive position for a captain-owner. In this chapter, the main conclusions and recommendations resulting from the research are synthesized. This is done on the basis of the four sub-research questions as defined in chapter 1.3:

1) *What are the practical upper limits of the dimensions of inland ships?*

2) *How do the main dimensions of an inland ship relate to its building cost and those technical properties that affect the cost of transport?*

3) *How do the main dimensions of an inland ship affect the cost of operating that ship?*

4) *How do the main dimensions of an inland ship affect the total logistical cost of a shipper?*

In sub-chapter 8.1, conclusions are drawn with regard to each of these questions. In sub-chapter 8.2, recommendations for further research are made.

8.1 Conclusions

In this sub-chapter, conclusions are drawn with regard to each of the four sub-research questions of this thesis. In paragraph 8.1.1, the conclusions with regard to the practical upper limits of the dimensions of inland ships are discussed and in paragraph 8.1.2 it is concluded how the main dimensions of inland ships relate to the relevant technical properties and building cost. In that paragraph, conclusions are also drawn with regard to the methods and data with which these properties can be determined. Paragraphs 8.1.3 and 8.1.4 discuss the effect that various main dimensions of inland ships have on operating cost and total logistical cost.

8.1.1 Practical upper limits of the dimensions of inland ships

On the largest waterways, there is a potential to use very large vessels have dimensions that are equal to those of 6-barge push convoys, which are either 269.5 m long and 22.8 m wide (long formation) or 190 m long and 34.2 m wide (wide formation). However, the port of Rotterdam is the only sea port that is connected to the Rhine, i.e. the geographical focus area of this thesis, to which vessels with a length that exceeds 195 meters or a beam that exceeds 22.9 meters have access. Larger ships also can not sail beyond Koblenz as a result of which a significant number of inland ports on the Rhine can not be reached. Vessels that do not exceed slightly smaller dimensions of 186.5 x 22.9 meters can reach the majority of ports on the Rhine as well as the seaports of Rotterdam, Amsterdam, Antwerp, Flushing, Gent and Terneuzen. Furthermore, the largest ships will have difficulties in turning on many locations, while ships of 186.5 m are not longer than existing coupled units, as a result of which problems with turning may be expected to be significantly less.

Moreover, it was concluded that the European inland waterway infrastructure will remain largely unaltered in the near future, despite the identification of missing links and a latent intention to allow ships of up to 172 x 11.4 x 2.8 m to sail on a larger number of waterways than today.

As a result, a length of 186.5 and a beam of 22.9 m are considered the practical upper size limit for inland ships that sail in the Rhine region and do not have long term contracts, as a result of which they need to be flexible in the geographic area in which they can operate. Such vessels can serve nearly the same geographical area as existing large inland ships. Such vessels are however significantly longer than the 135 m length limit for indivisible ships that is imposed by the CCNR.

Therefore, such ships can not be used unless it is agreed with the CCNR if, and under which circumstances, longer ships can be allowed or a method to divide such large ships when it is required is devised.

With regard to the draught of inland ships, it is concluded that the upper limit of the existing draughts, i.e. around 4.5 m, will not increase further in the future and that due to longer periods of low water levels, vessels with a smaller draught may be more beneficial, considering the lower mean water levels in especially the more distant future that are predicted by several studies.

8.1.2 The relationship between ship dimensions, technical properties and building cost

Various conclusions can be drawn with regard to the relationship between the dimensions, technical properties and building cost of inland ships. In this paragraph, conclusions are subdivided into conclusions with regard to the methods with which the properties of inland ships can be determined and conclusions with regard to the properties themselves.

Conclusions with regard to methods to determine the properties of inland ships

From the review in chapter 3, is has become apparent that on the basis of existing literature, it is not possible to link the main dimensions of inland ships to their technical properties or building cost when these main dimensions deviate from those of standard inland ships.

It has been shown that the cost studies for inland shipping that have been executed over the last decade only present basic data on common ship types and do not provide methods to extrapolate this data to ships with other main dimensions since length, beam and draught are not explicit variables in any of the studies. In a limited number of cost studies, the relationship between the technical properties of a ship and its cost is investigated, but these studies either focus exclusively on small barges and pushers [Hassel, 2011] or conclude that some of the necessary data and methods to determine the required technical characteristics of vessels are missing [Hofman, 2006].

A closer review of which methods are available to link the dimensions of inland ships to their technical characteristics, building cost and cargo carrying capacity revealed that proper methods for estimation of the weight, building cost and hold dimensions of inland ships with non-standard main dimensions were lacking. As a result, it is concluded that the state-of-the-art with regard to the knowledge about the technical properties of inland ships is insufficient to reach the main research goal.

These gaps in knowledge have been filled through the development of a ship design model and through the use of that model to generate large systematic series of dry bulk, container and tank ships. This newly generated knowledge is made accessible to the scientific community and ship designers through the development of a number of rules of thumb for the estimation of weight, cost and cargo carrying capacity of dry bulk, container and tank ships.

Apart from the previous conclusion that important methods to determine characteristics of inland ships were missing, it is also concluded that despite the availability of rough methods to predict the resistance and required propulsion power of inland ships, there is still much to be improved in this field before the required propulsion power of an inland ship sailing in shallow water can be reliably estimated without the need for expensive and time consuming towing tank tests and/or numerical calculation methods. These improvements are discussed further in chapter 8.2.2.

Conclusions with regard to the properties of inland ships

In this thesis, a large design space is explored in which ship length is varied from 40 to 185 meters, beam is varied from 5 to 25 meters and draught is varied from 1.5 to 4.5 meters. From this exploration, it becomes apparent that the properties of inland ships vary widely as a function of their main dimensions.

For dry bulk ships, steel weight varies between just below 10% of LBT for wide ships with a draught of 4.5 m and a length between 50 and 70 meters to more than 40% of LBT for the longest and narrowest ships with a draught of 1.5 meters. The lightweight of these ships, i.e. the steel weight plus all other weights of the ship itself, ranges from roughly 15% to more than 40% of LBT. When a block coefficient of 0.9 is assumed, this implies that the cargo carrying capacity of inland ships varies between roughly 50 and 75% of length x beam x draught.

The cost of the hull is strongly related to the weight of the hull and as a result, it has a strong link with the main dimensions of a ship. The cost of all other lightweight items has a far less distinct relationship with the dimensions of a ship and as a result, the yard-related cost of the ship (i.e. the cost of building the steel hull and management of the project) makes up between roughly 34% and 73% of the total building cost of the ship. For small ships, the majority of costs are due to the equipment, machinery, outfitting and accommodation, while for large ships the majority of the costs can be attributed to the cost of the hull. The cost per ton of cargo carrying capacity of the reviewed designs ranges from € 706 to € 7050. Container ships are very similar to dry bulk ships and as a result show nearly identical trends in weight and cost.

Tank ships are heavier and more expensive than dry bulk and container ships due to the subdivision of the tanks, a main deck that covers the entire width of the ship and the cargo piping system. Their lightweight ranges from just over 15% of LBT to more than 50% of LBT, while yard and non-yard costs shows a similar distribution as for dry bulk ships: Yard cost ranges from approximately 35% to well over 70% of the total cost. In absolute numbers, the modeled tank ships are more expensive than their dry bulk counterparts with the same dimensions: building cost ranges from € 850 to € 9500 per ton of cargo carrying capacity.

8.1.3 The relationship between main dimensions and the cost of operating a ship

In chapter 7, it was shown that the length of dry bulk ships with dimensions that result in the lowest cost for the operator (i.e. required ship rate) is not significantly larger than the maximum length of existing ships, i.e. 135 meters, most of the time. However, their beam is typically wider and that the ships have a draught that matches the maximum draught at normal water levels on the route.

When the main dimensions of dry bulk vessels are optimized, this leads to a 10-15% reduction in required ship rate compared to a standard 135 m vessel on short trips like Rotterdam – Dordrecht. On the longest investigated route, Rotterdam – Koblenz, the reduction in required ship rate compared to standard ships can be bigger than on short routes. In this case, savings of 15 to 21% compared to standard 135 m vessels are possible.

For tank ships, the dimensions that result in the lowest required ship rate are similar to those of dry bulk vessels. In the majority of cases the optimal ship is 135 m long, as wide as possible and has a design draught that approximates the maximum possible draught. Only on short trips like Rotterdam – Dordrecht do these ships perform worse than slightly smaller ships. The cost savings that these 135 x 25 m ships can achieve is typically between 13% and 33% compared to a standard 135 m vessel.

For container ships, general statements about the ship dimensions that lead to the lowest required ship rate can only be made as a function of the route: on short routes, small ships outperform large ships and on long routes, large ships outperform small ships. On the shortest route, short and wide ships can operate at a ship rate that is 21 to 35% lower than the smallest standard vessel of 86 m vessel while on the longest route, very large ships have required ship rates that are 11 to 19% lower than the largest standard ship of 135 m. The maximum draught of container ships is never larger than 3.5 meters, since containers are a relatively light and voluminous cargo.

From the above, it can be concluded that there is a strong link between the optimal ship dimensions, the sailing distance and the time that is spent in ports: in case of short waiting times at terminals, like for container ships in liner service, there is a clear link between the sailing distance and the ship dimensions that result in the lowest required ship rate. On short distances, small ships outperform larger ships due to a short turnaround time, while on long distances the economies of scale that large vessels can achieve makes them able to operate at lower required ship rates than smaller ships. In case of longer waiting times at terminals, the effect of sailing distance on the optimal ship dimensions is reduced since small ships lose their competitive edge over large ships at short sailing distances. This is the case for dry bulk and tank ships.

The abovementioned link between sailing distance, waiting times and optimal ship dimensions is much stronger than the link between the specific cost structure of the ship and optimal ship dimensions. In the case studies of chapter 7.3, it was shown that in the vast majority of investigated cases neither changes in fuel cost, crew cost, depreciation time or sailing regime nor internalization of external cost lead to major changes in the optimal dimensions of inland ships. However, these variables *do* strongly affect the required ship rate and as such change the competitiveness of a ship with other modes or with ships that are technically identical but have different cost parameters.

As a result, it can be concluded that the simplification of technical characteristics, building cost and operating cost of ships that is common in logistical/cost analyses of inland shipping can be detrimental to the quality of analyses if they are made for non-standard ship types. The rules of thumb of chapter 5.6 and the cost calculations in chapter 4.2.5 and appendix C provide useful contributions to the knowledge about the capital cost, capabilities and required ship rate of inland ships, thereby potentially improving the quality of logistical/cost analyses of inland ships and allowing assessment of the performance of inland ships with non-standard main dimensions.

8.1.4 The relationship between main dimensions and the total logistical cost

The dimensions of inland ships do not only have an impact on the price at which transport can be offered, but can also affect the size of shipments for a single shipper. As such, they affect both the out of pocket cost of a shipper and his stock cost. The transport of low value goods for shippers that require large annual volumes favors large shipments with low out-of-pocket transport costs. As a result, the optimal ship dimensions for the transport of these goods will be close to the dimensions that result in the lowest out-of-pocket cost of transport. Due to higher holding costs, the transport of more expensive goods for shippers that require small annual volumes favors smaller shipments on order to keep stock cost low. In these cases the relatively high out-of-pocket transport cost that is associated with small shipments does not outweigh the savings due to small stocks. As a result, the optimal ship length and beam for the transport of low value goods are larger than for high value goods while higher annual volumes also lead to an increase in the optimal size of a ship.

The results of the case studies show that in nearly all cases, length, beam and/or draught of the ships that lead to the lowest total logistical cost are larger than the maximum length, beam and draught of existing class IV vessels. This implies that in case dry bulk or container ships need to be able to sail on waterways of class III or IV, it is advisable to maximize ship dimensions for those waterways unless the ship is used in a transport chain for a shipper with high value goods and low demand. However, in case of low annual demand, some tank vessels with main dimensions that are smaller than the maximum length, beam and draught of class IV waterways are optimal.

In case of waterways of class Va and larger as well as for tank ships, considerations on a case-by-case basis are required to determine whether or not ship dimensions should be maximized or if the optimal ship dimensions are smaller than the maximum possible dimensions. A detailed flowchart for the determination of the optimal ship dimensions for a given logistics chain is provided in chapter 7.7.

Regarding the ships that are common on inland waterways today, it can be concluded that the main dimensions of ships that are intended for waterway classes I to IV are optimal for the majority of dry bulk and container transport chains. The standard 110 x 11.45 m vessel, however, is only optimal if it regularly sails on waterways that require it to pass locks of these dimensions. For large waterways like the lower Rhine, the vessel forms a sub-optimal solution from a cost perspective since nearly all optimal vessels are wider. As a result, the standard large Rhine vessel is a clear choice of transport operators to have a flexible general-purpose ship that has a wide operational area instead of a ship that can operate at the lowest possible required ship rate or that leads to the lowest total logistical cost for the shipper. The existing 135 meter vessels represent a more outspoken choice for cost minimization over flexibility.

From the results of this thesis, it can be concluded that inland ships will not benefit much from further increases in length, but that a further widening of ships compared to existing vessels can improve their competitiveness. However, further enlargement of the capacity of these ships brings them in the same capacity range as coupled units, which have not been researched in this thesis in detail. Further research needs to show where the tipping point between large ships and coupled units lies.

8.2 Recommendations

Apart from the conclusions that were drawn in the previous sub-chapter, recommendations can also be made with regard to each of the four sub-research questions. This is done in the next paragraphs.

8.2.1 Upper limits of the dimensions of inland ships

This research has focused on the performance of inland waterway ships and it was established what their maximum dimensions are from an infrastructural, operating cost and total logistical cost point-of-view. However, on most major waterway systems inside and outside of Europe, push convoys (i.e. a pushboat pushing one or more barges) or coupled units (a cargo ship pushing one or more barges) are also operated. These units have a number of advantages and disadvantages compared to single ships:

1) Multiple coupled barges can carry similar amounts of cargo as very large ships, but do not experience the same bending moments. As a result, they may be lighter and/or cheaper to build than large vessels and thus able to transport goods at lower cost.
2) The ability to detach a barge from its pushing unit allows for different operational scenarios like leaving the barge at a quay to be loaded or unloaded while the (expensive) pushing unit can continue to sail. This improves the amount of time during which it is used in a productive way.
3) The resistance of especially pushtows is higher than that of comparable single ships due to the shape discontinuity between the barges and the push boat. This increases fuel consumption.

4) The fact that, unlike cargo ships, push boats do not have to deal with large changes in draught allows for drive trains with a higher efficiency, which can reduce fuel consumption.
5) More crew is required to operate coupled units, leading to additional cost.

As a result of this, it is recommended to perform in-depth research into the operation of coupled units and pushtows in order to determine how their performance compares to that of single ships and in which cases they can be more cost-efficient. If this is done, a more complete picture of the optimal dimensions of inland waterway transport units can be obtained and a next step towards optimizing inland waterway transport can be taken. This research has a stronger focus on logistics than on technology but will still require knowledge of the technical properties of ships and barges.

8.2.2 The relationship between ship dimensions, technical properties and building cost

In chapter 8.1.2, it was concluded that especially in the field of resistance and propulsion of inland ships, there is still much room for improvement. The publicly available data and methods for the determination of the resistance and propulsion of inland ships in restricted and/or (very) shallow water are relatively old, rough and/or in need of further validation. As a result the uncertainty about an inland ship's fuel consumption, related cost and emissions will be quite large unless data from a reference vessel are available or a substantial amount of money is spent on specialized CFD-calculations and/or towing tank tests.

Therefore, it is recommended to improve the availability of basic powering prediction methods for inland ships sailing in (very) shallow and restricted water. Important aspects include the determination of wake fractions in very shallow water, methods to predict the increase of resistance in very shallow water and dedicated methods to predict the deep water resistance of inland ships (and coupled units & pushtows) that deviate substantially from seagoing vessels in terms of L/B, B/T or L/T ratios and/or block coefficient.

Over the years, a significant amount of research on the powering prediction for inland ships has already been done. However, this research is mostly not published in the English language and/or available digitally, e.g. the Meyne-VBD propeller series for inland ships. Much can be gained by a proper inventory and subsequent online publication in English of the available knowledge.

8.2.3 The relationship between main dimensions and the cost of operating a ship

The quality of analyses of the cost of operating inland ships can be improved by closer analysis of some of the variables for which assumptions were made in this thesis. Beelen [2011] has set up a more detailed cost model for 'standard' inland ships, including e.g. various options for financing the ship. A combination of such a detailed cost model with the technical data of inland ships with non-standard dimensions would combine the strengths of both approaches.

The analysis of the required ship rates of ships that sail on the Rhine corridor can be improved further by an analysis of the actual waiting times of ships at various terminals, which will enable better estimation of the roundtrip time of inland ships. An analysis of the actual fluctuation of water levels on the Rhine can provide more insight into the total amount of cargo that a ship can transport in a year and the associated cost.

Furthermore, better methods for the assessment of the fuel consumption of inland ships (see chapter 8.2.2) would lead to more insight into the fuel cost of inland ships as a function of the ship's specifications, the properties of the waterway and the sailing speed.

The cost study that is performed in this thesis has focused on the western-European waterways and in particular on the Rhine. Due to the e.g. the use of crewing regulations for the Rhine and the calculation of wages according to the non-official Dutch collective workers agreement for the inland waterway transportation sector, all cost calculations are only directly applicable to ships with a western-European crew that sail on the Rhine corridor. As a result, additional data is required before the operating cost and optimal main dimensions of ships that operate in other geographic markets for inland waterway transport can be determined. These markets could for instance include the Danube region, the Chinese inland waterway system and the Brazilian inland waterways.

8.2.4 The relationship between main dimensions and the total logistical cost

This research has focused strongly on the supply side of transport: the ships. However, the supply side provides only part of the equation, since the market and infrastructure also form important factors in the determination of the competitiveness of inland ships. Therefore, a better understanding of the way the market and the infrastructure affect the optimal size of ships will allow for a more well-founded choice of ship dimensions. The primary aspects to be researched further are:

- The distribution of demand, type of goods and location of shippers that use inland waterway transport.
- The relationship between water levels, required ship rates and actual ship rates.

More knowledge about the number of shippers along a given part of a given corridor that have an annual demand for a given type of goods in a given volume range provides more insight into the optimal batch sizes. This insight into the optimal batch sizes may lead to different conclusions about the optimal ship dimensions, since it provides more insight into the segregation of the market.

Deeper insight into the relationship between water levels and ship rates, combined with predictions about the fluctuations in water levels, will allow for better determination of the optimal design draught of inland ships. On one hand, fluctuating water levels lead to changing amounts of cargo that can be carried by the ship. This in turn leads to changes in the required ship rate of a ship. These changes will be larger for ships with a high design draught than for ships with a low design draught. On the other hand, since lower water levels lead to changes in supply, market rates will go up when water levels go down and in several cases, low-water surcharges will be applied to the actual ship rate.

As a result, once it is known how often certain water level occur, how they affect the supply of transport capacity and how high the low water surcharges are, further insight can be gained into the optimal dimensions of inland ships.

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A: Assessment of effectiveness of design changes

In chapter 1.2.2, the theoretical maximum attainable benefits of several options to improve the design of an inland ships were briefly discussed. In this appendix, the rationale behind the selected improvement options is presented, followed by an explanation of the how the potential benefits are quantified.

From the point of view of the design of a ship, there are two principal ways to reduce the cost of transport per unit of cargo:

1) To increase the amount of cargo that can be carried.
2) To decrease a ship's building and/or running cost.

Both approaches are discussed in respectively paragraph A.1 and A.2, leading to an overview of the aspects of the ship design that can be optimized and are, therefore, considered to be potential research topics. In paragraph A.3 each of these aspects is assessed in order to establish the maximum attainable improvement and to determine what the main drawbacks of each improvement option are. This leads to the selection of a final research topic.

A.1 Options to increase the cargo carrying capacity of an inland ship

In Figure A-1 the relationship between the primary aspects of a ship design and a ship's cargo carrying capacity is shown. The figure shows that the displacement of a ship is determined by its main dimensions and block coefficient[17]. Since the weight of a ship plus the weight of its cargo is by definition equal to the weight of the water it displaces, increasing the main dimensions or the block coefficient will increase the amount of cargo that can be carried.

Cargo carrying capacity is further influenced by the lightweight of the ship, i.e. the weight of the ship itself. Since at given main dimensions and block coefficient the maximum combined weight of ship and cargo are fixed, a lighter ship will result in a higher maximum cargo weight.

The third element that influences the cargo carrying capacity is the space that is available for cargo. The height to which cargo can be stacked is a function of the ship's stability, which is the result of the ship's design and is, therefore, affected by all other elements in figure A-1. Finally, the general arrangement of the ship will determine the length and width of the cargo hold(s) and as a result it will determine the amount of floor space that is available for the storage of cargo. This is especially important for containers, which are less easy to fit into a hold of given dimensions than bulk goods.

[17] A block coefficient is roughly defined as the volume of the underwater part of the ship divided by length x beam x draught

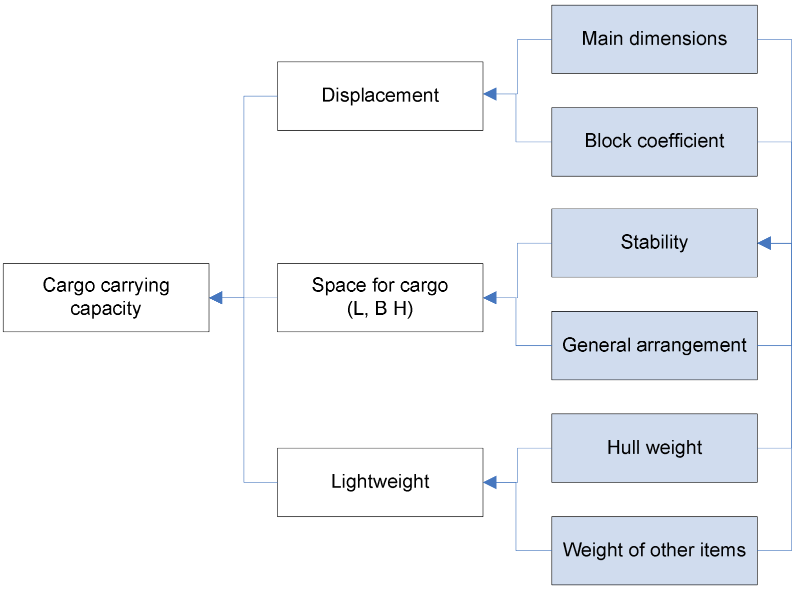

Figure A-1: The relationship between vessel properties and cargo carrying capacity

From the above, it becomes apparent that the main variables in the optimization of cargo carrying capacity are:

- Main dimensions
- Block coefficient
- General arrangement
- Hull weight
- Weight of other items

The extent to which a change in each variable will lead to a change in cargo carrying capacity or cost will be reviewed in appendix A.3.

A.2 Options to decrease the cost of building and operating inland ships

Figure A-2 shows how the cost of operating a ship relates to the technical properties of that ship. It shows that the building cost of an inland ship is determined by three design main aspects: main dimensions, propulsion & resistance and other items. The main dimensions determine the price of the hull and together with the design speed also strongly influence the amount of power that is required to propel the ship. The specification of the drive train affects the building cost of the ship, the fuel consumption and the cost of maintenance.

The other items that are on board (navigation equipment, accommodation, steering gear….) affect the maintenance cost, building cost and to a smaller extent also the fuel consumption of the ship. Finally, the crew cost is affected by the length of the ship, since ROS-R regulations prescribe the number of crew members as a function of the length of the ship [Central Commission for Navigation on the Rhine, 2007].

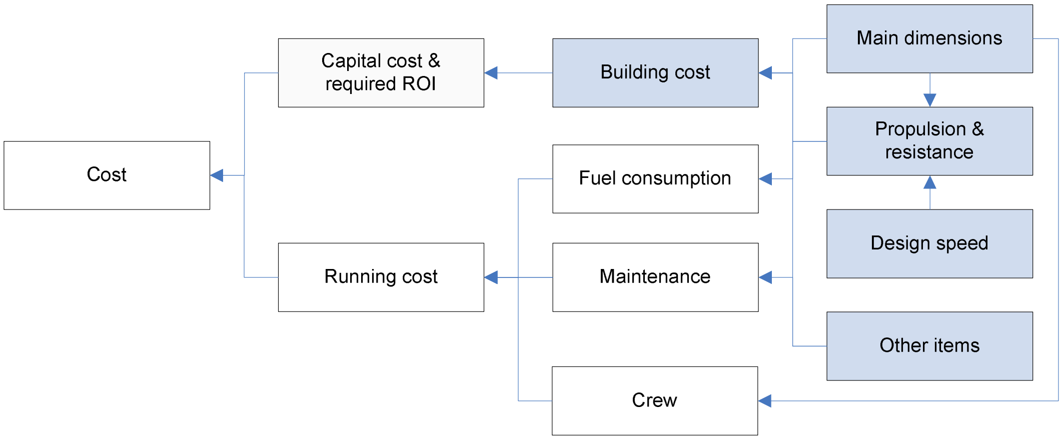

Figure A-2: The relationship between vessel properties and cost

From figure A-2 it can be concluded that there are four main design aspects that influence the cost of operating a ship:

- Main dimensions
- Design speed
- Specification of the drive train
- Specification of other items

The extent to which a change in each variable will lead to a change in cargo carrying capacity or cost will be reviewed in Appendix A.3.

A.3 Assessment of the effects of the options

In the previous two paragraphs, eight aspects of a ship's design that influence a transport operator's cost per unit of transported cargo are identified. These are:

- Block coefficient
- General arrangement
- Hull weight
- Weight of other items
- Design speed
- Specification of the drive train
- Specification of other items
- Main dimensions

It is possible to optimize each of these aspects to some extent and thereby reduce the cost per unit of transported cargo. However, since it is not possible to research all possible improvements in sufficient depth simultaneously, the most suitable topic for further research in this thesis needs to be selected. Therefore, in the next paragraphs a rough assessment is carried out in order to provide insight into the approximate upper limit of the benefits that the improvement of each aspect can bring and the drawbacks that are associated with these improvements.

Definition of default ship parameters

All of the aspects that are discussed above affect a ship's technical properties, its building cost and/or its running cost. Therefore, before an assessment is made of the benefits and drawbacks of each solution, several important default parameters for an inland ship are established and all comparisons will be made on the basis of these parameters. For each of the parameters, their default value and the source for that default value are shown in table A-1.

Table A-1: Default parameters for technical properties and cost of inland ships

Parameter	Value	Source
Technical properties		
Block coefficient, Cb (-)	≈ 0.9	Calculated on the basis of guidelines by Heuser [1987]
Displacement (T)	≈ 0.9 x L x B x T	By definition: displacement = Cb x L x B x T
Lightweight (T)	≈ 20% of displacement	Estimated using formula by Hofman [2006]
- Hull weight (T)	11-17% of displacement	Estimated using formula by Germanischer Lloyd [2006]
- Other weight (T)	3-9% of displacement	Other weight = lightweight – hull weight
Maximum cargo weight (T)	≈ 80% of displacement	Approximated by taking cargo weight equal to deadweight
Cost		
Fuel	15-30% of total cost	Based on Beelen [2011]
Labor	30-45% of total cost	Based on Beelen [2011]
Capital cost	30% of total cost	Based on Beelen [2011]
Building cost		
Hull	55% of building cost	VBD [2004]
Propulsion	25% of building cost	VBD [2004]
Other equipment	20% of building cost	VBD [2004]

The abovementioned estimate of the contribution of fuel, labor and capital cost to the total cost of operating the ship are based on case studies for a 110 m large Rhine vessel and a 135 m large container vessel by Beelen [2011], as shown in figure A-3 below, while building cost estimates are based on data provided by VBD [2004] and the block coefficient is estimated on the basis of design guidelines by Heuser [1987]. For the estimation of hull weight and other weight, the trend line for lightweight as presented by Hofman [2006] is combined with Germanischer Lloyd's [2006] estimate of hull weight.

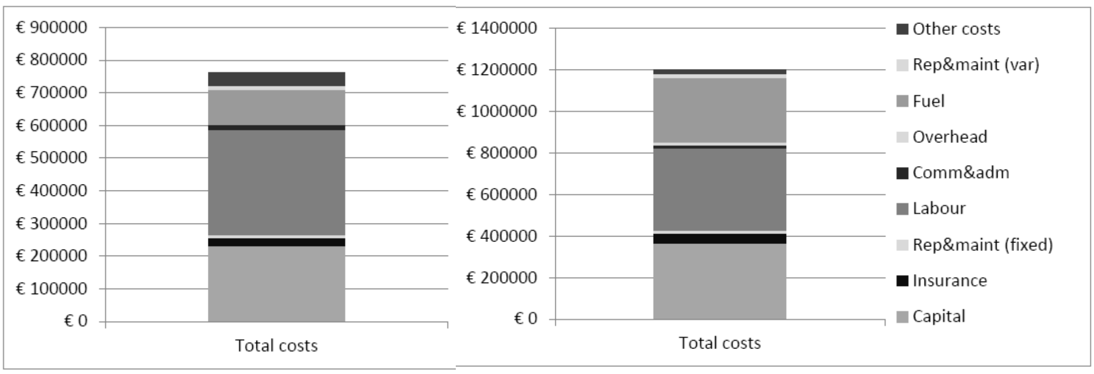

Figure A-3: Cost breakdown of inland ships. Source: Beelen [2011].
Left: Large Rhine Vessel. Right: large container ship

Based on these rough estimates of the technical characteristics, building cost and operating cost of inland ships, it is possible to make initial estimates of the benefits that the improvement of the various design aspects can bring. These initial estimates are elaborated in the next paragraph.

Estimation of the benefits of various changes in the design

In this paragraph it is assessed what the maximum attainable effect of this optimization of each of the aspects that were discussed in chapter A.1 and A.2 can be. For this optimization, the default values of the technical properties and cost of inland ships that were described above are used. Table A-2 provides an overview of the maximum attainable effect and potential negative aspects of each optimization measure compared to a ship with the default properties that were discussed above, while the remainder of this paragraph is dedicated to further explanation of the effect and potential associated negative effects of each measure.

Table A-1: Overview of effects of design changes

Optimization measure	**Maximum attainable effect**	**(Potential) negative aspects**
Increase block coefficient	≈ 11% more cargo	- Increased fuel consumption
Alter general arrangement	≈ 14 % more cargo	- Mainly effective for small vessels
Reduce hull weight	≈ 7 - 10% more cargo	- Higher building cost - Mainly applicable for small ships
Reduce weight of other items	≈ 2 - 5 % more cargo	- Composed of many different elements, so no single item to optimize
Lower design speed	≈ 12 - 19 % lower cost	- Increased round trip time
Optimize the drive train	≈ 4.5 - 12% lower cost	- Increased building cost
Optimize other items	≈ 3% lower cost	- Composed of many different elements, so no single item to optimize
Increase main dimensions	≈ 21.5 – 25.5% lower cost per unit of cargo compared to the largest ships, larger savings compared to small ships	- Restrictions in flexibility - Increase in shipment size - Increase in roundtrip time due to longer handling

Block coefficient

Increasing the block coefficient of a ship leads to an increase in displacement and thereby to an increase in cargo carrying capacity without changing the main dimensions. Since the typical block coefficient of inland ships is around 0.9 (see table A-1), and a block coefficient can never be significantly larger than 1, the maximum increase in block coefficient is roughly 0.1 and the resulting increase in cargo weight is just over 11% under the assumption that the lightweight-to-deadweight ratio does not change when the block coefficient changes.

However, in practice space needs to be allocated for the rudders, propeller and water flow to the propeller while a box-shaped ship will also have a very large resistance and will have major difficulties in maneuvering. As a result, a higher block coefficient will result in an increase in fuel consumption as well as an increase in building cost due to higher required propulsion power while the maximum practical increase in cargo carrying capacity will be lower than the previously indicated 11%. When the maximum amount of cargo that can be carried is determined by its volume rather than by its weight, however, this measure will not have a significant effect.

<u>General arrangement</u>
The general arrangement of a ship results from the need to fit all equipment on board as well as from a number of preferences or boundary conditions regarding their location. Altering the general arrangement will not necessarily change the weight, displacement or building cost of the ship. It can only make a limited amount of extra space available for the placement of cargo. Therefore, it will only affect the cargo carrying capacity of inland ships in a significant way if it allows for an extra row of containers to be placed in the hold.

In practice his has been done for a limited number of small ships (Neokemp/Hopper type container vessels of 63 x7 m), where accommodation space is sacrificed to allow more space for the containers. In this specific case, it becomes possible to place 4 additional containers, compared to the original 28. This implies an increase in cargo carrying capacity of just over 14%.

<u>Hull weight</u>
Reducing the weight of the hull of a ship will increase its cargo carrying capacity without increasing the displacement. In table A-1, hull weight is estimated to represent 11 to 17% of total displacement, as a result of which elimination of all weight of the hull would lead to an increase in cargo carrying capacity of 14 to 21%. However, it is not possible to reduce the hull weight to zero. In fact, only limited weight savings are possible by changing the steel structure of the ship and, therefore, alternative materials are usually investigated in attempts reduce the weight of a ship's hull.

Efforts to develop small lightweight ships that use materials that differ from steel like the INBAT project [Guesnet, 2005] and Compocanord project, [Lightweight structures, 2010] have, however, not left the drawing board, at least in part due to excessive cost of the materials. The solution by Lightweight Structures [2010] is said to lead to a hull weight reduction of 50%, which in turn results in roughly 7 to 10% more cargo carrying capacity in case weight is the limiting factor on the amount of cargo that can be carried.

<u>Weight of other items</u>
The weight of the items that are on board represent between 3 and 9 percent of the displacement of the ship. Therefore, if they can be eliminated completely, this will result in a 4 to 11% increase in cargo carrying capacity in case weight is the limiting factor on the amount of cargo that can be carried. However, the equipment on board consists of a large number of individual items, each of which each has a function to fulfill. As a result, major savings in weight are difficult to achieve.

If the weight of all items on board could be halved, thereby achieving similar weight savings as for the hull, this would result in a 2 to 5% increase in cargo carrying capacity in case weight is the limiting factor on the amount of cargo that can be carried. The impact that this weight reduction would have on the building cost of the ship cannot be estimated at this time, since it is not known how this weight saving will be achieved.

<u>Design speed</u>
The amount of power that is required to propel a ship is strongly influenced by its speed. Designing the ship for a lower speed will, therefore, lower the amount of power that needs to be installed as well as the ship's fuel consumption. Inland ships have a minimum required design speed of 13 km/h [European Parliament and Council of the European Union, 2006a], while large inland ships have a normal speed of around 16-18 km/h. This implies that the maximum speed reduction is between 3 and 5 km/h.

One of the simplest ways of estimating the amount of power that is needed to propel a ship of a given type main dimensions and speed is provided by the by the so-called admiralty formula, which reads:

$$P_{req} = \frac{\Delta^{2/3} \cdot V^3}{C}$$ Eq. A-1

Where:
P_{req} = required propulsion power (kW)
Δ = displacement (T)
V = ship speed (kn)
C = ship-type dependent constant ($T^{2/3}$ kn^3/kW)

From this equation, it can be concluded that power is roughly related to speed by a third power. Fuel consumption is, therefore, related to the square of the speed. It needs to be noted however that this formula does not include any shallow or restricted water effects.

As a result, reducing the design speed from 18 to 13 km/h will result in a reduction in installed power of about 62% and a reduction in fuel consumption of about 48%. Multiplying these values by the contribution that the building cost of the propulsion system and the fuel consumption have on the total cost leads to potential savings of 12 to 19%.

The primary drawback of lowering the design speed is an increase in the roundtrip time as a result of which the amount of cargo that can be transported in a given amount of time will be reduced. This in turn leads to an increase in the cost per unit of transported cargo. The extent to which the roundtrip time will increase can not be assessed at this time since it is not only dependent on the sailing speed but is also heavily influenced by the time that is spent in port and the distance of a round trip. Furthermore, in case the design speed is lowered, this does not automatically imply that the amount of installed power can be reduced, since the ship may need this power to overcome local currents, to maneuver or to stop.

Specification of the drive train

When the design speed is kept constant, there are still many ways to influence the fuel consumption and installed power of a ship and this has been the topic of a considerable amount of research. In project INBISHIP [2010] a diesel-electric ship was designed, while the PACSCAT project strived to develop a high speed inland cargo ship that is hybrid between a catamaran and a hovercraft. Neither of these left the theoretical stage, but some inland ships now do have diesel electric propulsion for which reduction of fuel consumption of 30-40% is claimed, although scientific proof of this claim is still lacking [Schuttevaer, 2010b].

The Futura Carrier concept [New-Logistics, 2010] features a novel hullform and thrusters on each corner of the vessel. Of this concept, several vessels have been built. Projects to develop air lubrication as a means to reduce the friction of the hull and thereby reduce the required propulsion power show promise, but are still in the testing phase, albeit that a full scale test is carried out on the first vessel of the Futura Carrier type [Foeth, 2008].

In the mid 1990's the Whale tail wheel was a much discussed new way of propelling inland ships, featuring a propulsor that mimics the up-and-down motion of a whale's tail rather than the conventional circular motion of a ship's propeller [Berg, Van den, 1996]. This concept, despite claiming high efficiencies and even making it to the stage of a full-scale demonstrator, never broke through as a reliable means of ship propulsion. However, at the end of the first decade of the 21st century there is renewed interest in this propulsion concept; a simpler version of the device is under development by the company *O foil wing propulsion,* who have done tests on a 10 meter long scale model and plan to have the concept ready for full scale operation in 2013 [O foil, 2011]. A reduction of fuel consumption of 33% is claimed.

The FP7 project STREAMLINE [2012] is also researching several ways to reduce fuel consumption through improvement of the ship's propulsor. No quantitative data have been published yet, but it is stated that in the past efficiency improvements of 5 to 20% have been achieved.

Summarizing, there are a number of developments to reduce the fuel consumption of ships by improving the hull or the propulsor, with an upper limit on the claimed reductions in fuel consumption of 30-40%, resulting in 4.5 to 12% reduction of the total cost since fuel consumption makes up 15 to 30% of the total cost. A reduction in fuel consumption implies a reduction of installed power and would, therefore, ordinarily lead to lower building cost as well. Thus far, however, as a result of the more complex machinery that is required to implement all abovementioned solutions, the building cost is actually expected to increase.

<u>Specifications of other items</u>
The 'other items' on board of a ship comprise everything from the navigation equipment and the furnishing of the accommodation to equipment like the bow thruster or the car crane. Since all of these fulfill a specific role, the cost savings that can be achieved by changing them are limited. Furthermore, since they make up about 20% of the cost of the vessel, saving e.g. 50% on the cost of these items will only lead to a 3% reduction in total cost.

<u>Main dimensions</u>
Changing the main dimensions of a ship directly affects the displacement of that ship. Since it is assumed in table A-1 that lightweight and displacement are linearly related, any increase in displacement will result in the same percentage of increase in cargo carrying capacity.

The largest units that can be operated on European waterways are pushing units of up to 280 m x 22.8 m (long formation) or 195 m x 33.4 m (wide formation) [European Conference of Ministers of Transport, 1992]. However, the largest commonly used inland ships are 135 m long and roughly 17.5 meters wide. The length of these ships is equal to the maximum allowed length of an 'indivisible' ship on the Rhine as stated by the CCNR in article 11.01 of the 'Rijnvaart Politiereglement' [Central Commission for Navigation on the Rhine, 2010]. As a result, increase of the main dimensions can only be achieved if it can be guaranteed that the ship can be divided when this is necessary or if the regulatory maximum length of inland ships can be increased. It is, however, believed to be possible to devise ways to divide a ship. Furthermore, since the length limit that is imposed by the CCNR has already been increased from 110 meters to 135 meters in the past and is not founded on a hard physical limitation, this limit is not considered to be so strict that it makes it useless to explore the benefits and drawbacks of larger ships.

Therefore, it is considered to be worthwhile to explore how longer ships would affect the competitiveness of inland waterway transport operators. When such ships prove to be substantially more competitive than existing ships, it will need to be discussed with the CCNR if, and under which circumstances, longer ships can be allowed or a method to divide such large ships will need to be devised.

The largest pushing units can be operated on a limited number of major waterway stretches including the Rhine (up to Koblenz), which is the primary inland shipping route in Europe. This implies that the size of single inland ships can be increased by a factor of 2.7 before the physical limits of the waterway are reached. However, such large vessels only have access to a limited number of sea ports and inland terminals and may have difficulty turning on the river or in inland ports.

Smaller 4-barge units of 195 x 22.8 m can access substantially more waterways and ports and will have less difficulty in turning.

When comparing the main dimensions of the largest single inland ships to those of 4-barge pushing units, it can be concluded that the cargo carrying capacity of single inland ships can be increased by almost 90% in case no increase in draught is assumed and the relatively small effects of the different shapes of pushing units and ships are neglected. The change in main dimensions affects the cost of operating the ship in different ways: since the ROS-R regulations [Central Commission for Navigation on the Rhine, 2007] only prescribe an increase in crew when lengths of 70 and 86 meters are exceeded, a further increase of dimensions will not lead to higher crew cost. As a result of this, an increase in cargo carrying capacity of 90% will result in a 47% reduction in crew cost per ton of cargo carrying capacity.

The effect that changing the dimensions of a ship will have on its installed power and fuel consumption can again by estimated with the admiralty formula (equation 2.1). Since the formula states that power is related to displacement by a power of 2/3, if the speed of a ship is kept constant, an increase in displacement by 90% will only increase the fuel consumption by 53%, thereby effectively reducing the fuel consumption per ton of cargo carrying capacity by 19%.

For the third main cost element, capital cost, no major scale effects are expected in the cost of the hull while the reduction in ‘other’ building cost is unknown and, therefore, assumed to be zero for now. However, there will be a reduction in the cost of the propulsion system due to the lower amount of installed power per ton of cargo carrying capacity. The abovementioned reduction of 19% in required power leads to a reduction of 5% in building cost.

When these part savings are combined with the data in table A-1, this leads to a total saving of 21.5 to 25.5%, as is shown in table A-3.

Table A-2: Summation of cost reductions by scale enlargement

Element	Share in total cost	Cost reduction of element	Total cost reduction
Crew cost	30-45%	47%	14 - 21%
Fuel cost	15-30%	19%	3 -6%
Capital cost	30%	5%	1.5%
Total			≈ 21.5-25.5%

Table A-3 above implies that compared to the largest, most cost-effective single inland ships that are operated today, a cost reduction per ton of cargo carrying capacity of 21.5 to 25.5% is possible. A comparison between an enlarged single ship and a 4-barge pushing unit is not so easily made due do the different crew requirement, higher fuel consumption due to worse hydrodynamics and the potential for different ways of operating of pushing units. However, on the basis of cost data provided by NEA [2003], savings of 12 to 16% may be expected.

However, there are a number of drawbacks associated with enlargement of main dimensions. Due to an increase in size, the operating area of the ship, and as a result its flexibility, will be restricted because it will no longer fit through certain locks or not be allowed to sail on certain waterways. Furthermore, larger ships typically carry larger shipments, which may increase the stock cost of shippers. This may in turn negate the reduction in his total logistical cost that is achieved through lower out-of-pocket cost of transport. Larger ships will also spend a longer time in port, thereby increasing their voyage time and decreasing the number of trips they can make in a year.

B : Equipment weights

When dividing the weight items that are typically on board of inland ships into various categories, the following subdivision can be made:

1. Propulsion & maneuvering
   - Engines
   - Gearboxes
   - Shafts
   - Propellers
   - Rudders
   - Steering machines
   - Bow thrusters/pumpjets
2. Electrical power system
   - Generator sets
   - Switchboards
   - Frequency converters
   - Electrical motors
3. Miscellaneous engine room weights
4. Accommodation
5. Piping
6. Miscellaneous items
   - Masts
   - Wheelhouse
   - Wheelhouse raising column
   - Winches
   - Anchors & chains
   - Small ironwork

This subdivision is used in the coming subparagraphs, where the way weights of the various groups are determined is elaborated.

It should be noted that many of the products offered by manufacturers are suitable for a certain bandwidth of power and that these products come in only a number of different variants. As a result of this, multiple types of equipment can usually be selected to deal with a given amount of power and there will be a stepwise increase in weight if the power range of one product is exceeded and there is the need to switch to a bigger, heavier product. For the purpose of this thesis, however, these effects have been smoothed out to continuous functions of weight vs. power. This can be justified by the large number of options that a transport operator has when he wants to select a suitable piece of equipment for his ship: there are several brands and types of engines to choose from.

B.1 Propulsion and maneuvering

Engines

Inland navigation engines are high-speed engines that run on high quality fuel (gasoil). As a result they are lighter than medium speed engines with the same rated power and have virtually no auxiliary equipment. This makes machinery weight predictions for seagoing ships such as that by Watson [1998] unusable. However, there is a relatively simple remedy available: A review of Caterpillar's line of high speed engines for inland ships [Caterpillar, 2010] reveal a dry weight of roughly 4.9 kg/kW, which is used as the standard value for this thesis. This is slightly higher than quoted by Watson [1998, p 110], who states a value of 3 to 4 kg per kW for high speed engines. The explanation for this may be found in the fact that inland navigation engines have relatively low power compared to seagoing ships: Watson's regression line for slow and medium speed engines and shows a lower relative weight as engines get more powerful and similar effects may be expected for high speed engines. Further explanation may be found in the fact that inland navigation engines are virtually self-contained units with very little separate auxiliary equipment, which is accounted for separately by Watson. Therefore, since almost all required auxiliary functions are incorporated in the engine, it will be relatively heavy.

Gear boxes

Based on the Reintjes WAF/LAF 164 – 572 series gearboxes for power ranges that are typical for inland ships, [Reintjes, 2010], we find gearboxes of 525 kg at the lower end of the range, with a power range of 220 - 420 kW and at the upper end of the range a gearbox of 2360 kg at a power range of 630 to 1200 kW. Here, like with the engines, there is a stepwise function of weight increase vs. power, due to the large range of powers that can be handled by a single gear box. For the purpose of this thesis, a linear relationship of 2 kg per kW is assumed.

Propellers

Gerr [2001] describes a relationship between weight and diameter of a conventional fixed pitch propeller as W= 0.00323 * D^3.05, where w is expressed in pounds and D in inches. Converting to the metric system, this results in W = 0.001465 * (D/2.54)^3.05 with W in kg and D in centimeters.

Based on data from Schottel's line of ducted rudder propellers [Schottel, 2010], a formula of W=1.5*Dp^3, with W in t and D in m, is established, although there is scatter between about 1.3 and 1.8.

Propeller shafts

Gerr [2001] also provides a formula for propeller shaft diameter for (Tobin bronze) propeller shafts, which, once converted to metric units, reads

D_{prop} (mm) = (1627.8*P(kW)*SF/(St(N/mm2)*RPM))^(1/3) *25.4,	Eq. B-1

Where SF is a safety factor, advised by Ger to be between 5 and 8 (selected as 8, to include additional weight of bearings etc.), and St is the yield strength in torsional shear. For both Tobin Bronze (selected by Ger) and stainless steel, this value is 138 N/mm^2. For further calculations, stainless steel shafts with a density of 7.916 T/m3 are used.

Rudders

No direct estimates for rudder weight were found, so a reference value is taken from a 110 * 11.45 m tanker, which has twin rudders of 2.5 t each. Relating this to the estimated size of the rudder of length x height =1*2.5 m, a weight of 1 ton per m of propeller diameter per rudder is found.

Steering machines

Information about steering machines is scarce. The limited data available, provided by Van der Velden Marine Systems [2010] does not differentiate between rudder sizes for selection of a steering machine, only whether it is a single or twin rudder. It also does not state weights. Therefore the reference value provided by actual data from a ship is used. It reveals a weight of 0.5 t for a twin rudder solution, which is used as the default weight for steering machines in this thesis.

Bow thrusters

For bow thrusters, based on Schottel's line of bow thrusters [Schottel, 2010], the ratio between power and weight is more constant than that between diameter^3 and weight (i.e. the parameters found by Ger for normal propellers). A weight of 5.4 kg/kW is used. The power of the bow thruster(s) is not calculated directly but based on statistical data from Vereniging 'De Binnenvaart' [Vereniging 'De Binnenvaart'] as shown below in figure A-1. It is clear that there is significant scatter but a value of 0.11 kW per m3 of LBT is used as a default value.

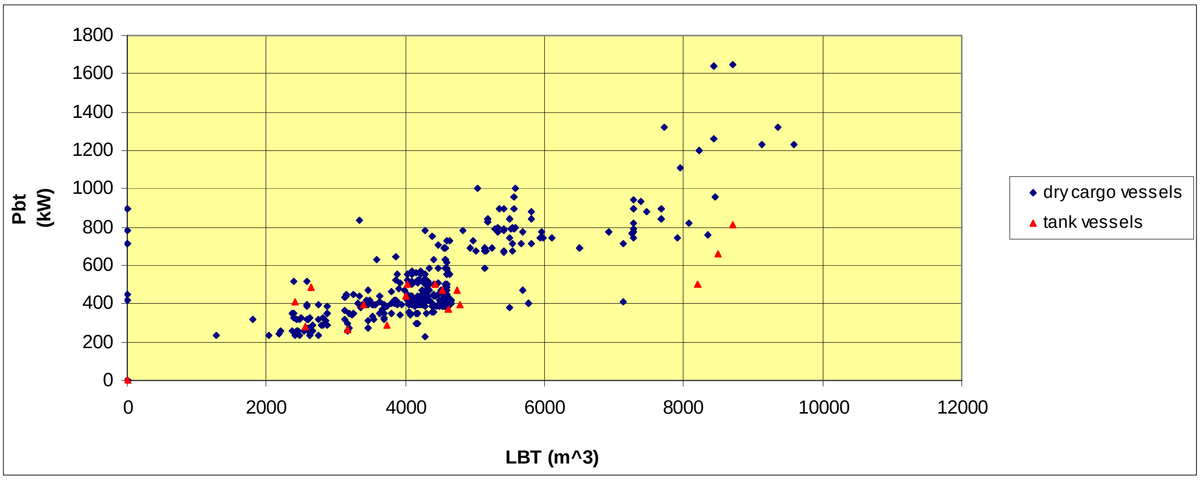

Figure B-1: Bow thruster power vs. LBT

Pumpjets

In Schottel's pumpjet line [Schottel, 2010], a progressive line of weight vs. power can be observed, implying that weight of units increases faster than power, ranging from 3.5 kg/kW for small units (up to 110 kW) to 12.7 kg/kW for units with a maximum rating of 2200 kW. Drawing a (well-fitting) trend line through the data points of maximum power and weight of the various models, a relationship of y = 0.003x2 + 6.0829x - 138.17 is found, y being the weight in kg and x being power in kW.

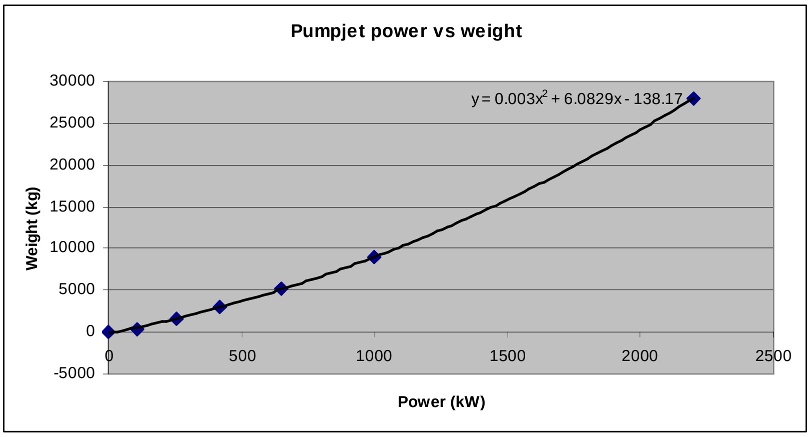

Figure B-2: Bow thruster weight vs. power

B.2 Electrical power system

Generator sets

For the determination of generator set weight, similar issues are at play as with diesel engines; they are virtually self-contained high speed units. Here, a review of Caterpillar's generator set line [Caterpillar, 2010], which is a generator set line that is commonly used in inland ships, reveals a weight of roughly 9 kg/kVA, which is used for this thesis.

Switchboards

Empty weight of a single switchboard cabinet[18] is defined at 250 kg. A complete (medium voltage) switchboard for 500 kVA of electrical power was estimated to weigh 500 -600 kgs, while a 2000 kW

18 From private conversations with an engineer at a company that manufactures electrical switchboards for the marine industry.

unit weighs 2000 – 2500 kgs. Reference data from an inland tank vessel (for which e-power is not known exactly, but estimated at 1500 kVA) reveals two 1300 kg main switchboards, confirming the abovementioned data. Although weight as a function of power is not a continuous linear curve, but a stepwise function (e.g. addition of a second cabinet), for the estimation here a linear relationship of 1 kg per kVA of installed electrical power is maintained, with a minimum value of 300 kg.

Frequency converters

Based on a review of the datasheet of the PCS100 SFC frequency converter range of ABB [2010], a weight of 900 kg + 2 kg per kVA of installed electrical power is used.

Electric drives

A large selection is of electric drives is available on the market. Data based on the EURODEEM database and ABB's range of electrical motors for marine applications [ABB, 2010], shows values in the range of 5-10 kg/kW. For this thesis a value of 6 kg/kW is used.

B.3 Miscellaneous engine room weights

Apart from the main components identified above, there are several smaller items such as air bottles, pumps, fans etc. as well as a substantial amount of piping, ducting, cable trays and electrical wiring. The weight of these items cannot be so easily identified as the components described above, both due to their diversity and number and due to their relationship with engine room dimensions and lay-out.

For a reference ship with approximately 1250 kW of main propulsion, the weight of small items is roughly 1 kg/kW of main propulsion power. For piping, ducting etc. the weight is only partly related to the amount of power installed: E.g. all engine rooms need ventilation and every engine needs control wires, no matter how big it is. Based on a limited set of reference data from existing vessels, this weight is estimated at 3 tons plus 2.5 kg/kW of installed power for both engine room and bow thruster room, as long as there is any installed power present.

B.4 Accommodation

The weight of the accommodation of an inland ship is substantially different from ship to ship: Accommodations intended to house a captain-owner and his family can be much more luxury and as a result significantly heavier than those accommodations set up as simple accommodation for a hired crew. For the purpose of this thesis, for the entire accommodation (incl. steel structure), a value of 0.17 t/m3 is used, based on a reference vessel.

B.5 Piping

The weight of piping is strongly dependent on the routing of the pipes itself. Therefore, the main pipes are routed explicitly instead of relying entirely on an empirical formula for the determination of its weight. The typical dimensions of the pipes were obtained through private conversations with a piping installation company and a review of several pipe schematics for existing inland ships. The following piping elements and configurations are included in the design model:

a. Ballast pipes (light blue), which can be configured in either a ring-system accessing all tanks or a set of separate pipes leading to each tank, in both cases having water inlets at the front of the engine room. Their weight is determined by using steel pipes with a diameter of 0.203 m (7 inch) with a wall thickness of 5 mm and 10% margin for paint, connections, valves etc.
b. De-aeration pipes (black), identical to the main ballast pipes, leading from each double bottom tank to the main deck.

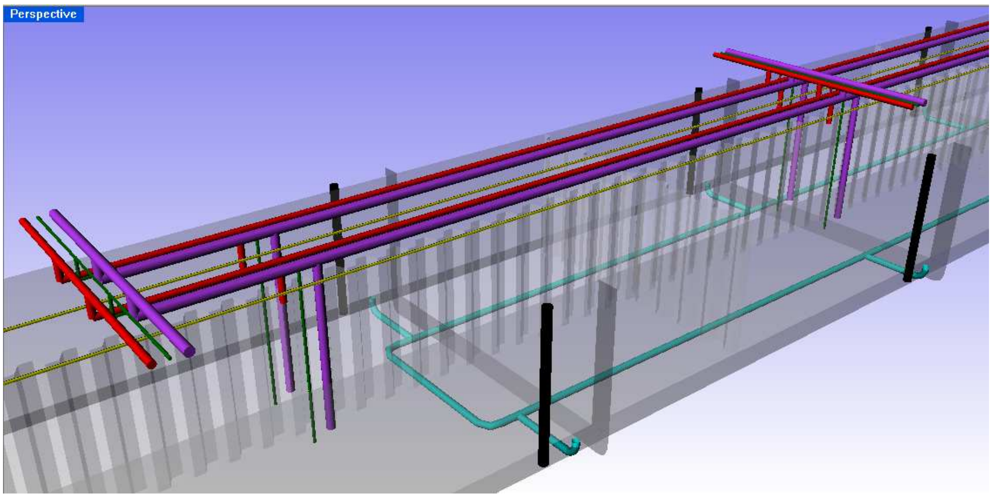

Figure B-3: modeled piping in the midship region of a tank ship

c. Main cargo pipes for tankers (purple), with a diameter of 21.9 cm for the vertical connections to the tanks & shore connections and 27.3 cm or the main lines. Wall thickness of the pipes is set at 6 mm and a 20% weight margin for supports, paint, connections, valves, pumps etc. is applied. This margin is deliberately chosen larger than for ballast pipes since on-deck mounting will require more support than pipes that run through a steel structure, to which they can be mounted directly.
d. Aftersuction pipes for tankers (green), with a diameter of 7.6 cm for all pipe elements, with a wall thickness of 3 mm and a 20% weight margin.
e. Deck wash pipes for tankers (yellow), with a diameter of 7.6 cm for all pipe elements with a wall thickness of 3 mm and a 20% weight margin.
f. Vapor return lines for tankers (red), with a diameter of 16.8 cm for all pipe elements, with a wall thickness of 3 mm and a 20% weight margin.

B.6 Miscellaneous items

The weight of anchors and anchor chains is based on the requirements set forth in European Directive 2006/87/EC [European Parliament and Council of the European Union, 2006a], which includes requirements for the weight of the anchor. The weight of the chains is determined by a review of product data from H-lift industries [2010], which shows a wide range of possible weights, depending on the grade of the chain. However, using a relatively simple chain, a more or less constant weight of 0.079 kg per kN of proof load per meter of length is revealed. The weight of the wheelhouse, wheelhouse raising column, fore mast and anchor winches are based on weight data from a reference ship: The weight of the wheelhouse is set at 8 t, the raising column at 5 t, fore mast at 2 t and anchor winches at 2 t each.

Further weights added to the ship are 3 tons of miscellaneous weights in both the bow and stern sections (lettering, bollards, small items etc.), 2 tons of miscellaneous liquids (drinking water, lubrication oil, hydraulic oil,…) 1 ton of lost buoyancy due to the water in the bilge coolers. The weight of the water in the bow thruster tunnels is based directly on the volume of the tunnels. Fuel weight is determined on the basis of the volume of the tanks, which is in turn determined by the required range and installed power of the vessel.

Together all these elements are thought to make up the total weight of the ship.

C : Ship building cost

For the purpose of this thesis, the costs of the ship are broken down into 12 different categories:

1. General object cost
2. Hull
3. Propulsion & maneuvering
4. Electrical system
5. Bilge & ballast systems
6. Cargo pumps & piping for tankers
7. Accommodation
8. Mooring gear
9. Hatch covers
10. Outfitting
11. Miscellaneous equipment
12. Profit margin

Below, the way costs for each category are arrived at is explained. All costs are expressed in 2011 values; they are derived on the basis of scaling rules from literature and reference cost data from quotations from 2011.

General object cost

General object costs include acquisition, overhead and engineering. Coenen [2008, p. 15] states that in shipbuilding the cost of engineering, including procurement and ship management equals roughly 20-35% of a shipyard's labor hours. What is included in the yard's labor varies from yard to yard, as is also discussed by amongst others Stopford [2009, p. 646], but in the case of the yard at which Coenen did her PhD work, the yard's labor costs typically consist of the building of the steel hull, including small steelwork & installation of the main piping and project management. Other tasks, such as painting, installation of the major mechanical and electrical systems and the propulsion units are subcontracted.

Here, we need to take into account that the yard Coenen performed her research at builds complex one-off vessels (i.e. dredgers), while inland ships are vastly simpler and highly standardized. At the same time, we need to realize that the engineers and project managers that are paid for through the general object costs are higher skilled than yard workers that build the vessel's steel structure and paid accordingly. As a result, a value of 15% of the labor cost for the building of the ship's hull is estimated as typical cost of cost category 'general object costs'.

Hull

The cost of the ship's hull can be estimated in various ways. Commonly accepted values[19] are in the range of 2.5 to 3 €/kg of steel weight. This claim can further be substantiated by research by Kerlen [1981, p 104]. Kerlen quotes the required number of man-hours per ton of steel (for general cargo, bulk and tank vessels (between 20.000 m3 and 100.000 m3 LBD) as:

$$k_{fr} = 45.36\left(\frac{LBD}{1000}\right)^{-0.115} \cdot \frac{0.866}{\sqrt[3]{C_B}} + x_{II}\,, \qquad \text{Eq. C-1}$$

where x_{II} represents a compensation for yard-specific variations, which for the purpose of this thesis is left out of the equation.

It will be shown later on that when this equation is used, costs per ton of steel end up in the same range as the abovementioned 2.5 to 3 €/kg.

The second main aspect, the cost of the purchased materials, is directly related to the amount of steel that goes into the hull's structure. This amount is calculated directly through the design model.

[19] Obtained through private conversations with shipyards and owners

Multiplying this weight with the steel price per ton will result in an acceptable first estimate of the material cost of the hull.

Tuning the above equation with a man-hour cost of 45 €/h, and a steel price of 950 €/ton results in costs for the hull of a typical inland ship that closely match the quoted cost of 2.5 to 3 €/kg. It should be noted that these man-hour costs not only include the direct labor cost, but also includes indirect cost.

Propulsion & maneuvering

For the determination of the cost of the propulsion system, an approach as detailed as for the weight determination of that system is not possible, since there is a much larger variation in equipment prices and the system is made up of a host of different items.

As a rule of thumb, Aalbers [unknown year, 200X] arrives at cost of the entire drive train of \$4700*$P_{prop}^{0.79}$, with P, the installed power in kW, while Hunt and Butman [1995, 9-2] use K_3 * $P_{prop}^{0.82}$. Due to the fact that Aalbers, Hunt and Butman look at seagoing ships with medium and slow speed engines, running on MDO and HFO, the coefficient of 4700 is not believed to be representative for high speed inland ship engines that run on gasoil. The power of 0.79-0.82, however, is believed to provide an acceptable indication for scale effects.

In absolute cost for the main engine, Aalbers quotes a value of \$ 200 to \$ 300 per kW (values from unknown year). Based on quotations for modern inland ship engines of 330 to 500 kW of rated power, a price of roughly 220 €/kW (2011 values) is found. However, there is a large spread in prices. Stapersma [2001] arrives at a more physically correct approximation of specific unit purchase cost (supc) of an engine (2001 values) as follows.

$$\sup c = \frac{upc}{P_b} = 270 \cdot \left(\frac{c_m}{9.5} \cdot \frac{1.25}{\lambda_S} \cdot \frac{10}{n} \right)^{0.7} \qquad \text{Eq. C-2}$$

Where:

upc = unit purchase cost (k€)

P_b = brake engine power (kW)

C_m = piston speed (m/s)

λ_s = stroke/bore ratio

Although the approach by Stapersma provides the most well-founded comparison between engines with different specifications, it requires quite detailed knowledge about the engine. Since engine design is beyond the scope of this thesis, the more simple approximation of 220 €/kW is used.

For propellers, shafting and attached hydraulics (if any), lecture material from Delft University of technology [2009] quotes 55 €/kW for a fixed pitch propeller at 100 rpm and 65 €/kW for a fixed pitch propeller at 250 rpm. For controllable pitch propellers (not used in inland shipping), it quotes, 70 €/kW for propellers operating at 100 €/kW and 110 €/kW for propellers operating at 250 rpm.

For the gear box, values are not quoted in terms of €/kW, but as 15-25 €/kg of gearbox weight. As discussed earlier, for the purpose of this thesis, a weight of 2 kg/kW is assumed as a standard gearbox weight for this thesis, bringing cost of the gearbox to roughly 40 €/kW.

As a result of the above, the cost of the drive train is estimated at around 325 Euro per kW. For the remainder of this thesis, material cost for the drive train are based on a cost of 330 €/kW for a drive train with a 750 kW engine and a power of 0.82 to relate cost to engine size. This results in a cost of

$C = N*1086\ P^{0.82}$,with N as the number of propellers and P as the installed power per propeller. For bow thrusters and their engine, the same formula is used. Per propeller, € 50.000 is added for rudders and steering machines, based on an actual quotation.

Electrical system
The cost of electrical system is hard to estimate, especially since it interacts with virtually all other systems. Based on a quotation for a number of actual ships, generator sets are cost is estimated at 175 €/kW, while the cost of the total electrical system (including gensets) is estimated at 500 €/kVA.

Bilge and ballast systems
Bilge & ballast systems are related to vessel length and are estimated to cost € 450 per m of ship length, based on some quotations.

Cargo pumps and piping
In a similar approach a value of 145 €/m3 of LBD is used for cargo pumps and pipes for tankers, although it should be noted that this is a rudimentary approximation, since the system is significantly influenced by the number of different parcels and the size of the tanks.

Accommodation
For the accommodation, an estimated price of 600 €/m2 is used, based on some quotations.

Mooring gear
The cost of mooring gear is estimated at 13 €/m3 of LBT, based on a quotation and the reasoning that L, B and T of the vessel all affect the forces on the anchors.

Hatch covers
Schneekluth and Bertram [1998, p95] provide a trend for hatch covers: They state that hatch cover price depends linearly on length and to the power 1.6 on width. As a result the cost of hatch covers is estimated at € 24 * Lhold * Bhold^1.6 of the vessel, again based on those same quotations.

Outfitting
Outfitting cost, being generally recognized as one of the most difficult and design-specific factors to calculate, is determined as a function of outfitting weight to the 2/3 power both by Watson [1998, p478] and Hunt & Butman [1995]. In this case, in line with the weight estimate made earlier in this chapter, it is assumed that if any engine is present in a space, it will have an x-amount of outfitting (cable trays, control lines,…), independent of engine rated power. For each kW of power, a y-amount of outfit weight is added.

Again based on a reference vessel, the cost of outfitting is estimated at 40.000 * $W^{2/3}$, with W, expressed in tons, subdivided in weight in the fore and aft part of the ship. The coefficient of 40000 is again arrived at by analysis of a quotation for a ship.

Miscellaneous equipment
Cost for miscellaneous non-ship size related equipment (wheelhouse, navigation masts etc.) may vary from case to case but is hardly dependent on ship size, apart from anchor winches. For the analyses made here these items are grouped together with class cost, cost of required software etc and estimated at € 100.000,- In case the wheelhouse is raisable, another € 65.000 is added to this, although commercial figures show that this is strongly dependent on the raising height.

Risk margin
Since the price for which a ship owner buys a ship will include a risk margin for the yard, a 5% margin for the yard is included in the price of the ship.

D : Simple rules of thumb for weight, cost and cargo carrying capacity

In this appendix, rules of thumb are presented in the form of 2nd order polynomial trend lines of steel weight, lightweight, cargo carrying capacity and building cost, expressed as a function of LBT. The rules of thumb are valid for L/B values between 6 and 12 for vessels with a length up to 135 m. Results are presented for each of the 5 combinations of vessel type and framing system: Longitudinally and transversely framed dry bulk and container vessels and longitudinally tank vessels.

D.1 Dry bulk vessels

In this paragraph, the rules of thumb for steel weight, lightweight, cargo carrying capacity and building cost of dry bulk vessels are discussed. Separate rules of thumb are presented for longitudinally and transversely framed vessels.

The rules of thumb are presented in an order that requires decreasing amounts of technical knowledge about ships, but also decreases a user's design freedom. First the rule of thumb for steel weight is presented, which gives a user of this rule of thumb the opportunity to still make his own decisions regarding all items that need to be on board. Second, the total lightweight of the ships, as modeled is provided. This provides a user with a finished weight estimate but takes away the freedom to design the equipment, machinery, outfitting and accommodation. The third set of rules of thumb provides estimates of the cargo carrying capacity of a ship, thereby not only fixating its weight, but also its hullform and making it harder to estimate the cargo carrying capacity at reduced draught. This rule of thumb does, however, allow for a reasonable estimate of the cargo carrying capacity of a ship for people without substantial knowledge of ship technology.

Steel weight

The trend line for the steel weight of dry bulk vessels is assumed to be a second order polynomial with a zero-crossing at (0,0) since all of the scantlings have a direct relationship with the vessel's main dimensions. When separate regressions are made for draughts ranging from 1.5 to 4.5 meters with 0.5 meter intervals, this results in the trend lines as shown in figure D-1 below.

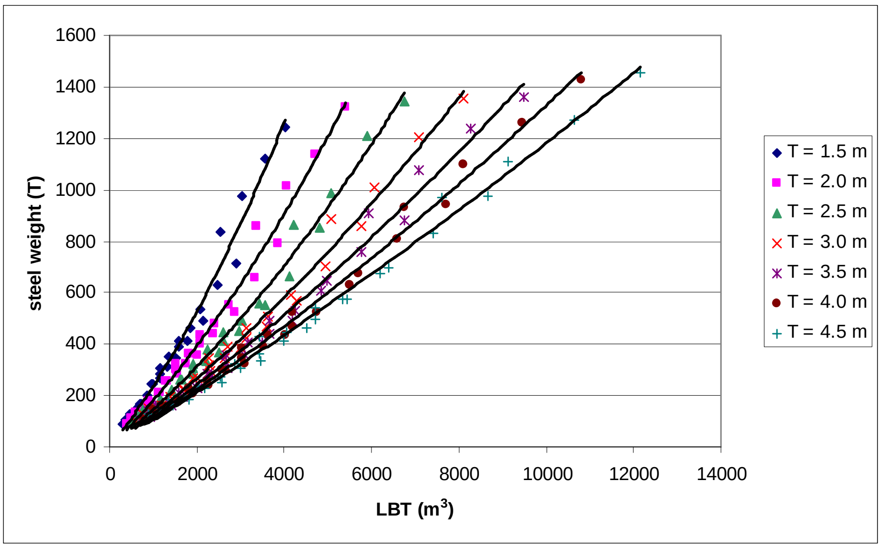

Figure D-1: Steel weight of longitudinally framed dry bulk vessels

Each of these trend lines is the visualization of an equation of the form:

$$W_{steel} = c_1 \cdot (LBT)^2 + c_2 \cdot LBT \qquad \text{Eq. D-1}$$

In table D-1 below, the coefficients are given for both transversely and longitudinally framed container vessels, together with the R^2 values of the regression. From these R^2 values, it can be concluded that within the validity range of the trend line, it provides a close match with the original data.

Table D-1: Steel weight - coefficients for dry bulk vessels

Transverse framing

T (m)	c1	c2	R^2
1.5	1.80E-05	2.37E-01	0.980
2	8.33E-06	1.89E-01	0.986
2.5	7.18E-06	1.51E-01	0.987
3	3.00E-06	1.37E-01	0.988
3.5	1.73E-06	1.25E-01	0.988
4	1.78E-06	1.16E-01	0.991
4.5	1.61E-06	1.09E-01	0.988

Longitudinal framing

T (m)	c1	c2	R^2
1.5	2.62E-05	2.11E-01	0.978
2	1.49E-05	1.67E-01	0.984
2.5	9.86E-06	1.37E-01	0.988
3	6.04E-06	1.22E-01	0.989
3.5	3.72E-06	1.14E-01	0.989
4	2.58E-06	1.07E-01	0.992
4.5	1.50E-06	1.03E-01	0.992

Lightweight

For the lightweight of dry bulk vessels, similar trend lines can be drawn as for steel weight. The main difference between the trend lines for lightweight and steel weight are that the formula for the estimation of lightweight has a residual term due to weight items like the wheelhouse, winches, masts, outfitting etc. that are not directly related to L, B or T.

As a result, the regression formula for lightweight is:

$$W_{light} = c_1 \cdot (LBT)^2 + c_2 \cdot LBT + c_3 \qquad \text{Eq. D-2}$$

In the tables below, the coefficients and R^2 values are given for both transversely and longitudinally framed vessels. Like with steel weight, the regression provides a close match with the original data, as can be observed from the high R^2 values.

Table D-2: Lightweight - coefficients for dry bulk vessels

Transverse framing

T (m)	C1	c2	c3	R^2
1.5	5.34E-06	2.96E-01	4.98E+01	0.986
2	1.48E-06	2.35E-01	4.86E+01	0.990
2.5	2.88E-06	1.82E-01	6.29E+01	0.989
3	2.00E-07	1.66E-01	5.85E+01	0.991
3.5	2.01E-06	1.33E-01	8.27E+01	0.993
4	3.60E-06	1.10E-01	1.06E+02	0.994
4.5	2.73E-06	1.05E-01	1.15E+02	0.994

Longitudinal framing

T (m)	c1	c2	c3	R^2
1.5	2.59E-05	2.33E-01	6.93E+01	0.981
2	1.49E-05	1.84E-01	7.08E+01	0.987
2.5	1.07E-05	1.44E-01	8.09E+01	0.990
3	6.34E-06	1.31E-01	7.85E+01	0.991
3.5	3.10E-06	1.30E-01	6.74E+01	0.991
4	2.15E-06	1.21E-01	6.90E+01	0.993
4.5	1.22E-06	1.15E-01	7.33E+01	0.993

Cargo carrying capacity

Under the previous two headings, the rules of thumb for the steel weight and lightweight of dry bulk ships were discussed, which are useful for the preliminary stages of ship designs. However, for assessment of the performance of inland ships in logistics chains, lightweight and steel weight are of secondary importance since in the end, it is not the self-weight of the ship that is of importance, but the amount of cargo that the ship can carry. Therefore, in table D-3 below the coefficients to be used in the estimation of cargo carrying capacity of both transversely and longitudinally framed dry bulk vessels are presented. The variables in the rule of thumb are identical to those in the rule of thumb for lightweight estimation:

$$W_{cargo} = c_1 \cdot (LBT)^2 + c_2 \cdot LBT + c_3 \qquad \text{Eq. D-3}$$

Table D-3: Cargo carrying capacity - coefficients for dry bulk vessels

Transverse framing

T (m)	C1	c2	c3	R^2
1.5	-1.36E-05	6.39E-01	-7.33E+01	0.998
2	-6.79E-06	7.05E-01	-8.10E+01	1.000
2.5	-6.03E-06	7.62E-01	-1.07E+02	1.000
3	-2.36E-06	7.84E-01	-1.19E+02	1.000
3.5	-2.47E-06	8.11E-01	-1.49E+02	1.000
4	-3.87E-06	8.36E-01	-1.90E+02	1.000
4.5	-2.47E-06	8.37E-01	-1.95E+02	1.000

Longitudinal framing

T (m)	c1	c2	c3	R^2
1.5	-2.59E-05	6.45E-01	-1.43E+02	0.997
2	-1.58E-05	7.13E-01	-1.54E+02	0.999
2.5	-1.14E-05	7.67E-01	-1.79E+02	1.000
3	-7.24E-06	7.94E-01	-1.99E+02	1.000
3.5	-3.23E-06	7.99E-01	-2.03E+02	1.000
4	-1.08E-06	7.97E-01	-2.03E+02	1.000
4.5	-1.13E-07	8.05E-01	-2.13E+02	1.000

From the very high R^2 values, it can be seen that the rule of thumb explains the vast majority of the variance in the original data.

Building cost

As a final rule of thumb, a building cost estimate is provided. Like with lightweight, the formula features a residual term due to the cost of items like the wheelhouse, winches, masts, outfitting etc. that are not directly related to L, B or T. As a result, the regression formula for building cost is:

$$C_{ship} = c_1 \cdot (LBT)^2 + c_2 \cdot LBT + c_3 \qquad \text{Eq. D-4}$$

In the tables below, the coefficients and R^2 values are given for both transversely and longitudinally framed vessels.

Table D-4: Building cost - coefficients for dry bulk vessels

Transverse framing

T	C1	c2	c3	r2
1.5	-2.36E-02	1.39E+03	3.54E+05	0.984
2	-1.20E-03	9.67E+02	4.54E+05	0.994
2.5	1.50E-02	6.97E+02	5.56E+05	0.988
3	8.00E-04	6.41E+02	5.65E+05	0.993
3.5	-1.30E-03	5.82E+02	5.85E+05	0.993
4	3.50E-03	5.06E+02	6.78E+05	0.992
4.5	1.90E-03	4.81E+02	7.06E+05	0.992

Longitudinal framing

T	c1	c2	c3	R^2
1.5	6.14E-02	1.18E+03	4.91E+05	0.988
2	3.81E-02	8.79E+02	5.22E+05	0.991
2.5	3.24E-02	6.55E+02	6.14E+05	0.993
3	1.83E-02	5.83E+02	6.29E+05	0.993
3.5	2.46E-03	6.03E+02	5.62E+05	0.992
4	1.34E-04	5.67E+02	5.75E+05	0.993
4.5	-1.79E-03	5.38E+02	6.06E+05	0.993

D.2 Container vessels

For container ships, which differ very little from dry bulk vessels, the same analyses are done, resulting in rules of thumb for the estimation of steel weight, lightweight, cargo carrying capacity and building cost of transversely and longitudinally framed container ships with L/B ratios between 6 and 12 and a maximum length of 135 meters.

Steel weight

Like for dry bulk vessels, the regression line for the steel weight of container vessels is assumed to be a second order polynomial with a zero-crossing at (0,0) since all of the scantlings have a direct relationship with the vessel's main dimensions.

This again results in a formula of the form:

$$W_{steel} = c_1 \cdot (LBT)^2 + c_2 \cdot LBT \qquad \text{Eq. D-5}$$

With the following coefficients and R^2 values:

Table D-5: Steel weight - coefficients for container vessels

Transverse framing

T (m)	c1	C2	R^2
1.5	3.00E-05	2.39E-01	0.977
2	1.36E-05	1.95E-01	0.980
2.5	8.10E-06	1.61E-01	0.983
3	5.59E-06	1.38E-01	0.987
3.5	3.66E-06	1.26E-01	0.987
4	3.45E-06	1.14E-01	0.989
4.5	3.49E-06	1.05E-01	0.989

Longitudinal framing

T (m)	c1	c2	R^2
1.5	3.27E-05	2.13E-01	0.978
2	1.83E-05	1.70E-01	0.984
2.5	1.14E-05	1.39E-01	0.987
3	7.97E-06	1.21E-01	0.990
3.5	5.20E-06	1.12E-01	0.989
4	3.10E-06	1.09E-01	0.991
4.5	1.91E-06	1.04E-01	0.992

Lightweight

For the lightweight of container vessels, similar trend lines can be drawn as for steel weight. The main difference between the trend lines for lightweight and steel weight are that for steel weight there is a residual term due to weight items like the wheelhouse, winches, masts, outfitting etc. that are not directly related to L, B or T. As a result, the regression formula for lightweight is:

$$W_{light} = c_1 \cdot (LBT)^2 + c_2 \cdot LBT + c_3 \qquad \text{Eq. D-6}$$

In tables D-6 and D-7, the coefficients are given for both transversely and longitudinally framed container vessels, together with the R^2 values of the regression. The only difference between the lightweight of container vessels and dry bulk vessels is the weight of the steel structure.

Table D-6: Lightweight - coefficients for container vessels

Transverse framing

T (m)	c1	c2	c3	R^2
1.5	2.81E-05	2.68E-01	6.30E+01	0.979
2	1.05E-05	2.30E-01	4.93E+01	0.982
2.5	7.25E-06	1.81E-01	6.19E+01	0.986
3	5.32E-06	1.53E-01	6.95E+01	0.988
3.5	3.19E-06	1.40E-01	7.05E+01	0.989
4	3.83E-06	1.19E-01	9.24E+01	0.991
4.5	4.50E-06	9.94E-02	1.19E+02	0.992

Longitudinal framing

T (m)	c1	c2	c3	R^2
1.5	3.30E-05	2.33E-01	7.16E+01	0.980
2	1.73E-05	1.92E-01	6.40E+01	0.987
2.5	1.19E-05	1.49E-01	7.64E+01	0.989
3	8.05E-06	1.32E-01	7.51E+01	0.992
3.5	4.74E-06	1.26E-01	7.06E+01	0.991
4	2.26E-06	1.28E-01	5.81E-01	0.992
4.5	1.48E-06	1.18E-01	6.79E+01	0.993

Cargo carrying capacity

Under the previous two headings, the rules of thumb for the steel weight and lightweight of container ships were discussed, which are useful for the preliminary stages of ship designs. However, for assessment of the performance of inland ships in logistics chains, lightweight and steel weight are of secondary importance since in the end, it is not the self-weight of the ship that is of importance, but the amount of cargo that the ship can carry. Therefore, in table D-7 below the coefficients to be used in the estimation of cargo carrying capacity of both transversely and longitudinally framed container ships are presented. The variables in the rule of thumb are identical to those in the rule of thumb for lightweight estimation:

$$W_{cargo} = c_1 \cdot (LBT)^2 + c_2 \cdot LBT + c_3 \qquad \text{Eq. D-7}$$

The coefficients and R^2 value of the rule of thumb are again provided below.

Table D-7: Cargo carrying capacity - coefficients for container vessels

Transverse framing

T (m)	c1	c2	c3	R^2
1.5	-3.50E-05	6.67E-01	-9.14E+01	0.995
2	-1.53E-05	7.10E-01	-8.61E+01	0.999
2.5	-1.02E-05	7.65E-01	-1.11E+02	1.000
3	-5.17E-06	7.86E-01	-1.23E+02	1.000
3.5	-2.27E-06	8.02E-01	-1.39E+02	1.000
4	-3.56E-06	8.23E-01	-1.71E+02	1.000
4.5	-3.75E-06	8.39E-01	-1.99E+02	1.000

Longitudinal framing

T (m)	c1	c2	c3	R^2
1.5	-4.00E-05	7.03E-01	-1.00E+02	0.996
2	-2.20E-05	7.48E-01	-1.01E+02	0.999
2.5	-1.48E-05	7.97E-01	-1.26E+02	1.000
3	-7.89E-06	8.07E-01	-1.28E+02	1.000
3.5	-4.27E-06	8.17E-01	-1.39E+02	1.000
4	-2.00E-06	8.13E-01	-1.37E+02	1.000
4.5	-7.36E-07	8.20E-01	-1.47E+02	1.000

Building cost

For the building cost of container vessels, similar trend lines can again be drawn as for lightweight and cargo carrying capacity. Like with lightweight and cargo carrying capacity, there is a residual term due to the cost of items like the wheelhouse, winches, masts, outfitting etc. that are not directly related to L, B or T. As a result, the rule of thumb for building cost has the following form:

$$C_{ship} = c_1 \cdot (LBT)^2 + c_2 \cdot LBT + c_3 \qquad \text{Eq. D-8}$$

In the tables below, the coefficients are given for both transversely and longitudinally framed vessels together with R^2 values of the regression.

Table D-8: Building cost - coefficients for container vessels

Transverse framing

T (m)	c1	c2	c3	R^2
1.5	6.55E-01	1.29E+03	4.82E+05	0.986
2	2.36E-02	1.02E+03	4.67E+05	0.988
2.5	2.13E-02	7.65E+02	5.69E+05	0.991
3	1.47E-02	6.51E+02	6.12E+05	0.991
3.5	2.61E-03	6.35E+02	5.84E+05	0.991
4	4.80E-03	5.60E+02	6.57E+05	0.992
4.5	7.48E-03	4.92E+02	7.52E+05	0.992

Longitudinal framing

T (m)	c1	c2	c3	R^2
1.5	8.20E-02	1.18E+03	5.06E+05	0.987
2	4.49E-02	9.06E+02	5.08E+05	0.991
2.5	3.55E-02	6.69E+02	6.08E+05	0.992
3	2.30E-02	5.89E+02	6.23E+05	0.993
3.5	7.30E-03	5.92E+02	5.78E+05	0.992
4	3.72E-04	5.87E+02	5.49E+05	0.993
4.5	-1.06E-03	5.47E+02	5.96E+05	0.993

D.3 Tank vessels

For tank vessels, the same analysis can be made as for dry bulk and container vessels, except for the fact that designs have only been made for longitudinally framed vessels. The analyses lead to the following results:

Steel weight

Like for dry bulk vessels, the regression line for the steel weight of container vessels is assumed to be a second order polynomial with a zero-crossing at (0,0) since all of the scantlings have a direct relationship with the vessel's main dimensions.

This again results in a formula of the form:

$$W_{steel} = c_1 \cdot (LBT)^2 + c_2 \cdot LBT \qquad \text{Eq. D-9}$$

With the following coefficients and R^2 values:

Table D-9: Steel weight - coefficients for tank vessels

T (m)	c1	c2	R^2
1.5	6.70E-06	2.69E-01	0.993
2	-1.56E-07	2.33E-01	0.992
2.5	-1.24E-06	2.08E-01	0.990
3	-1.96E-06	1.97E-01	0.993
3.5	-1.61E-06	1.85E-01	0.991
4	-2.26E-06	1.82E-01	0.991
4.5	-1.99E-06	1.74E-01	0.990

Lightweight

For the lightweight of tank vessels, similar trend lines can be drawn as for steel weight. The main difference between the trend lines for lightweight and steel weight are that for steel weight there is a residual term due to weight items like the wheelhouse, winches, masts, outfitting etc. that are not directly related to L, B or T. As a result, the regression formula for lightweight is:

$$W_{light} = c_1 \cdot (LBT)^2 + c_2 \cdot LBT + c_3 \qquad \text{Eq. D-10}$$

In the tables below, the coefficients and R^2 values are given:

Table D-10: Lightweight - coefficients for tank vessels

T (m)	c1	c2	c3	R^2
1.5	8.13E-06	2.90E-01	7.55E+01	0.995
2	7.57E-07	2.49E-01	7.72E+01	0.994
2.5	1.40E-06	2.06E-01	1.00E+02	0.994
3	-2.17E-07	1.96E-01	1.01E+02	0.995
3.5	1.00E-07	1.80E-01	1.17E+02	0.995
4	-5.47E-07	1.73E-01	1.30E+02	0.996
4.5	-2.96E-07	1.62E-01	1.43E+02	0.995

Cargo carrying capacity

Like for the other ship types, rules of thumb are also provided for the cargo carrying capacity of tank vessels. The formula used is again identical to that of lightweight, but with the coefficients as shown in table D-11.

$$W_{cargo} = c_1 \cdot (LBT)^2 + c_2 \cdot LBT + c_3 \qquad \text{Eq. D-11}$$

Table D-11: Cargo carrying capacity - coefficients for tank vessels

T (m)	c1	c2	c3	R^2
1.5	-1.55E-05	6.46E-01	-1.04E+02	0.999
2	-5.58E-06	6.92E-01	-1.14E+02	1.000
2.5	-4.44E-06	7.40E-01	-1.50E+02	1.000
3	3.14E-07	7.43E-01	-1.55E+02	1.000
3.5	1.16E-06	7.57E-01	-1.79E+02	1.000
4	8.25E-07	7.69E-01	-2.09E+02	1.000
4.5	1.81E-06	7.70E-01	-2.12E+02	1.000

Building cost

For the building cost of container vessels, similar trend lines can again be drawn. Like with lightweight, there is a residual term due to the cost of items like the wheelhouse, winches, masts, outfitting etc. that are not directly related to L, B or T. As a result, the regression formula for building cost is:

$$C_{ship} = c_1 \cdot (LBT)^2 + c_2 \cdot LBT + c_3 \qquad \text{Eq. D-12}$$

In the table below, the coefficients and R^2 values are given.

Table D-12: Building cost - coefficients for tank vessels

T (m)	c1	c2	c3	R^2
1.5	-4.89E-03	1.41E+03	5.30E+05	0.996
2	-8.90E-03	1.12E+03	5.85E+05	0.996
2.5	3.60E-03	8.70E+02	7.52E+05	0.994
3	-4.05E-03	8.29E+02	7.77E+05	0.995
3.5	-8.20E-03	8.01E+02	8.12E+05	0.996
4	-8.96E-03	7.59E+02	8.91E+05	0.995
4.5	-7.51E-03	7.12E+02	9.54E+05	0.995

E : Advanced rules of thumb for building cost, lightweight and steel weight

In appendix D, simple rules of thumb in the form of second-order polynomials have been presented. Each of these polynomials is valid for a given draught under the boundary condition that the L/B ratio of the vessel is between 6 and 12 and vessel length does not exceed 135 m. This means that these rules of thumb are not validated for vessels with larger or smaller L/B ratios and larger lengths. As a result, these rules of thumb are suitable for the logistical studies, conceptual design and early cost estimate of inland vessels with conventional main dimensions, but are not valid for the design of more ‘exotic’ vessels. This is where the advanced rules of thumb have an added value.

In this appendix, more elaborate rules of thumb are presented that provide lightweight, deadweight and building cost estimates based on all designs in the design datasets of chapter 5. The rules of thumb have a higher level of detail than the ones in the previous paragraphs: Lighweight is broken down into steel weight, weight of the accommodation, weight of machinery, equipment & outfitting and weight of piping outside the engine room. Building cost is subdivided in yard cost and non-yard cost. Here, yard cost is defined as the material cost of the hull, man-hour cost of the hull and general object cost, while non-yard cost is defined as the cost of all machinery, equipment & outfitting and the cost of the accommodation.

In the following paragraphs, the rules of thumb as discussed above are elaborated for dry bulk, container and tank vessels and the steel weight and yard cost are given for both longitudinally framed vessels of each vessel type.

E.1 Dry bulk vessels

In this paragraph, the steel weight, lightweight and building cost of dry bulk ships are discussed consecutively.

Steel weight

For the estimation of steel weight of both transversely and longitudinally framed dry bulk vessels, the following formula has been developed:

$$W_{steel} = c_1 + c_2 \cdot LB + c_3 \cdot L^2T + c_4 \cdot LBT + c_5 \cdot L^{3.5}B + c_6 \cdot \frac{L^{1.3}T^{0.7}}{B} + c_7 \cdot \frac{1}{B^2T^{1.5}} \qquad \text{Eq. E-1}$$

The variables in this formula were used on the following grounds:

LB: LB is the variable that has a large role in the estimation of the weight of the double bottom since it affects the number and length of all plates and stiffeners.

LBT: In a similar way as LB, LBT will impact the size of all main structural elements.

L^2T: Since the still water bending moment of a ship increases with increasing length, the plate thickness and stiffener dimensions of longitudinal structural elements will increase at a rate of L^n. Since the draught of the ship directly affects the amount of cargo that can be loaded, and thereby affects the bending moment, L^nT is considered a suitable variable. Through systematic variation of power n, it was determined that L^2T is a parameter that leads to good results.

$L^{3.5}B$ Since the bending moment increases with increasing length, plate thickness and stiffener dimensions of longitudinal structural elements will increase at a rate of L^n. Since both the amount of cargo the ship can carry and the amount of material that is available in the double bottom to deal with the bending moment are directly related to the beam of the ship, L^nB is deemed a suitable variable and through systematic variation of power n, it was determined that $L^{3.5}B$ is a parameter that leads to good results.

$L^{1.3}T^{0.7}/B$ An assessment of the results of the regression using the first four variables resulted in a systematic error where the weight of the narrow vessels was underestimated and there was an overestimation of the weight of short deep draught vessels. Through systematic variation of the powers of L and T, $L^{1.3}T^{0.7}/B$ was found to lead to good results. From the small standardized coefficient Beta for this variable in tables E-2 and E-4, it becomes clear that this parameter is used to 'tune' secondary effects in the structure.

$1/B^2T^{1.5}$ Assessment of the results of the regression using the first five variables still resulted in a minor systematic error in case of the narrow, low draught vessels, especially for the longitudinally framed ones. As a result a variable was sought that would especially impact these vessels. Through systematic variation of the powers of B and T, $1/B^2T^{1.5}$ was found to lead to good results.

Transverse framing

When applying the parameters discussed above to the dataset of transversely framed dry bulk vessels that was generated in chapter 5, it is found that there is a very large part of the variance of the data is explained, as is shown by the R square and adjusted R square values in table E-1.

Table E-1: Steel weight - R^2 for transversely framed dry bulk vessels

R	R^2	Adjusted R^2	Std. Error of the Estimate
0.996	0.992	0.992	56.764

The coefficients to be used with each of the variables from equation E-1 are presented in table E-2 below. When assessing the significance of the variables, it can be seen that all variables are significant, with the possible exception of the last variable, which was already identified as a correction for especially longitudinally framed vessels. From the beta-value, it can be seen that its effect is very small. As a result it is not removed from the formula in order to keep the variables in the rule of thumb identical for both framing systems and for both dry bulk and container vessels.

Table E-2: Steel weight - coefficients for transversely framed dry bulk vessels

	Unstandardized Coefficients		Standardized Coefficients		
	value	Std. Error	Beta	t	Sig.
c1	-2.597E+01	11.305		-2.297	0.022
c2	2.320E-01	9.047E-03	0.339	25.600	0.000
c3	-1.552E-03	3.583E-04	-0.079	-4.332	0.000
c4	4.444E-02	2.659E-03	0.226	16.715	0.000
c5	8.134E-07	1.856E-08	0.533	43.823	0.000
c6	1.024E+00	0.132	0.072	7.784	0.000
c7	7.691E+02	399.793	0.009	1.924	0.055

That the regression provides a good match with the original data is apparent from figure E-1 below, in which the error distribution is shown: about 60% of all original data points deviate less than 5% from the value predicted by the rule of thumb, while only about 10% of the data points deviate more than 10% from the value resulting from the rule of thumb.

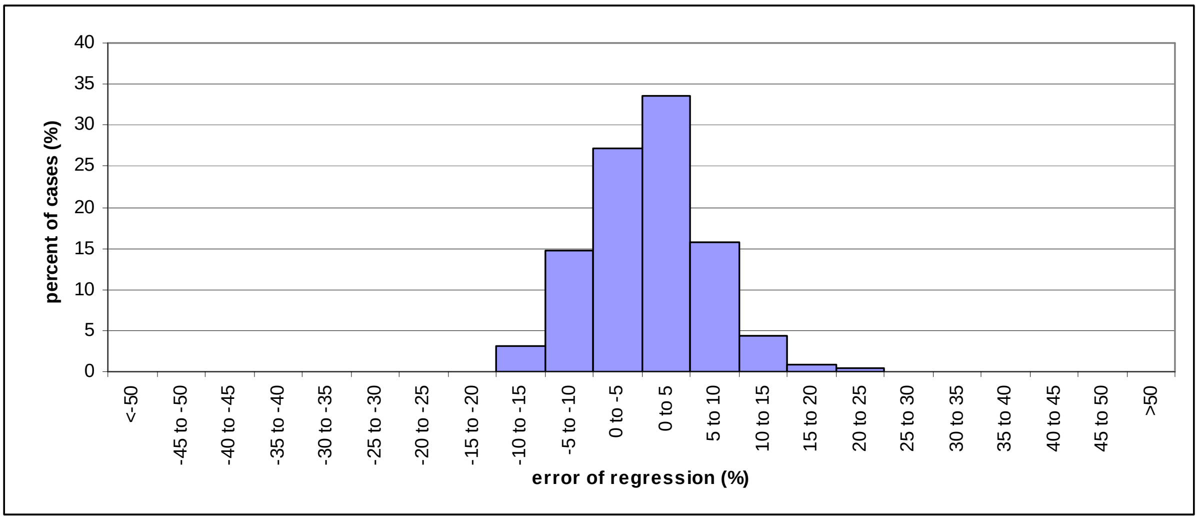

Figure E-1: Steel weight – error distribution for transversely framed dry bulk vessels

Longitudinal framing

When equation E-1, which was used for the regression of the transversely framed vessels, is used for longitudinally framed dry bulk vessels as well, good results are achieved again: R^2 values are even higher and the standard error of the estimate is even smaller, as is clear from table E-3 below.

Table E-3: Steel weight - R^2 for longitudinally framed dry bulk vessels

R	R^2	Adjusted R^2	Std. Error of the Estimate
0.998	0.996	0.996	40.048

The coefficients to be used for longitudinally framed dry bulk vessels are shown in table E-4 below. It can be seen that all variables with the exception of the variable belonging to c3 (= variable L^2T) are significant. However, it can also be seen from the beta-value that its contribution to the final result is negligible. As a result, in order to still be able to provide a single rule of thumb for the steel weight of all dry bulk and container vessels, the variable is not taken out of the equation.

Table E-4: Steel weight – coefficients for longitudinally framed dry bulk vessels

	Unstandardized Coefficients		Standardized Coefficients		
	Value	Std. Error	Beta	t	Sig.
c1	4.985E+01	7.976		6.250	0.000
c2	2.290E-01	6.383E-03	0.324	35.899	0.000
c3	-1.234E-05	2.528E-04	-0.001	-0.049	0.961
c4	1.910E-02	1.876E-03	0.094	10.181	0.000
c5	9.584E-07	1.310E-08	0.608	73.185	0.000
c6	2.880E-01	0.093	0.020	3.099	0.002
c7	-1.066E+03	282.060	-0.013	-3.781	0.000

From the error distribution shown in figure E-2, it is again clear that the rule of thumb provides a good approximation for the steel weight of longitudinally framed dry bulk ships: over 60% of the data points deviate less than ±5% from the value predicted by the rule of thumb, while less than 10% of the data points deviate more than ±10% from the value resulting from the rule of thumb.

Figure E-2: Steel weight – error distribution for longitudinally framed dry bulk vessels

Other lightweight items

In the previous paragraph, rules of thumb were provided for the steel weight of dry bulk vessels. However, in order to be able to make an estimate of the amount of cargo that a ship can carry, it is necessary to estimate its entire lightweight. Since the elements besides steel weight that make up the lightweight of the ship are strongly dependent on designers' choices regarding the size of the accommodation and the choice of the drive train, rules of thumb are provided for three separate parts of the lightweight: weight of the accommodation, weight of piping outside of the machinery spaces and weight of the machinery, equipment & outfitting.

For the accommodation, no regression is performed, since both the weight per m^3 (i.e. 0.173 T/m3) and the rules according to which accommodations are sized in the datasets of ship designs are known. As a result the formula that was used in the design of the ships is iterated below:

$$W_{acc} = 0.173 \cdot 2.5 \cdot \max[L/4 \cdot (B-2), 100] \qquad \text{Eq. E-2}$$

Piping, excluding piping in machinery spaces, which is part of outfit weight, is a minor weight item for dry bulk ships, which is made up entirely of the ballast system in the design model. It is directly related to beam and depth of the ship, but is not directly related to ship length, since it extends from the engine room bulkhead (water intake) to the aft end of the forwardmost ballast tank in the midship.

Since tanks in the design model are approximately 20 meters long, the limited amount of piping in short ships will distort the overall image considerably and as a result they are left out of the analysis. Regression analysis performed on vessels of 60 m and more in length results in the following formula:

$$W_{piping} = c_1 + c_2 \cdot L + c_3 \cdot B + c_4 \cdot T + c_5 \cdot LBT \qquad \text{Eq. E-3}$$

The R^2 value in table E-5 below shows that this formula explains a very large part of the variance in the actual data. The coefficients for each variable are shown in table E-6.

Table E-5: Piping weight - R^2 for dry bulk vessels

R	R^2	Adjusted R^2	Std. Error of the Estimate
0.998	0.995	0.995	0.20813

Table E-6: Piping weight- coefficients for dry bulk vessels

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
c1	-2.723E+00	9.064E-02		-30.036	0.000
c2	6.232E-02	4.493E-04	0.843	138.706	0.000
c3	5.048E-02	3.731E-03	0.089	13.529	0.000
c4	9.968E-02	1.663E-02	0.034	5.994	0.000
c5	1.343E-04	9.085E-06	0.153	14.786	0.000

That the rule of thumb provides a good estimate of the weight of piping is further underlined by the error distribution shown in figure E-3, which shows that about 75% of all original data points deviate less than ±5% and that there are no deviations larger than ±20%.

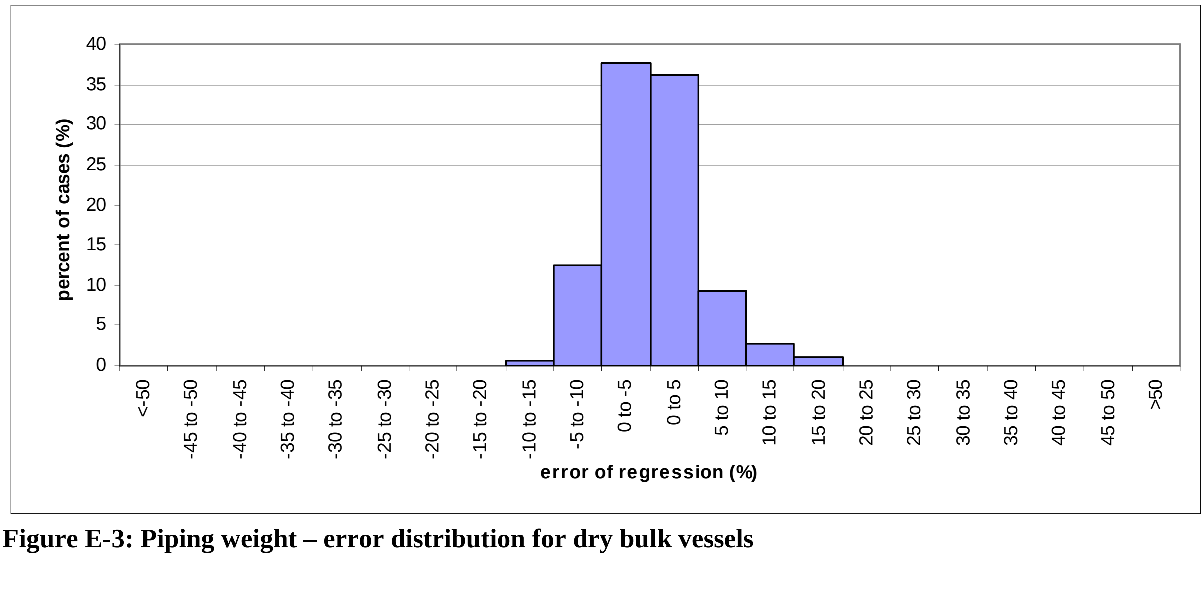

Figure E-3: Piping weight – error distribution for dry bulk vessels

The final part of lightweight, the weight of machinery, equipment and outfitting is also assessed using a regression analysis. This leads to a formula of the form:

$$W_{m,e,o} = c_1 + c_2 \cdot T + c_3 \cdot LB + c_4 \cdot LBT + c_5 \cdot \frac{1}{L^3} \quad \text{Eq. E-5}$$

From table E-7, it can be observed that the R^2 value is somewhat lower than for the previous regressions. This is due to the fact that there is more scatter in the data on which the regression is based as a result of different sailing speeds and different drive train configurations, as was discussed in detail in chapter 5.2.

Table E-7: Machinery, equipment & outfitting - R^2 for dry bulk vessels

R	R^2	Adjusted R^2	Std. Error of the Estimate
0.982	0.965	0.965	5.437

The coefficients resulting from the regression analysis are shown in table E-8 below.

Table E-8: Machinery, equipment & outfitting – coefficients for bulk vessels

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
c1	2.804E+01	1.39E+00		20.197	0.000
c2	4.605E+00	4.15E-01	0.159	11.109	0.000
c3	2.097E-02	8.34E-04	0.688	25.133	0.000
c4	2.240E-03	2.56E-04	0.256	8.735	0.000
c5	-4.258E+05	7.66E+04	-0.056	-5.559	0.000

The error distribution in figure E-4 shows that about for 64% of all designs, the rule of thumb has an error of less than ±5%, while in a limited number of cases, errors larger than ±15%

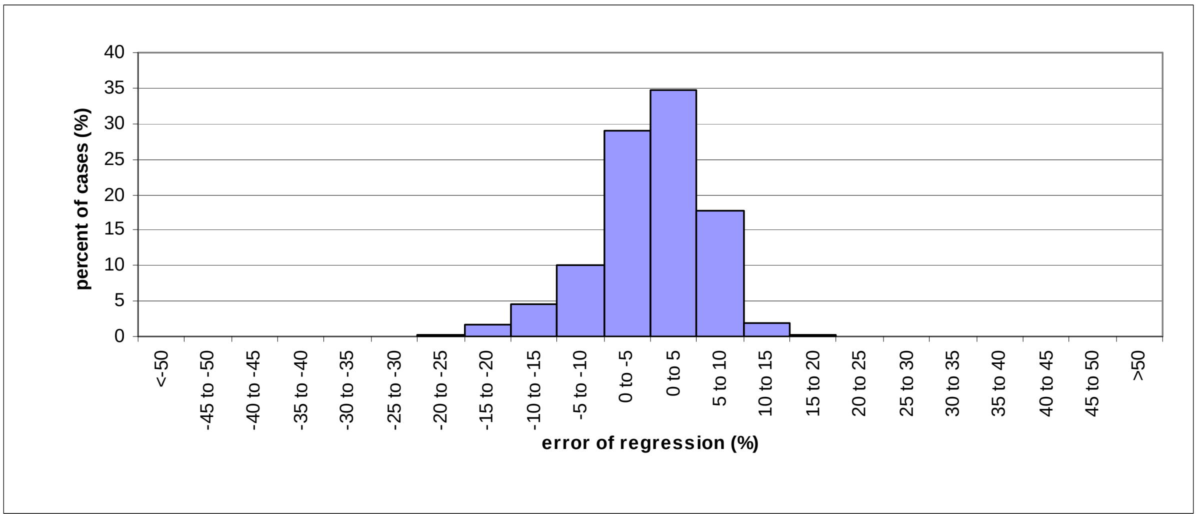

Figure E-4: Machinery, equipment & outfitting – error distribution for dry bulk vessels

Building cost

After presenting rules of thumb for the weight of inland dry bulk vessels in the previous paragraphs, in this paragraph rules of thumb for the building cost of these vessels are provided. For these rules of thumb, costs are broken down into two parts: Yard cost and non-yard cost. Yard cost comprise of general object cost and cost of building the hull, while non-yard cost covers the purchase and installation of all the accommodation and all equipment, machinery and outfitting. For a more detailed overview of the underlying assumptions on cost, the reader is referred to appendix C.

Yard cost

For yard cost (without a share of the margin), the regression function naturally resembles that of steel weight, albeit with some minor differences. Good results are achieved with the formula:

$$Cost_{yard} = c_1 + c_2 \cdot LB + c_3 \cdot (L^2T)^{0.7} + c_4 \cdot LBT + c_5 \cdot L^{3.5}B + c_6 \cdot \frac{L^{1.3}T^{0.7}}{B} \qquad \text{Eq. E-6}$$

For transversely framed vessels, the coefficients as shown in table E-9 provide good results. It can be seen from table E-9 that all variables are significant and that LB and $L^{3.5}B$ are the most influential parameters.

Table E-9: Yard cost - coefficients for transversely framed dry bulk vessels

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
c1	5.956E+04	2.630E+04		2.265	0.024
c2	7.717E+02	2.702E+01	0.448	28.555	0.000
c3	-1.367E+02	4.718E+01	-0.078	-2.897	0.004
c4	6.241E+01	7.859E+00	0.126	7.940	0.000
c5	1.926E-03	4.746E-05	0.502	40.582	0.000
c6	3.244E+03	5.234E+02	0.091	6.198	0.000

That the regression explains nearly all of the variance in the original data can again be observed from table E-10.

Table E-10: Yard cost - R^2 for transversely framed dry bulk vessels

R	R^2	Adjusted R^2	Std. Error of the Estimate
0.995	0.989	0.989	1.716E+05

The error distribution in figure E-5 shows that about the rule of thumb has an error of less than ±5% for over 60% of all designs, while the error is larger than ±10% for only 10% of the designs, with a maximum error that is below ±25%.

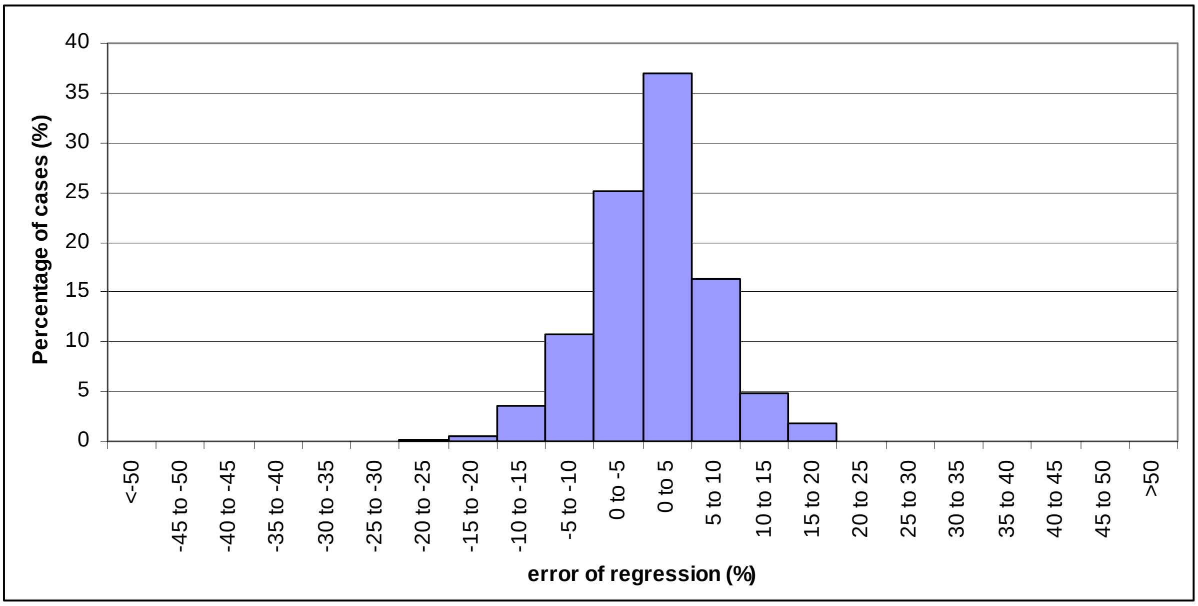

Figure E-5: Yard cost – error distribution for transversely framed dry bulk vessels

For longitudinally framed vessels, the coefficients as shown in table E-11 should be used. In this case the variables belonging to coefficients c4 and c6 do not meet the significance criterion of 0.05 and can, therefore, be left out of the equation. However, like with the regression for steel weight, it was decided use a standardized rule of thumb for the yard cost estimate for all dry bulk and container vessels, so they are left in the equation. Considering their small beta values of -0.02 and -0.011, the effect of doing so is minor.

Table E-11: Yard cost – coefficients for longitudinally framed dry bulk vessels

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
c1	1.632E+05	1.996E+04		8.174	0.000
c2	7.826E+02	2.052E+01	0.406	38.147	0.000
c3	1.858E+02	3.582E+01	0.094	5.188	0.000
c4	-1.106E+01	5.967E+00	-0.020	-1.854	0.064
c5	2.413E-03	3.603E-05	0.561	66.979	0.000
c6	-4.385E+02	3.974E+02	-0.011	-1.103	0.270

That a nearly all variance in the original data is explained by the regression becomes clear from the data in table E-12 below.

Table E-12: Yard cost - R^2 for longitudinally framed dry bulk vessels

R	R^2	Adjusted R^2	Std. Error of the Estimate
0.997	0.995	0.995	1.303E+05

The error distribution in figure E-6 reveals that the difference between the original data and the values resulting from the regression are less than ±10% for about 85% of the cases and that the error is never more than ±20%.

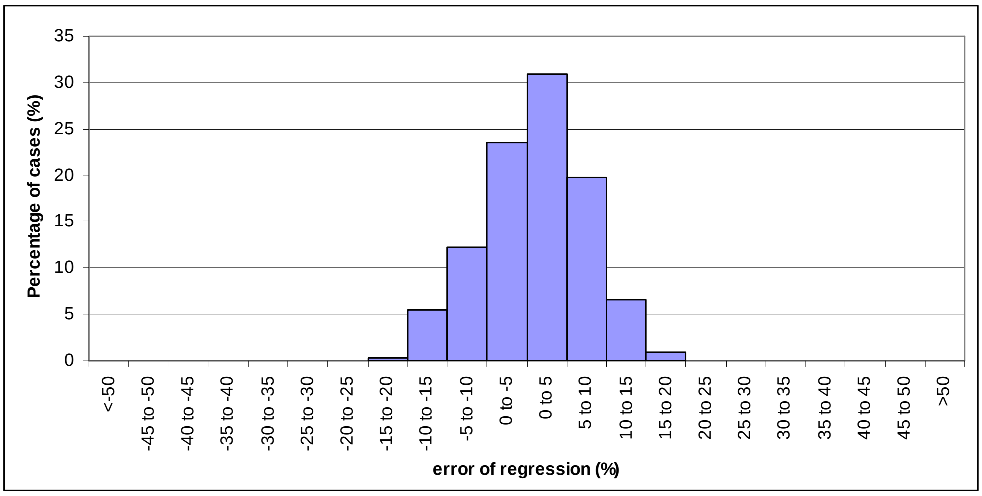

Figure E-6: Yard cost – error distribution for longitudinally framed dry bulk vessels

Non-yard cost

The cost of non-yard items (accommodation, piping, machinery, equipment and outfitting) is identical for longitudinally and transversely framed ships. They are also turned into a rule of thumb by means of a regression analysis, which leads to good results when using a formula of the form:

$$Cost_{misc} = c_1 + c_2 \cdot \frac{L^{1.5}}{B} + c_3 \cdot LBT + c_4 \cdot LB + c_5 \cdot \frac{1}{LT} \qquad \text{Eq. E-7}$$

Here, LBT and LB are the main parameters, while the other two variables are used to tune the rule of thumb. The coefficients in table E-13 show that all variables are significant and that LBT and LB have the biggest impact.

Table E-13: Non-yard cost – coefficients for dry bulk vessels

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
c1	6.075E+05	2.230E+04		27.241	0.000
c2	4.008E+02	9.922E+01	0.034	4.039	0.000
c3	4.905E+01	3.263E+00	0.250	15.036	0.000
c4	4.742E+02	1.014E+01	0.696	46.757	0.000
c5	-2.081E+07	2.488E+06	-0.089	-8.364	0.000

That the rule of thumb explains nearly all of the variance in the original data becomes apparent from the high R^2 value in table E-14.

Table E-14: Non-yard cost - R^2 for dry bulk vessels

R	R^2	Adjusted R^2	Std. Error of the Estimate
0.987	0.974	0.974	1.04E+05

The error distribution in figure E-7 below shows that the error is less than ±10% in about 90% of all cases.

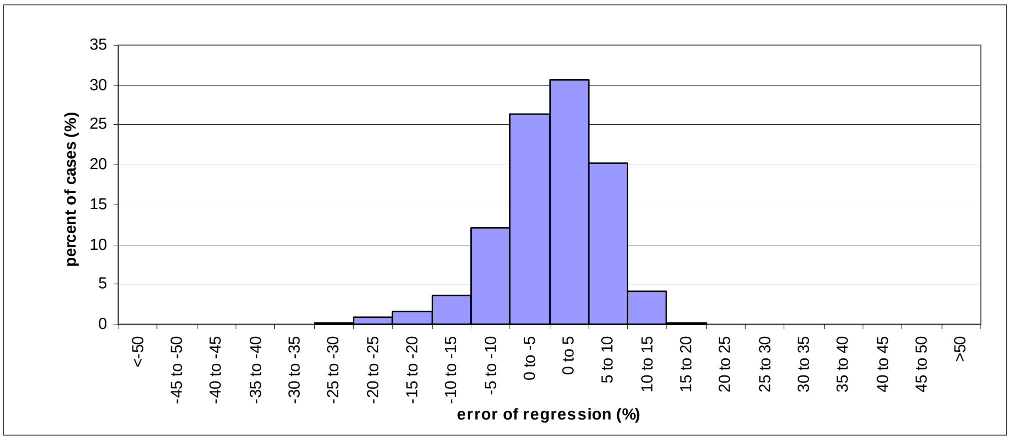

Figure E-7: Non-yard cost – error distribution for dry bulk vessels

E.2 Container ships

For container ships, the same rules of thumb are derived as for dry bulk vessels. Since the weight and cost of all elements of the ship besides the steel hull are identical for dry bulk and container vessels, only steel weight and yard cost are discussed again.

Steel weight

Since the only fundamental difference between the steel structure of container ships and dry cargo ships is the depth, weights are very similar. In order to prove rules of thumb for container ships, the same formula as used for dry bulk vessels is iterated:

$$W_{steel} = c_1 + c_2 \cdot LB + c_3 \cdot L^2T + c_4 \cdot LBT + c_5 \cdot L^{3.5}B + c_6 \cdot \frac{L^{1.3}T^{0.7}}{B} + c_7 \cdot \frac{1}{B^2T^{1.5}} \qquad \text{Eq. E-8}$$

For transversely framed vessels, coefficients to be used are as shown in table E-15. From the table it becomes clear that c1 and c7 do not meet the significance criterion and as such they can be left out of the rule of thumb. However, as was discussed before, in order to be able to use the same rule of thumb for all container ships and dry bulk ships and the effect of the variables is small, they are left in.

Table E-15: Steel weight - coefficients for transversely framed container vessels

	Unstandardized Coefficients		Standardized Coefficients		
	Value	Std. Error	Beta	t	Sig.
c1	-2.200E+01	12.848		-1.713	0.087
c2	2.540E-01	1.028E-02	0.317	24.658	0.000
c3	-1.975E-03	4.072E-04	-0.086	-4.851	0.000
c4	4.473E-02	3.021E-03	0.194	14.803	0.000
c5	1.059E-06	2.110E-08	0.593	50.218	0.000
c6	9.600E-01	0.149	0.058	6.430	0.000
c7	6.676E+02	454.349	0.007	1.469	0.142

That nearly all of the variance in the original is explained by the formula becomes clear from table E-16.

Table E-16: Steel weight - R^2 for transversely framed container vessels

R	R^2	Adjusted R^2	Std. Error of the Estimate
0.996	0.993	.993	64.510

The good match between the original data and the results of the regression analysis is also underlined by the error distribution shown in figure E-8, which reveals that the difference between the original data and the value from the rule of thumb is less than ±10% in more than 90% of all cases.

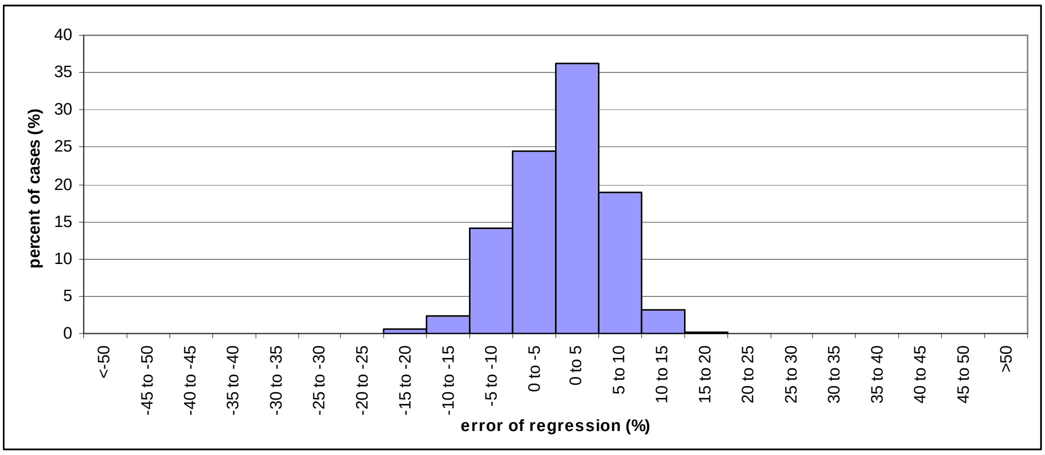

Figure E-8: Steel weight – error distribution for transversely framed container vessels

For longitudinally framed container vessels, coefficients as shown in table E-17 should be used. The variable belonging to coefficient c5 (=$L^{3.5}B$) does not meet the significance criterion, but is again not removed from the equation in order to allow use of a single rule of thumb for all container and dry bulk vessels.

Table E-17: Steel weight - coefficients for longitudinally framed container vessels

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	Value	Std. Error	Beta		
c1	5.107E+01	8.562		5.965	0.000
c2	2.440E-01	6.852E-03	0.317	35.603	0.000
c3	-1.772E-04	2.714E-04	-0.008	-0.653	0.514
c4	1.588E-02	2.014E-03	0.072	7.888	0.000
c5	1.100E-06	1.406E-08	0.641	78.245	0.000
c6	3.120E-01	0.100	0.020	3.131	0.002
c7	-1.164E+03	302.799	-0.013	-3.844	0.000

Table E-18 again confirms that almost all of the variance is explained.

Table E-18: Steel weight - R^2 for longitudinally framed container vessels

R	R^2	Adjusted R^2	Std. Error of the Estimate
0.998	0.997	0.997	42.992

From the error distribution in figure E-9, it can be observed that the error is less than ±10% in over 85% of all cases, but also that there are a few cases where the error is higher than 30%. This error occurs for the smallest ships.

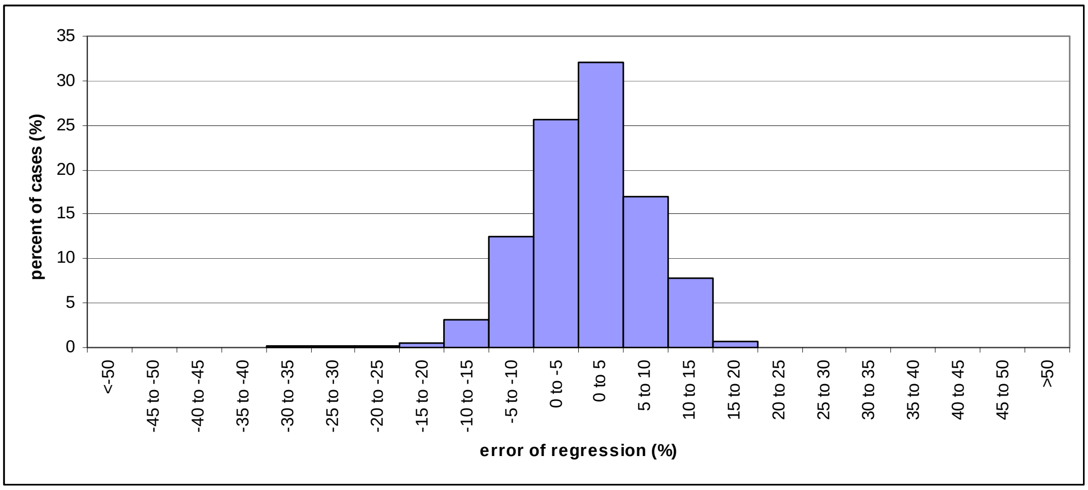

Figure E-9: Steel weight – error distribution for longitudinally framed container vessels

Building cost

The only difference in the cost between container ships and dry bulk vessels is the price of the steel hull, so only the yard cost are discussed here again. Non-yard costs are identical to those of dry bulk vessels. Like with steel weight, the yard cost for container ships are very similar to those of dry bulk vessels, so the same regression formula is used:

$$C_{yard} = c_1 + c_2 \cdot LB + c_3 \cdot (L^2T)^{0.7} + c_4 \cdot LBT + c_5 \cdot L^{3.5}B + c_6 \cdot \frac{L^{1.3}T^{0.7}}{B} \qquad \text{Eq. E-9}$$

For transversely framed ships, the coefficients as shown in table E-19 provide good results. One variable fails to meet the significance criterion, but is kept in the equation in order to allow use of the same rule of thumb for all container ships and dry bulk ships. The small beta-value for this variable shows that its negative impact is small.

Table E-19: Yard cost - Coefficients for transversely framed container vessels

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
c1	6.880E+04	3.043E+04		2.261	0.024
c2	9.208E+02	3.127E+01	0.422	29.442	0.000
c3	-9.132E+01	5.460E+01	-0.041	-1.672	0.095
c4	5.022E+01	9.095E+00	0.080	5.521	0.000
c5	2.668E-03	5.493E-05	0.549	48.575	0.000
c6	2.651E+03	6.057E+02	0.059	4.377	0.000

The reliability of the rule of thumb is again shown through the high R^2 value in table E-20.

Table E-20: Yard cost - R^2 for transversely framed container vessels

R	R^2	Adjusted R^2	Std. Error of the Estimate
0.995	0.991	0.991	1.986E+05

The error distribution in figure E-10 shows that in 90% of all cases, the difference between the original data and the value predicted by the rule of thumb is less than 10%.

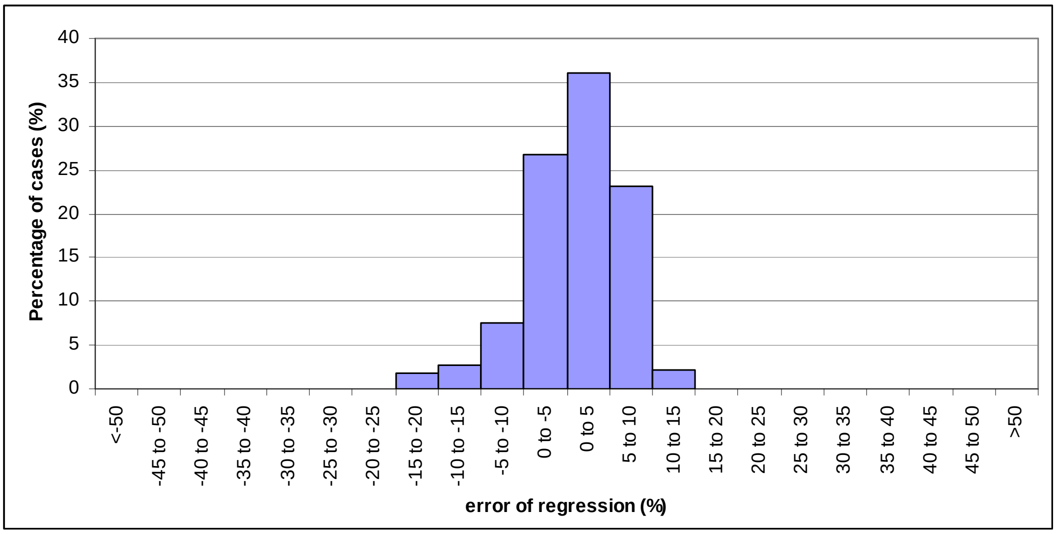

Figure E-10: Yard cost – error distribution for transversely framed container vessels

The regression for longitudinally framed ships, with the same variables as were used for transversely framed ships leads to the coefficients as shown in table E-21. Only the last variable fails to meet the significance criterion, but is kept in the equation in order to allow use of the same rule of thumb for all container ships and dry bulk ships. The small beta-value for this variable shows that its negative impact is small.

Table E-21: Yard cost - coefficients for longitudinally framed container vessels

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
c1	1.646E+05	2.157E+04		7.632	0.000
c2	8.422E+02	2.216E+01	0.401	38.000	0.000
c3	1.931E+02	3.869E+01	0.090	4.992	0.000
c4	-2.714E+01	6.445E+00	-0.045	-4.210	0.000
c5	2.774E-03	3.892E-05	0.592	71.272	0.000
c6	-5.093E+02	4.293E+02	-0.012	-1.186	0.236

The high predictive ability of the regression is again shown through he R^2 values in table E-22.

Table E-22: Yard cost - R^2 for transversely framed dry bulk vessels

R	R^2	Adjusted R^2	Std. Error of the Estimate
0.998	0.995	0.995	1.407E+05

The error distribution in figure E-11 shows that the error is less than ± 10% in about 85 percent of all cases, while it never exceeds ± 25%.

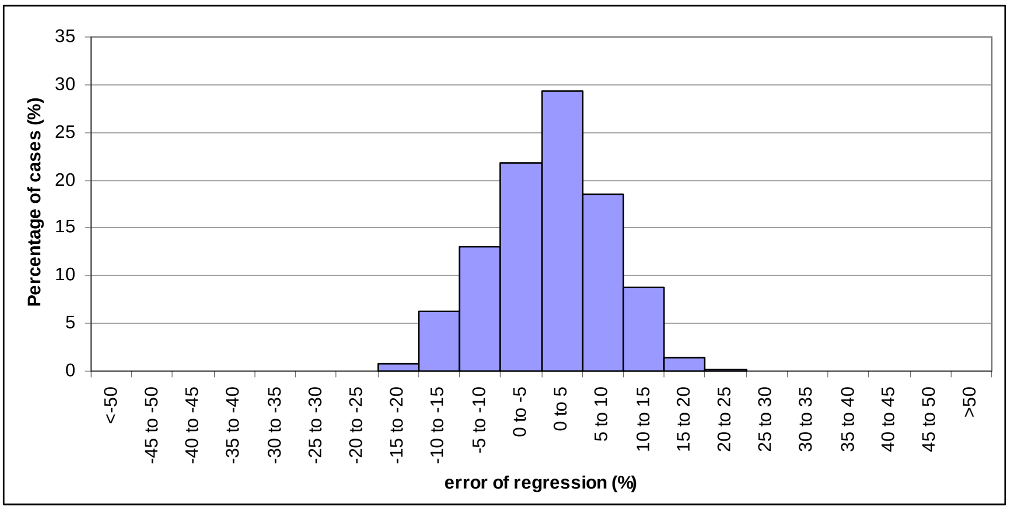

Figure E-11: Yard cost – error distribution for longitudinally framed container vessels

E.3 Tank ships

Like for dry bulk and container vessels, rules of thumb are provided for the steel weight, lightweight and building cost of tank ships. However, in contrast with the other ship types, no dataset for transversely framed tank vessels was created and as a result, rules of thumb are only created for longitudinally framed vessels.

Steel weight

Since the steel structure of tank vessels is very different from that of dry bulk and container vessels due to the presence of the main deck and corrugated bulkheads that separate the cargo area in individual tanks, a different (but similar set of variables is identified for the regression analysis. It is found that the variables in equation E-10 lead to good results.

$$W_{steel} = c_1 + c_2 \cdot L^2T + c_3 \cdot LBT + c_4 \cdot L^{3.5}B + c_5 \cdot \frac{1}{(LBT)^{0.5}} \qquad \text{Eq. E-10}$$

Table E-23, which shows the values of the coefficients, also reveals that all variables are significant and that LBT and $L^{3.5}B$ are the most influential variables. The R^2 values in table E-24 again show that the rule of thumb is a good predictor for the steel weights of the designs.

Table E-23: Steel weight – coefficients for tank vessels

	Unstandardized Coefficients		Standardized Coefficients		
	Value	Std. Error	Beta	t	Sig.
c1	4.220E+02	1.600E+01		26.372	0.000
c2	-7.694E-04	1.783E-04	-0.035	-4.314	0.000
c3	7.311E-02	1.939E-03	0.333	37.704	0.000
c4	1.157E-06	1.197E-08	0.679	96.688	0.000
c5	-7.922E+03	5.270E+02	-0.095	-15.030	0.000

Table E-24: Steel weight - R^2 for tank vessels

R	R^2	Adjusted R^2	Std. Error of the Estimate
0.996	0.992	0.992	64.133

The error distribution in figure E-12 shows that the error is less than ± 10% in about 80% of all cases. However, there are a limited number of cases where the prediction deviates more than 25% from the original values. These cases represent the 5 m wide vessels with a draught of 1.5 m and/or a length of 40 meters. In these cases the depth needs to be increased substantially in order to accommodate the required tank volume (see chapter 5.5.1), thus throwing off predictors that only incorporate L, B and T.

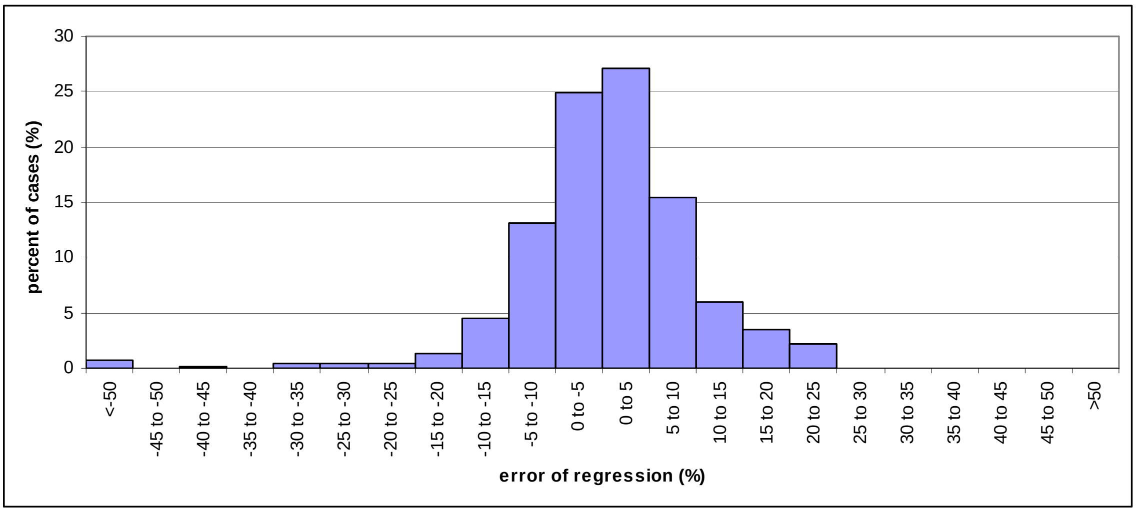

Figure E-12: Steel weight – error distribution for tank vessels

Other lightweight items

Apart from the steel weight, the only difference between the lightweight of tank ships and dry cargo ships lies in the weight of the cargo handling system, i.e. the piping and associated pumps.

For the piping weight of piping, there is a strong stepwise dependency between weight and vessel beam: if the number of tanks abreast is increased because of an increase in ship width, an entire longitudinal set of pipes will be added on the deck. This phenomenon also becomes apparent in the errors of the weight estimate in figure E-13. It shows a broad band of errors between -20 and +20 percent without a clear peak at ±5% that was present in all previous error distributions. Furthermore, the R^2 value in table E-25 reveals that a smaller part of the variance in the data is explained by the formula.

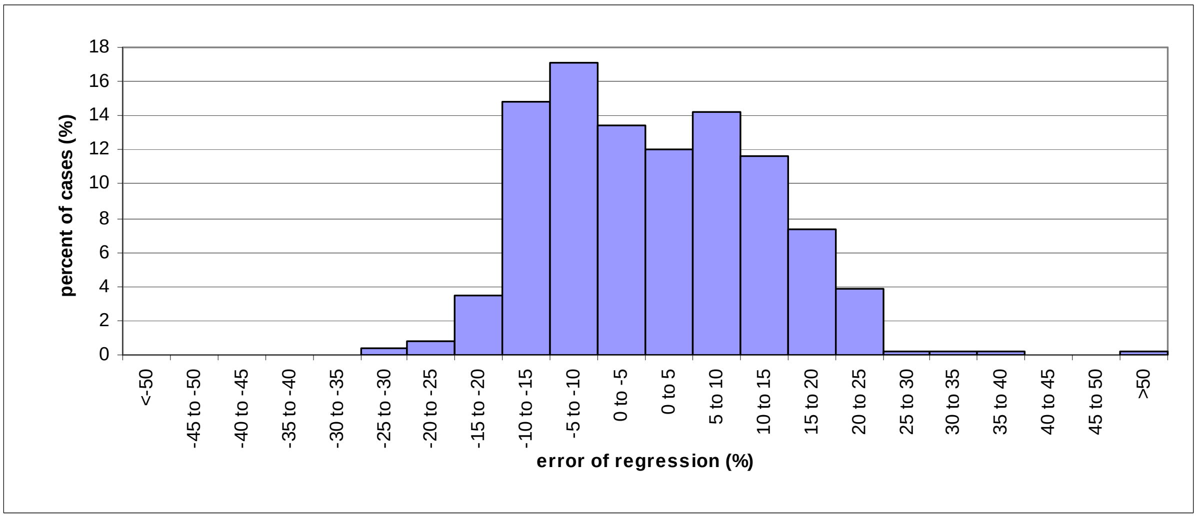

Figure E-13: Piping weight – error distribution for tank vessels

Notwithstanding the above, good results are achieved with a set of variables of the following form:

$$W_{piping} = c_1 + c_2 \cdot L + c_3 \cdot B + c_4 \cdot LBT + c_5 \cdot L^{0.6} B + c_6 \frac{B}{L^3} \qquad \text{Eq. E-11}$$

The coefficients for these variables are shown in table E-26. All variables meet the significance criterion and especially the first five have a significant impact.

Table E-25: Piping weight - R^2 for tank vessels

R	R^2	Adjusted R^2	Std. Error of the Estimate
0.987	0.975	0.975	1.96341

Table E-26: Piping weight– coefficients for tank vessels

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
c1	-3.949E+00	7.242E-01		-5.452	0.000
c2	8.191E-02	6.725E-03	0.285	12.179	0.000
c3	-4.407E-01	8.982E-02	-0.185	-4.906	0.000
c4	1.065E-03	5.362E-05	0.286	19.851	0.000
c5	6.966E-02	5.573E-03	0.662	12.500	0.000
c6	1.228E+04	4.200E+03	0.030	2.923	0.004

Building cost

Like with the other two ship types, the building cost of tank vessels is broken down in yard cost and non-yard cost, where the yard cost are the sum of the general object cost, man-hour cost of the hull and material cost of the hull, while non-yard cost covers all other costs.

Yard cost

The formula for the estimation of yard cost shows is nearly identical to the steel weight estimation formula:

$$Cost_{yard} = c_1 + c_2 \cdot LBT + c_3 \cdot L^{3.5} B + c_4 \cdot \frac{1}{(LBT)^{0.5}} \qquad \text{Eq. E-12}$$

The coefficients for the equation are shown in table E-27. The table shows that all variables meet the significance criterion and that L^3B is the most influential variable.

Table E-27: - Yard cost – coefficients for tank vessels

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
c1	1.514E+06	5.100E+04		29.681	0.000
c2	1.437E+02	5.794E+00	0.244	24.803	0.000
c3	3.204E-03	3.424E-05	0.703	93.559	0.000
c4	-2.829E+07	1.697E+06	-0.127	-16.672	0.000

The R^2 values in table E-28 again show that the rule of thumb explains nearly all variance for the yard cost of the designs.

Table E-28: Yard cost - R^2 for tank vessels

R	R^2	Adjusted R^2	Std. Error of the Estimate
0.994	0.989	0.988	2.089E+05

The error distribution shown in figure E-14 is similar to that for the steel weight of the designs: in over 80% of all cases the error is less than ±10%, but there are some outliers. These outliers represent the 5 m wide vessels with a draught of 1.5 m and/or a length of 40 meters. In these cases the depth, and thereby the cost of the hull, needs to be increased substantially in order to accommodate the required tank volume (see chapter 5.5.1), thus introducing errors in predictors that only incorporate L, B and T.

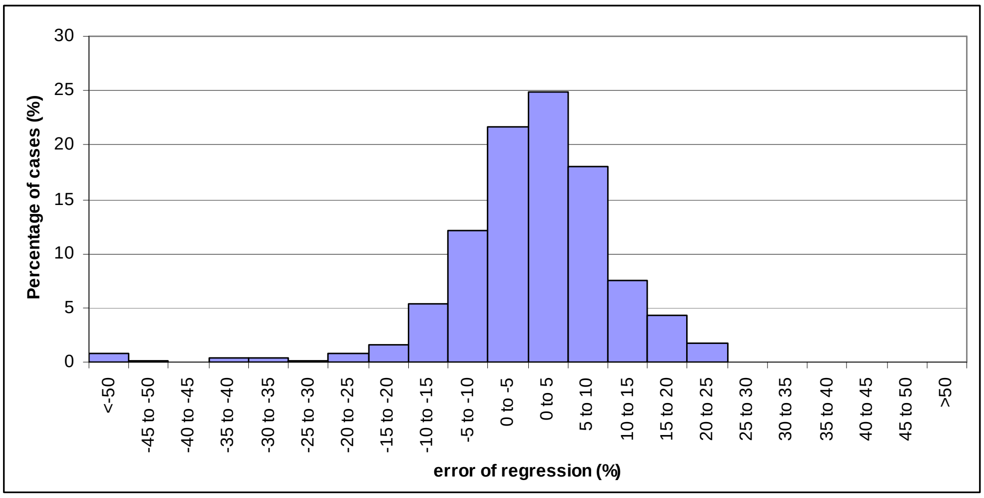

Figure E-14: Yard cost – error distribution for tank vessels

Non-yard cost

The non-yard cost, being the cost of all machinery, equipment and outfitting and the accommodation (i.e. all cost apart from the general object cost, man-hour cost and material cost of the hull.

$$Cost_{misc} = c_1 + c_2 \cdot \frac{L^{1.5}}{B} + c_3 \cdot LBT + c_4 \cdot LB + c_5 \cdot \frac{1}{LT} \qquad \text{Eq. E-13}$$

The coefficients for the cost formula are as displayed in table E-29 below. One of the variables does not meet the significance criterion, but is kept in the equation to allow use of the same rule of thumb for all ship types. It can be seen from the small beta value that the impact of doing so on the final result is very limited.

Table E-29: Non-yard cost – coefficients for tank vessels

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
c1	9.608E+05	2.667E+04		36.022	0.000
c2	8.475E+01	1.187E+02	0.004	0.714	0.476
c3	2.444E+02	3.903E+00	0.696	62.615	0.000
c4	3.129E+02	1.213E+01	0.256	25.806	0.000
c5	-4.116E+07	2.975E+06	-0.098	-13.835	0.000

The R^2 values in table E-30 confirm the good match between the rule of thumb and the original data, while the error distribution in figure E-15 shows that in 90% of all cases the error is less than ±10%.

Table E-30: Non-yard cost - R^2 for tank vessels

R	R^2	Adjusted R^2	Std. Error of the Estimate
0.994	0.989	0.988	1.248E+05

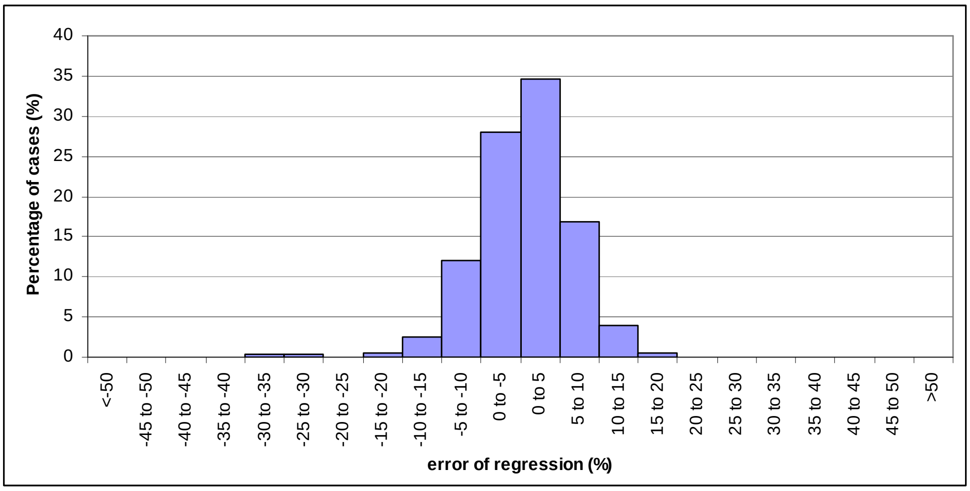

Figure E-15: Non-yard cost – error distribution for tank vessels

F : Scenario analyses of minimum required ship rate

F.1 Dry bulk vessels

Rotterdam – Koblenz (430 km) – Dry bulk vessels

Water depth 5 meters (Tmax = 4.5 m)

sailing regime	B			
depreciation time	30/15		30/15	
fuel price (€/T)	700		400	
crew cost	full	reduced	full	reduced
optimal dimensions	160x25x4.5 m	160x25x4.5 m	160x25x4.5 m	160x25x4.5 m
required ship rate (€/T)	€ 4.01	€ 3.89	€ 3.44	€ 3.32
optimal dimensions	100%	100%	100%	100%
standard 135 m vessel	127%	124%	127%	124%
standard 110 m vessel	168%	163%	169%	162%
standard 86 m vessel	240%	230%	247%	236%
+ 1 length step (+25 m)	103%	103%	105%	105%
- 1 length step (-25 m)	101%	101%	101%	100%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step (-5 m)	102%	102%	103%	102%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step (-0.5 m)	114%	114%	115%	115%

sailing regime	B			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	160x25x4.5 m	160x25x4.5 m	160x25x4.5 m	160x25x4.5 m
required ship rate (€/T)	€ 4.57	€ 4.45	€ 4.38	€ 4.25
optimal	100%	100%	100%	100%
standard 135 m vessel	127%	125%	125%	123%
standard 110 m vessel	168%	163%	164%	159%
standard 86 m vessel	235%	226%	234%	226%
+ 1 length step (+25 m)	102%	102%	104%	104%
- 1 length step (-25 m)	102%	101%	101%	100%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step (-5 m)	102%	102%	102%	102%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step (-0.5 m)	113%	113%	114%	115%

Water depth 3.3/3 meters (Tmax = 2.5 m)

sailing regime	B			
depreciation time	30/15		30/15	
fuel price	700		400	
crew cost	full	reduced	full	reduced
optimal dimensions	160x20x2.5 m	160x20x2.5 m	135x20x2.5 m	135x20x2.5 m
required ship rate (€/T)	€ 6.79	€ 6.52	€ 5.88	€ 5.57
optimal	100%	100%	100%	100%
standard 135 m vessel	119%	118%	120%	119%
standard 110 m vessel	148%	145%	148%	145%
standard 86 m vessel	152%	147%	155%	151%
+ 1 length step (+25 m)	108%	108%	100%	101%
- 1 length step (-25 m)	101%	100%	111%	110%
+ 1 beam step (+ 5 m)	103%	104%	103%	104%
-1 beam step (-2.5 m)	115%	114%	113%	113%
+ 1 draught step (+ 5 m)	102%	102%	103%	103%
- 1 draught step (-0.5 m)	122%	121%	123%	122%

sailing regime	B			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	160x20x2.5 m	160x20x2.5 m	160x20x2.5 m	135x20x2.5 m
required ship rate (€/T)	€ 7.70	€ 7.43	€ 7.38	€ 7.08
optimal	100%	100%	100%	100%
standard 135 m vessel	119%	118%	118%	117%
standard 110 m vessel	148%	145%	145%	143%
standard 86 m vessel	150%	145%	149%	145%
+ 1 length step (+25 m)	106%	107%	109%	100%
- 1 length step (-25 m)	101%	101%	100%	110%
+ 1 beam step (+ 5 m)	102%	103%	104%	104%
- 1 beam step (-2.5 m)	114%	114%	115%	112%
+ 1 draught step (+ 5 m)	102%	102%	102%	102%
- 1 draught step (-0.5 m)	118%	118%	123%	118%

Water depth 2.25 m (Tmax = 1.75 m)

sailing regime	B			
depreciation time	30/15		30/15	
fuel price	700		400	
crew cost	full	reduced	full	reduced
optimal dimensions	160x25x2 m	160x25x2 m	160x25x2 m	160x25x2 m
required ship rate (€/T)	€ 9.48	€ 9.09	€ 8.58	€ 8.19
optimal	100%	100%	100%	100%
standard 135 m vessel	127%	125%	128%	125%
standard 110 m vessel	162%	157%	164%	158%
standard 86 m vessel	168%	162%	168%	162%
+ 1 length step (+25 m)	114%	114%	114%	115%
- 1 length step (-25 m)	105%	104%	104%	104%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step (-5 m)	110%	109%	110%	110%
+ 1 draught step (+ 5 m)	119%	120%	121%	121%
- 1 draught step (-0.5 m)	no data	no data	no data	no data

sailing regime	B			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	160x25x2 m	160x25x2 m	160x25x2 m	160x25x2 m
required ship rate (€/T)	€ 10.37	€ 9.99	€ 10.46	€ 10.07
optimal	100%	100%	100%	100%
standard 135 m vessel	126%	124%	125%	123%
standard 110 m vessel	160%	155%	158%	153%
standard 86 m vessel	167%	162%	163%	158%
+ 1 length step (+25 m)	113%	114%	115%	115%
- 1 length step (-25 m)	105%	105%	104%	104%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step (-5 m)	110%	109%	109%	109%
+ 1 draught step (+ 5 m)	118%	119%	120%	121%
- 1 draught step (-0.5 m)	no data	no data	no data	no data

Rotterdam – Duisburg (247 km) – Dry bulk vessels

Water depth 5 m (Tmax = 4.5 m)

sailing regime	B		A1		B	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	160x25x4.5	135x25x4.5	135x20x4.5	135x20x4.5	135x25x4.5	135x25x4.5
required ship rate (€/T)	€ 3.11	€ 2.99	€ 2.99	€ 2.87	€ 2.78	€ 2.65
optimal	100%	100%	100%	100%	100%	100%
standard 135 m vessel	125%	122%	115%	114%	125%	123%
standard 110 m vessel	166%	161%	141%	137%	167%	161%
standard 86 m vessel	239%	229%	201%	194%	244%	235%
+ 1 length step	105%	100%	103%	103%	100%	101%
- 1 length step	100%	104%	106%	105%	104%	103%
+ 1 beam step	no data	no data	101%	102%	no data	no data
- 1 beam step	102%	101%	104%	104%	102%	101%
+ 1 draught step	no data	no data	no data	no data	no data	no data
- 1 draught step	114%	113%	112%	111%	114%	114%

sailing regime	B		B	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	160x25x4.5	160x25x4.5	135x25x4.5	135x25x4.5
required ship rate (€/T)	€ 3.43	€ 3.32	€ 3.43	€ 3.30
optimal	100%	100%	100%	100%
standard 135 m vessel	125%	123%	123%	121%
standard 110 m vessel	166%	161%	162%	157%
standard 86 m vessel	235%	226%	233%	225%
+ 1 length step	104%	104%	100%	101%
- 1 length step	101%	100%	103%	103%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	102%	102%	101%	101%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step	114%	114%	114%	114%

Water depth 3.3 m (Tmax = 2.8 m)

sailing regime	B		A1		B	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	160x20x3.5	135x17.5x3	135x17.5x3	135x17.5x3	135x17.5x3	135x17.5x3
required ship rate (€/T)	€ 4.77	€ 4.52	€ 4.41	€ 4.18	€ 4.27	€ 4.01
optimal	100%	100%	100%	100%	100%	100%
standard 135 m vessel	113%	112%	110%	110%	113%	112%
standard 110 m vessel	144%	141%	132%	129%	144%	141%
standard 86 m vessel	163%	159%	146%	143%	166%	162%
+ 1 length step	106%	103%	105%	106%	103%	103%
- 1 length step	102%	110%	112%	105%	111%	118%
+ 1 beam step	109%	103%	104%	105%	102%	102%
- 1 beam step	108%	107%	105%	104%	108%	108%
+ 1 draught step	110%	105%	105%	106%	105%	105%
- 1 draught step	102%	120%	120%	121%	121%	121%

sailing regime	B		B	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	160x20x3.5	135x17.5x3	135x17.5x3	135x17.5x3
required ship rate (€/T)	€ 5.26	€ 5.04	€ 5.20	€ 4.93
optimal	100%	100%	100%	100%
standard 135 m vessel	113%	112%	112%	112%
standard 110 m vessel	144%	141%	142%	140%
standard 86 m vessel	160%	156%	160%	157%
+ 1 length step	106%	102%	103%	103%
- 1 length step	103%	115%	110%	116%
+ 1 beam step	110%	103%	103%	103%
- 1 beam step	108%	107%	107%	107%
+ 1 draught step	110%	105%	105%	105%
- 1 draught step	102%	118%	120%	120%

Water depth 2.25 m (Tmax = 1.75 m)

sailing regime	B		A1		B	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	160x25x2	160x25x2	135x20x2	135x20x2	160x25x2	160x25x2
required ship rate (€/T)	€ 7.27	€ 6.94	€ 7.32	€ 6.92	€ 6.75	€ 6.42
optimal	100%	100%	100%	100%	100%	100%
standard 135 m vessel	126%	123%	118%	117%	126%	124%
standard 110 m vessel	159%	154%	138%	134%	161%	155%
standard 86 m vessel	163%	157%	141%	138%	163%	157%
+ 1 length step	114%	115%	110%	111%	115%	116%
- 1 length step	104%	104%	108%	107%	104%	103%
+ 1 beam step	no data	no data	103%	104%	no data	no data
- 1 beam step	109%	109%	103%	103%	109%	109%
+ 1 draught step	120%	121%	104%	104%	122%	122%
- 1 draught step	no data	no data	118%	117%	no data	no data

sailing regime	B		B	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	160x25x2	160x25x2	160x25x2	160x25x2
required ship rate (€/T)	€ 7.78	€ 7.46	€ 8.09	€ 7.77
optimal	100%	100%	100%	100%
135x15x3.5	125%	123%	123%	121%
110x11.45X3.5	158%	153%	155%	150%
86x9.5x2.5	163%	158%	158%	152%
+ 1 length step	114%	114%	115%	116%
- 1 length step	105%	104%	104%	103%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	109%	109%	109%	108%
+ 1 draught step	120%	120%	121%	122%
- 1 draught step	no data	no data	no data	no data

Rotterdam Nijmegen (136 km) – Dry bulk vessels

Water depth 5 m (Tmax = 4.5 m)

sailing regime	B		A1		A1	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	135x25x4.5	135x25x4.5	135x20x4.5	135x20x4.5	135x20x4.5	135x15x4.5
required ship rate (€/T)	€ 2.54	€ 2.43	€ 2.26	€ 2.16	€ 2.07	€ 1.96
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	124%	122%	114%	112%	113%	111%
110x11.45X3.5	166%	160%	138%	133%	137%	132%
86x9.5x2.5	240%	230%	197%	190%	198%	192%
+ 1 length step	101%	101%	104%	105%	104%	107%
- 1 length step	104%	103%	104%	103%	103%	106%
+ 1 beam step	no data	no data	102%	102%	102%	104%
- 1 beam step	102%	101%	104%	103%	103%	108%
+ 1 draught step	no data	no data	no data	no data	no data	no data
- 1 draught step	115%	114%	112%	112%	112%	108%

sailing regime	A1		A1	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x20x4.5	135x20x4.5	135x20x4.5	135x15x4.5
required ship rate (€/T)	€ 2.45	€ 2.35	€ 2.58	€ 2.48
optimal	100%	100%	100%	100%
135x15x3.5	114%	112%	113%	111%
110x11.45X3.5	140%	135%	137%	132%
86x9.5x2.5	196%	190%	196%	190%
+ 1 length step	103%	104%	104%	106%
- 1 length step	104%	104%	103%	106%
+ 1 beam step	101%	102%	102%	103%
- 1 beam step	104%	103%	103%	108%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step	112%	111%	111%	108%

Water depth 3.3 m (Tmax = 2.8 m)

sailing regime	B		A1		A1	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	135x17.5x3	135x17.5x3	135x17.5x3	135x17.5x3	135x17.5x3	135x17.5x3
required ship rate (€/T)	€ 3.83	€ 3.60	€ 3.23	€ 3.05	€ 2.95	€ 2.77
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	113%	113%	111%	110%	111%	110%
110x11.45X3.5	143%	141%	130%	127%	129%	125%
86x9.5x2.5	164%	160%	145%	142%	146%	143%
+ 1 length step	103%	104%	107%	108%	107%	108%
- 1 length step	111%	110%	106%	105%	106%	104%
+ 1 beam step	103%	103%	105%	106%	105%	105%
- 1 beam step	108%	108%	105%	105%	105%	105%
+ 1 draught step	105%	105%	106%	106%	105%	106%
- 1 draught step	121%	121%	122%	123%	123%	124%

sailing regime	A1		A1	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x17.5x3	135x17.5x3	135x17.5x3	135x17.5x3
required ship rate (€/T)	€ 3.51	€ 3.33	€ 3.67	€ 3.49
optimal	100%	100%	100%	100%
135x15x3.5	111%	111%	111%	110%
110x11.45X3.5	131%	128%	129%	126%
86x9.5x2.5	144%	141%	145%	142%
+ 1 length step	106%	107%	107%	108%
- 1 length step	106%	105%	106%	105%
+ 1 beam step	105%	105%	105%	106%
- 1 beam step	105%	105%	105%	105%
+ 1 draught step	106%	106%	106%	106%
- 1 draught step	121%	122%	123%	123%

Water depth 2.25 (Tmax = 1.75 m)

sailing regime	B		A1		A1	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	160x25x2	160x25x2	135x20x2	135x20x2	135x20x2	135x20x2
required ship rate (€/T)	€ 5.93	€ 5.64	€ 5.38	€ 5.06	€ 5.07	€ 4.76
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	124%	122%	117%	116%	117%	116%
110x11.45X3.5	157%	151%	136%	131%	136%	131%
86x9.5x2.5	159%	153%	136%	133%	135%	132%
+ 1 length step	115%	116%	110%	112%	111%	112%
- 1 length step	104%	103%	107%	107%	107%	106%
+ 1 beam step	no data	no data	104%	105%	104%	105%
- 1 beam step	109%	108%	103%	103%	103%	102%
+ 1 draught step	122%	122%	104%	105%	105%	105%
- 1 draught step	no data	no data	119%	119%	120%	120%

sailing regime	A1		A1	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x20x2	135x20x2	135x20x2	135x20x2
required ship rate (€/T)	€ 5.68	€ 5.37	€ 6.20	€ 5.89
optimal	100%	100%	100%	100%
135x15x3.5	117%	116%	116%	116%
110x11.45X3.5	135%	131%	134%	130%
86x9.5x2.5	137%	134%	134%	131%
+ 1 length step	110%	111%	111%	112%
- 1 length step	108%	107%	107%	106%
+ 1 beam step	104%	104%	104%	105%
- 1 beam step	103%	102%	103%	102%
+ 1 draught step	104%	104%	105%	105%
- 1 draught step	118%	117%	120%	119%

Rotterdam – Dordrecht (45 km) – Dry bulk vessels

5 m water depth (Tmax = 4.5 m)

sailing regime	A1			
depreciation time	30/15		30/15	
fuel price	700		400	
crew cost	full	reduced	full	reduced
optimal dimensions	135x15x4.5	60x15x4.5	135x15x4.5	135x15x4.5
required ship rate (€/T)	1.64	1.53	1.58	1.47
optimal	100%	100%	100%	100%
135x15x3.5	113%	112%	112%	112%
110x11.45X3.5	136%	132%	135%	131%
86x9.5x2.5	194%	190%	194%	189%
+ 1 length step	108%	107%	108%	110%
- 1 length step	107%	no data	106%	105%
+ 1 beam step	104%	no data	104%	105%
- 1 beam step	109%	112%	109%	108%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step	110%	110%	109%	109%

sailing regime	A1			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x15x4.5	60x15x4.5	135x15x4.5	60x15x4.5
required ship rate (€/T)	1.71	1.59	1.9	1.8
optimal	100%	100%	100%	100%
135x15x3.5	112%	113%	113%	112%
110x11.45X3.5	136%	133%	135%	131%
86x9.5x2.5	193%	190%	193%	188%
+ 1 length step	107%	106%	108%	106%
- 1 length step	107%	no data	107%	no data
+ 1 beam step	104%	no data	104%	no data
- 1 beam step	109%	111%	109%	111%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step	109%	110%	109%	111%

3.3 m water depth (Tmax = 2.8 m)

sailing regime	A1			
depreciation time	30/15		30/15	
fuel price	700		400	
crew cost	full	reduced	full	reduced
optimal dimensions	135x17.5x3	135x17.5x3	135x17.5x3	135x17.5x3
required ship rate (€/T)	2.27	2.12	2.18	2.03
optimal	100%	100%	100%	100%
135x15x3.5	111%	110%	111%	110%
110x11.45X3.5	127%	123%	126%	122%
86x9.5x2.5	144%	140%	144%	140%
+ 1 length step	109%	110%	109%	110%
- 1 length step	106%	104%	106%	104%
+ 1 beam step	106%	107%	106%	107%
- 1 beam step	106%	105%	106%	105%
+ 1 draught step	106%	106%	106%	106%
- 1 draught step	125%	125%	125%	126%

sailing regime	A1			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x17.5x3	135x17.5x3	135x17.5x3	135x17.5x3
required ship rate (€/T)	2.36	2.21	2.63	2.48
optimal	100%	100%	100%	100%
135x15x3.5	111%	111%	111%	110%
110x11.45X3.5	128%	124%	126%	123%
86x9.5x2.5	143%	140%	143%	140%
+ 1 length step	108%	110%	109%	110%
- 1 length step	106%	105%	105%	104%
+ 1 beam step	106%	107%	107%	108%
- 1 beam step	106%	105%	105%	105%
+ 1 draught step	106%	106%	105%	106%
- 1 draught step	125%	125%	125%	126%

2.25 m water depth (Tmax = 1.75 m)

sailing regime	A1			
depreciation time	30/15		30/15	
fuel price	700		400	
crew cost	full	reduced	full	reduced
optimal dimensions	135x20x2	135x20x3	135x20x4	70x17.5x2
required ship rate (€/T)	3.78	3.54	3.68	3.4
optimal	100%	100%	100%	100%
135x15x3.5	116%	115%	116%	116%
110x11.45X3.5	131%	127%	131%	128%
86x9.5x2.5	129%	125%	128%	126%
+ 1 length step	112%	113%	112%	105%
- 1 length step	107%	105%	107%	no data
+ 1 beam step	105%	106%	105%	no data
- 1 beam step	103%	102%	103%	104%
+ 1 draught step	105%	105%	105%	106%
- 1 draught step	121%	121%	122%	117%

sailing regime	A1			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x20x2	135x20x3	135x20x4	70x17.5x2
required ship rate (€/T)	3.88	3.64	4.42	4.17
optimal	100%	100%	100%	100%
135x15x3.5	116%	115%	115%	115%
110x11.45X3.5	131%	127%	130%	126%
86x9.5x2.5	130%	126%	127%	124%
+ 1 length step	111%	113%	112%	105%
- 1 length step	107%	106%	106%	no data
+ 1 beam step	105%	106%	106%	no data
- 1 beam step	103%	102%	103%	104%
+ 1 draught step	105%	105%	105%	106%
- 1 draught step	120%	120%	121%	117%

F.2 Container vessels

Rotterdam – Koblenz (430 km) – Container vessels

5 m water depth (Tmax = 4.5 m)

sailing regime	B			
depreciation time	30/15		30/15	
fuel price	700		400	
crew cost	full	reduced	full	reduced
optimal dimensions	160x20x3.5	160x20x3.6	160x20x3.7	160x20x3.8
required ship rate (€/T)	€ 3.48	€ 3.38	€ 2.83	€ 2.73
required ship rate (€/TEU)	48.72	47.32	39.62	38.22
optimal	100%	100%	100%	100%
135x15x3.5	112%	112%	110%	109%
110x11.45X3.5	140%	138%	135%	133%
86x9.5x2.5	176%	173%	175%	170%
+ 1 length step	108%	108%	109%	110%
- 1 length step	103%	103%	101%	101%
+ 1 beam step	109%	110%	111%	112%
- 1 beam step	105%	105%	104%	104%
+ 1 draught step	103%	104%	104%	104%
- 1 draught step	116%	117%	115%	115%

sailing regime	B			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	160x20x3.5	160x20x3.6	160x20x3.7	160x20x3.8
required ship rate (€/T)	€ 4.12	€ 4.02	€ 3.73	€ 3.63
required ship rate (€/TEU)	57.68	56.28	52.22	50.82
optimal	100%	100%	100%	100%
135x15x3.5	114%	114%	111%	110%
110x11.45X3.5	144%	143%	137%	135%
86x9.5x2.5	178%	175%	173%	169%
+ 1 length step	107%	107%	109%	109%
- 1 length step	105%	104%	102%	102%
+ 1 beam step	108%	109%	110%	111%
- 1 beam step	106%	106%	105%	104%
+ 1 draught step	104%	104%	103%	104%
- 1 draught step	117%	118%	116%	117%

3.3/3 m water depth (Tmax = 2.5 m)

sailing regime	B			
depreciation time	30/15		30/15	
fuel price	700		400	
crew cost	full	reduced	full	reduced
optimal dimensions	135x20x2.5	135x20x2.6	135x20x2.7	135x20x2.8
required ship rate (€/T)	€ 4.99	€ 4.83	€ 4.00	€ 3.84
required ship rate (€/TEU)	69.86	67.62	56	53.76
optimal	100%	100%	100%	100%
135x15x3.5	113%	112%	113%	113%
110x11.45X3.5	135%	134%	135%	133%
86x9.5x2.5	136%	134%	139%	136%
+ 1 length step	105%	105%	107%	107%
- 1 length step	106%	105%	105%	104%
+ 1 beam step	103%	103%	104%	104%
- 1 beam step	106%	106%	106%	106%
+ 1 draught step	101%	101%	102%	102%
- 1 draught step	110%	109%	115%	114%

sailing regime	B			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x20x2.5	135x20x2.6	135x20x2.7	135x20x2.8
required ship rate (€/T)	€ 5.91	€ 5.79	€ 5.30	€ 5.14
required ship rate (€/TEU)	82.74	81.06	74.2	71.96
optimal	100%	100%	100%	100%
135x15x3.5	114%	113%	113%	112%
110x11.45X3.5	137%	135%	133%	132%
86x9.5x2.5	137%	134%	135%	133%
+ 1 length step	108%	108%	106%	106%
- 1 length step	104%	103%	105%	105%
+ 1 beam step	no data	no data	104%	104%
- 1 beam step	105%	105%	106%	106%
+ 1 draught step	109%	109%	102%	102%
- 1 draught step	107%	106%	111%	110%

2.25 m water depth (Tmax = 1.75 m)

sailing regime	B			
depreciation time	30/15		30/15	
fuel price	700		400	
crew cost	full	reduced	full	reduced
optimal dimensions	135x25x2	135x25x2	135x25x2	135x25x2
required ship rate (€/T)	€ 6.82	€ 6.59	€ 5.81	€ 5.57
required ship rate (€/TEU)	€ 95.48	€ 92.26	€ 81.34	€ 77.98
optimal	100%	100%	100%	100%
135x15x3.5	124%	123%	126%	125%
110x11.45X3.5	146%	142%	149%	145%
86x9.5x2.5	154%	150%	155%	151%
+ 1 length step	105%	106%	107%	107%
- 1 length step	105%	105%	105%	104%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	105%	104%	105%	105%
+ 1 draught step	113%	113%	114%	114%
- 1 draught step	113%	112%	115%	115%

sailing regime	B			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x25x2	135x25x2	135x25x2	135x25x2
required ship rate (€/T)	€ 7.84	€ 7.60	€ 7.37	€ 7.13
required ship rate (€/TEU)	€ 109.76	€ 106.4	€ 103.18	€ 99.82
optimal	100%	100%	100%	100%
135x15x3.5	123%	121%	123%	122%
110x11.45X3.5	143%	140%	143%	140%
86x9.5x2.5	153%	149%	151%	148%
+ 1 length step	104%	105%	106%	107%
- 1 length step	106%	106%	105%	104%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	105%	104%	105%	104%
+ 1 draught step	112%	112%	113%	113%
- 1 draught step	110%	110%	113%	113%

Rotterdam – Duisburg (247 km) – Container vessels

5 m water depth (Tmax = 4.5 m)

sailing regime	B		A1		B	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	Full	reduced	full	reduced	full	reduced
optimal dimensions	160x20x3.5	135x20x3.5	70x15x3	70x15x3	86x20x3.5	80x17.5x3
required ship rate (€/T)	€ 2.37	€ 2.30	€ 3.12	€ 2.94	€ 1.96	€ 1.88
required ship rate (€/TEU)	€ 33.18	€ 32.2	€ 43.68	€ 41.16	€ 27.44	€ 26.32
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	107%	106%	110%	111%	107%	105%
110x11.45X3.5	129%	127%	120%	120%	126%	123%
86x9.5x2.5	158%	155%	146%	147%	156%	153%
+ 1 length step	110%	103%	105%	106%	109%	101%
- 1 length step	101%	106%	111%	110%	103%	107%
+ 1 beam step	113%	105%	105%	105%	no data	102%
- 1 beam step	104%	108%	107%	106%	102%	106%
+ 1 draught step	104%	107%	113%	114%	114%	104%
- 1 draught step	115%	107%	114%	114%	103%	120%

sailing regime	B		B	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	160x20x3.5	160x20x3.5	80x17.5x3	80x17.5x3
required ship rate (€/T)	€ 2.75	€ 2.67	€ 2.56	€ 2.46
required ship rate (€/TEU)	€ 38.5	€ 37.38	€ 35.84	€ 34.44
optimal	100%	100%	100%	100%
135x15x3.5	109%	109%	106%	106%
110x11.45X3.5	133%	132%	126%	125%
86x9.5x2.5	161%	159%	154%	153%
+ 1 length step	108%	109%	102%	102%
- 1 length step	102%	102%	105%	105%
+ 1 beam step	111%	112%	103%	103%
- 1 beam step	104%	104%	106%	105%
+ 1 draught step	103%	103%	104%	104%
- 1 draught step	115%	116%	121%	121%

3.3 m water depth (Tmax = 2.8 m)

sailing regime	B		A1		B	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	80x17.5x3	80x17.5x3	70x17.5x3	70x17.5x3	80x17.5x3	80x17.5x3
required ship rate (€/T)	€ 2.91	€ 2.79	€ 3.74	€ 3.54	€ 2.38	€ 2.26
required ship rate (€/TEU)	€ 40.74	€ 39.06	€ 52.36	€ 49.56	€ 33.32	€ 31.64
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	111%	111%	116%	116%	111%	111%
110x11.45X3.5	130%	129%	123%	122%	128%	127%
86x9.5x2.5	140%	138%	133%	132%	141%	139%
+ 1 length step	102%	102%	101%	102%	100%	101%
- 1 length step	100%	100%	no data	no data	101%	101%
+ 1 beam step	103%	104%	no data	no data	103%	103%
- 1 beam step	104%	104%	101%	101%	105%	104%
+ 1 draught step	108%	108%	106%	107%	107%	107%
- 1 draught step	112%	112%	109%	109%	111%	111%

sailing regime	B		B	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	Full	reduced	full	reduced
optimal dimensions	70x17.5x3	70x17.5x3	80x17.5x3	80x17.5x3
required ship rate (€/T)	€ 3.43	€ 3.31	€ 3.09	€ 2.96
required ship rate (€/TEU)	€ 48.02	€ 46.34	€ 43.26	€ 41.44
optimal	100%	100%	100%	100%
135x15x3.5	111%	111%	111%	112%
110x11.45X3.5	131%	131%	128%	128%
86x9.5x2.5	139%	138%	139%	138%
+ 1 length step	100%	100%	101%	102%
- 1 length step	no data	no data	100%	101%
+ 1 beam step	no data	no data	103%	104%
- 1 beam step	103%	103%	104%	104%
+ 1 draught step	106%	107%	107%	108%
- 1 draught step	111%	111%	112%	112%

2.25 m water depth (Tmax = 1.75 m)

sailing regime	B		A1		B	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	135x25x2	135x25x2	110x17.5x2	110x17.5x2	135x25x2	135x25x2
required ship rate (€/T)	€ 4.31	€ 4.15	€ 6.31	€ 5.94	€ 3.72	€ 3.56
required ship rate (€/TEU)	€ 60.34	€ 58.1	€ 88.34	€ 83.16	€ 52.08	€ 49.84
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	121%	120%	116%	117%	123%	121%
110x11.45X3.5	140%	137%	123%	121%	142%	139%
86x9.5x2.5	146%	143%	126%	125%	147%	143%
+ 1 length step	106%	107%	105%	106%	108%	108%
- 1 length step	104%	103%	102%	101%	103%	103%
+ 1 beam step	no data	no data	no data	no data	no data	no data
- 1 beam step	104%	103%	101%	101%	104%	104%
+ 1 draught step	112%	113%	105%	105%	113%	114%
- 1 draught step	112%	111%	109%	109%	114%	114%

sailing regime	B		B	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	Full	reduced	full	reduced
optimal dimensions	135x25x2	135x25x2	135x25x2	135x25x2
required ship rate (€/T)	€ 4.89	€ 4.73	€ 4.67	€ 4.51
required ship rate (€/TEU)	€ 68.46	€ 66.22	€ 65.38	€ 63.14
optimal	100%	100%	100%	100%
135x15x3.5	120%	119%	120%	119%
110x11.45X3.5	139%	136%	138%	135%
86x9.5x2.5	146%	143%	143%	140%
+ 1 length step	106%	106%	107%	108%
- 1 length step	105%	104%	103%	103%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	104%	103%	103%	103%
+ 1 draught step	112%	112%	113%	113%
- 1 draught step	110%	110%	112%	112%

Rotterdam – Nijmegen (136 km) – Container vessels

5 m water depth (Tmax = 4.5 m)

sailing regime	B		A1		A1	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	70x15x3	70x15x3	70x15x3	70x15x3	70x15x3	70x15x3
required ship rate (€/T)	€ 1.56	€ 1.48	€ 2.02	€ 1.89	€ 1.80	€ 1.68
required ship rate (€/TEU)	€ 21.84	€ 20.72	€ 28.28	€ 26.46	€ 25.20	€ 23.52
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	110%	111%	119%	120%	119%	120%
110x11.45X3.5	126%	126%	121%	121%	118%	117%
86x9.5x2.5	148%	147%	141%	142%	137%	137%
+ 1 length step	104%	105%	106%	107%	105%	106%
- 1 length step	112%	111%	109%	108%	111%	109%
+ 1 beam step	no data	no data	105%	106%	105%	105%
- 1 beam step	108%	108%	105%	105%	106%	104%
+ 1 draught step	no data	no data	no data	no data	no data	no data
- 1 draught step	114%	114%	113%	113%	113%	112%

sailing regime	A1		A1	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	70x15x3	70x15x3	70x15x3	70x15x3
required ship rate (€/T)	€ 2.23	€ 2.11	€ 2.27	€ 2.15
required ship rate (€/TEU)	€ 31.22	€ 29.54	€ 31.78	€ 30.10
optimal	100%	100%	100%	100%
135x15x3.5	119%	120%	119%	120%
110x11.45X3.5	125%	125%	120%	119%
86x9.5x2.5	145%	145%	140%	139%
+ 1 length step	107%	108%	106%	107%
- 1 length step	108%	107%	109%	108%
+ 1 beam step	106%	106%	106%	106%
- 1 beam step	106%	105%	105%	105%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step	113%	113%	113%	113%

Water depth 3.3 m (Tmax = 2.8 m)

sailing regime	B		A1		A1	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	70x17.5x3	70x17.5x3	70x17.5x3	70x15x3	70x17.5x3	70x15x3
required ship rate (€/T)	€ 1.82	€ 1.74	€ 2.38	€ 2.25	€ 2.10	€ 1.97
required ship rate (€/TEU)	€ 25.48	€ 24.36	€ 33.32	€ 31.50	€ 29.40	€ 27.58
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	115%	116%	122%	123%	123%	123%
110x11.45X3.5	129%	128%	124%	122%	121%	119%
86x9.5x2.5	136%	134%	129%	128%	128%	126%
+ 1 length step	140%	141%	172%	104%	180%	104%
- 1 length step	101%	101%	103%	101%	103%	103%
+ 1 beam step	no data	no data	no data	100%	no data	100%
- 1 beam step	103%	102%	101%	102%	100%	102%
+ 1 draught step	105%	106%	106%	106%	106%	106%
- 1 draught step	110%	110%	108%	104%	108%	105%

sailing regime	A1		A1	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	70x17.5x3	70x15x3	70x17.5x3	70x15x3
required ship rate (€/T)	€ 2.66	€ 2.53	€ 2.68	€ 2.55
required ship rate (€/TEU)	€ 37.24	€ 35.42	€ 37.52	€ 35.70
optimal	100%	100%	100%	100%
135x15x3.5	121%	122%	122%	122%
110x11.45X3.5	126%	125%	122%	120%
86x9.5x2.5	130%	130%	128%	127%
+ 1 length step	165%	105%	175%	104%
- 1 length step	103%	100%	103%	102%
+ 1 beam step	no data	100%	no data	100%
- 1 beam step	101%	102%	100%	102%
+ 1 draught step	106%	107%	106%	106%
- 1 draught step	109%	104%	108%	104%

Water depth 2.25 m (Tmax = 1.75 m)

sailing regime	B		A1		A1	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	135x25x2	135x25x2	86x17.5x2	95x15x2	86x17.5x2	95x15x2
required ship rate (€/T)	€ 2.78	€ 2.67	€ 3.93	€ 3.69	€ 3.50	€ 3.30
required ship rate (€/TEU)	€ 38.92	€ 37.38	€ 55.02	€ 51.66	€ 49.00	€ 46.20
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	117%	116%	119%	119%	123%	122%
110x11.45X3.5	132%	129%	121%	120%	125%	121%
86x9.5x2.5	135%	132%	121%	121%	123%	121%
+ 1 length step	108%	108%	102%	101%	101%	102%
- 1 length step	102%	101%	102%	102%	103%	102%
+ 1 beam step	no data	no data	103%	101%	103%	101%
- 1 beam step	102%	101%	102%	103%	102%	103%
+ 1 draught step	112%	112%	105%	103%	105%	103%
- 1 draught step	110%	110%	111%	108%	114%	109%

sailing regime	A1		A1	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	110x17.5x2	95x15x2	86x17.5x2	95x15x2
required ship rate (€/T)	€ 4.35	€ 4.08	€ 4.42	€ 4.19
required ship rate (€/TEU)	€ 60.90	€ 57.12	€ 61.88	€ 58.66
optimal	100%	100%	100%	100%
135x15x3.5	115%	117%	120%	120%
110x11.45X3.5	119%	118%	121%	120%
86x9.5x2.5	120%	121%	121%	120%
+ 1 length step	106%	100%	101%	101%
- 1 length step	101%	103%	102%	102%
+ 1 beam step	101%	101%	103%	101%
- 1 beam step	101%	103%	102%	103%
+ 1 draught step	105%	103%	105%	103%
- 1 draught step	107%	106%	112%	108%

Rotterdam – Dordrecht (45 km) – Container vessels

Water depth 5 m (Tmax = 4.5 m)

sailing regime	A1		B		A1	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	70x15x3	70x15x3	70x15x3	70x15x3	70x15x3	70x11.45x3
required ship rate (€/T)	€ 1.11	€ 1.03	€ 0.83	€ 0.78	€ 1.04	€ 0.95
required ship rate (€/TEU)	€ 15.54	€ 14.42	€ 11.62	€ 10.92	€ 14.56	€ 13.30
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	141%	142%	124%	124%	141%	145%
110x11.45X3.5	129%	125%	141%	138%	129%	126%
86x9.5x2.5	130%	130%	135%	133%	127%	127%
+ 1 length step	109%	110%	105%	105%	109%	108%
- 1 length step	105%	104%	107%	106%	105%	104%
+ 1 beam step	107%	108%	102%	104%	107%	102%
- 1 beam step	102%	102%	105%	104%	102%	121%
+ 1 draught step	111%	112%	110%	109%	110%	104%
- 1 draught step	109%	109%	110%	110%	109%	111%

sailing regime	A1			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	70x15x3	70x11.45x3	70x15x3	70x11.45x3
required ship rate (€/T)	€ 1.19	€ 1.10	€ 1.28	€ 1.19
required ship rate (€/TEU)	€ 16.66	€ 15.40	€ 17.92	€ 16.66
optimal	100%	100%	100%	100%
135x15x3.5	138%	141%	140%	143%
110x11.45X3.5	127%	125%	127%	125%
86x9.5x2.5	132%	134%	127%	129%
+ 1 length step	108%	109%	108%	108%
- 1 length step	103%	105%	104%	104%
+ 1 beam step	106%	102%	106%	102%
- 1 beam step	102%	123%	102%	121%
+ 1 draught step	110%	105%	110%	104%
- 1 draught step	109%	115%	109%	112%

Water depth 3.3 m (Tmax = 2.8 m)

sailing regime	A1		B		A1	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	60x15x3	60x15x3	70x17.5x3	70x15x3	70x12.5x3	70x12.5x3
required ship rate (€/T)	€ 1.24	€ 1.15	€ 0.93	€ 0.88	€ 1.15	€ 1.06
required ship rate (€/TEU)	€ 17.36	€ 16.10	€ 13.02	€ 12.32	€ 16.10	€ 14.84
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	141%	143%	126%	126%	143%	144%
110x11.45X3.5	123%	121%	137%	134%	123%	120%
86x9.5x2.5	123%	123%	127%	125%	121%	121%
+ 1 length step	101%	101%	102%	103%	105%	107%
- 1 length step	no data	no data	no data	102%	104%	103%
+ 1 beam step	no data	no data	no data	100%	101%	101%
- 1 beam step	104%	103%	101%	103%	102%	101%
+ 1 draught step	104%	104%	104%	106%	104%	104%
- 1 draught step	104%	103%	106%	105%	104%	104%

sailing regime	A1			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	60x15x3	60x15x3	70x12.5x3	60x15x3
required ship rate (€/T)	€ 1.33	€ 1.23	€ 1.42	€ 1.32
required ship rate (€/TEU)	€ 18.62	€ 17.22	€ 19.88	€ 18.48
optimal	100%	100%	100%	100%
135x15x3.5	139%	142%	141%	144%
110x11.45X3.5	124%	123%	123%	120%
86x9.5x2.5	124%	125%	121%	122%
+ 1 length step	101%	102%	106%	102%
- 1 length step	no data	no data	104%	no data
+ 1 beam step	no data	no data	101%	no data
- 1 beam step	105%	104%	102%	104%
+ 1 draught step	105%	105%	104%	105%
- 1 draught step	103%	103%	104%	103%

Water depth 2.25 m (Tmax = 1.75 m)

sailing regime	A1		B		A1	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	70x15x2	70x12.5x2	86x17.5x2	86x17.5x2	70x15x2	70x12.5x2
required ship rate (€/T)	€ 1.90	€ 1.76	€ 1.37	€ 1.30	€ 1.73	€ 1.60
required ship rate (€/TEU)	€ 26.60	€ 24.64	€ 19.18	€ 18.20	€ 24.22	€ 22.40
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	129%	131%	119%	118%	135%	136%
110x11.45X3.5	143%	140%	165%	162%	143%	139%
86x9.5x2.5	115%	115%	123%	120%	117%	117%
+ 1 length step	103%	103%	109%	107%	104%	104%
- 1 length step	104%	106%	102%	102%	103%	105%
+ 1 beam step	103%	101%	101%	102%	103%	100%
- 1 beam step	101%	105%	102%	102%	101%	104%
+ 1 draught step	102%	104%	104%	103%	102%	104%
- 1 draught step	110%	111%	109%	108%	112%	112%

sailing regime	A1			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	70x15x2	70x12.5x2	70x15x2	70x12.5x2
required ship rate (€/T)	€ 2.07	€ 1.93	€ 2.16	€ 2.02
required ship rate (€/TEU)	€ 28.98	€ 27.02	€ 30.24	€ 28.28
optimal	100%	100%	100%	100%
135x15x3.5	124%	125%	131%	132%
110x11.45X3.5	143%	140%	142%	139%
86x9.5x2.5	113%	113%	115%	115%
+ 1 length step	102%	102%	103%	102%
- 1 length step	105%	107%	104%	106%
+ 1 beam step	102%	101%	103%	100%
- 1 beam step	100%	105%	100%	104%
+ 1 draught step	101%	104%	102%	104%
- 1 draught step	108%	109%	110%	111%

F.3 Tank vessels

Rotterdam – Koblenz (430 km) – Tank vessels

water depth 5 m (Tmax = 4.5 m)

sailing regime	B			
depreciation time	30/15		30/15	
fuel price	700		400	
crew cost	full	reduced	full	reduced
optimal dimensions	135x25x4.5	135x25x4.5	135x25x4.5	135x25x4.5
required ship rate (€/T)	€ 4.95	€ 4.81	€ 4.36	€ 4.21
optimal	100%	100%	100%	100%
standard 135 m vessel	126%	124%	126%	124%
standard 110 m vessel	160%	156%	159%	155%
standard 86 m vessel	220%	212%	222%	214%
+ 1 length step	101%	101%	102%	102%
- 1 length step	105%	105%	105%	104%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	102%	101%	102%	102%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step	109%	109%	109%	110%

sailing regime	B			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x25x4.5	135x25x4.5	135x25x4.5	135x25x4.5
required ship rate (€/T)	€ 5.55	€ 5.41	€ 5.53	€ 5.39
optimal	100%	100%	100%	100%
standard 135 m vessel	126%	124%	124%	123%
standard 110 m vessel	160%	157%	156%	152%
standard 86 m vessel	217%	211%	213%	207%
+ 1 length step	101%	101%	102%	102%
- 1 length step	105%	105%	105%	104%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	102%	101%	102%	101%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step	109%	109%	109%	109%

Water depth 3.3 / 3 m (Tmax = 2.5 m)

sailing regime	B			
depreciation time	30/15		30/15	
fuel price	700		400	
crew cost	full	reduced	full	reduced
optimal dimensions	135x25x2.5	135x25x2.5	135x25x2.5	135x25x2.5
required ship rate (€/T)	€ 7.52	€ 7.25	€ 6.57	€ 6.31
optimal	100%	100%	100%	100%
standard 135 m vessel	133%	132%	134%	133%
standard 110 m vessel	170%	167%	172%	168%
standard 86 m vessel	156%	152%	159%	154%
+ 1 length step	102%	102%	103%	103%
- 1 length step	107%	107%	107%	106%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	107%	106%	107%	106%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step	111%	110%	114%	114%

sailing regime	B			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x25x2.5	135x25x2.5	135x25x2.5	135x25x2.5
required ship rate (€/T)	€ 8.46	€ 8.19	€ 8.31	€ 8.04
optimal	100%	100%	100%	100%
standard 135 m vessel	131%	131%	132%	131%
standard 110 m vessel	168%	166%	167%	164%
standard 86 m vessel	153%	150%	153%	149%
+ 1 length step	101%	101%	102%	103%
- 1 length step	108%	107%	107%	106%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	106%	106%	106%	106%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step	108%	108%	111%	111%

Water depth 2.25 m (Tmax = 1.75 m)

sailing regime	B			
depreciation time	30/15		30/15	
fuel price	700		400	
crew cost	full	reduced	full	reduced
optimal dimensions	135x25x2	135x25x2	135x25x2	135x25x2
required ship rate (€/T)	€ 10.78	€ 10.32	€ 9.81	€ 9.36
optimal	100%	100%	100%	100%
standard 135 m vessel	154%	153%	157%	156%
standard 110 m vessel	200%	196%	204%	200%
standard 86 m vessel	183%	178%	184%	179%
+ 1 length step	103%	104%	104%	104%
- 1 length step	108%	108%	108%	107%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	107%	106%	107%	107%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step	107%	107%	109%	108%

sailing regime	B			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x25x2	135x25x2	135x25x2	135x25x2
required ship rate (€/T)	€ 11.75	€ 11.29	€ 12.00	€ 11.54
optimal	100%	100%	100%	100%
standard 135 m vessel	152%	151%	154%	153%
standard 110 m vessel	196%	193%	198%	194%
standard 86 m vessel	181%	177%	179%	175%
+ 1 length step	103%	103%	104%	104%
- 1 length step	108%	108%	107%	107%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	107%	106%	106%	106%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step	106%	105%	107%	107%

Rotterdam – Duisburg (247 km) – Tank vessels

water depth 5 m (Tmax = 4.5 m)

sailing regime	B		A1		B	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	135x25x4.5	135x25x4.5	135x25x4.5	135x25x4.5	135x25x4.5	135x25x4.5
required ship rate (€/T)	€ 3.90	€ 3.77	€ 3.99	€ 3.87	€ 3.56	€ 3.43
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	125%	123%	116%	115%	125%	123%
110x11.45X3.5	157%	153%	138%	134%	156%	152%
86x9.5x2.5	215%	208%	185%	179%	216%	208%
+ 1 length step	102%	103%	105%	106%	103%	103%
- 1 length step	104%	104%	102%	102%	104%	103%
+ 1 beam step	no data	no data	100%	101%	no data	no data
- 1 beam step	102%	101%	105%	105%	102%	101%
+ 1 draught step	no data	no data	no data	no data	no data	no data
- 1 draught step	110%	110%	108%	108%	110%	110%

sailing regime	B		B	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x25x4.5	135x25x4.5	135x25x4.5	135x25x4.5
required ship rate (€/T)	€ 4.24	€ 4.12	€ 4.41	€ 4.28
optimal	100%	100%	100%	100%
135x15x3.5	125%	123%	123%	121%
110x11.45X3.5	158%	154%	153%	149%
86x9.5x2.5	214%	207%	208%	201%
+ 1 length step	102%	102%	103%	103%
- 1 length step	104%	104%	104%	104%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	102%	101%	101%	101%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step	110%	109%	110%	110%

water depth 3.3 m (Tmax = 2.8 m)

sailing regime	B		A1		B	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	135x25x3	135x25x3	135x25x3	135x25x3	135x25x3	135x25x3
required ship rate (€/T)	€ 5.46	€ 5.26	€ 5.58	€ 5.41	€ 4.95	€ 4.75
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	126%	125%	120%	119%	127%	125%
110x11.45X3.5	160%	156%	143%	140%	160%	156%
86x9.5x2.5	161%	156%	142%	138%	163%	157%
+ 1 length step	101%	102%	104%	105%	101%	102%
- 1 length step	106%	106%	104%	104%	105%	105%
+ 1 beam step	no data	no data	no data	no data	no data	no data
- 1 beam step	106%	105%	104%	104%	105%	105%
+ 1 draught step	110%	110%	111%	111%	110%	110%
- 1 draught step	104%	104%	102%	101%	104%	104%

sailing regime	B		B	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x25x3	135x25x3	135x25x3	135x25x3
required ship rate (€/T)	€ 5.98	€ 5.78	€ 6.13	€ 5.93
optimal	100%	100%	100%	100%
135x15x3.5	125%	124%	125%	124%
110x11.45X3.5	159%	156%	156%	153%
86x9.5x2.5	159%	154%	157%	152%
+ 1 length step	101%	101%	102%	102%
- 1 length step	107%	106%	105%	105%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	106%	106%	105%	105%
+ 1 draught step	109%	110%	110%	110%
- 1 draught step	104%	103%	104%	104%

water depth 2.25 m (Tmax = 1.75 m)

sailing regime	B		A1		B	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	135x25x2	135x25x2	135x25x2	135x25x2	135x25x2	135x25x2
required ship rate (€/T)	€ 8.31	€ 7.93	€ 8.53	€ 8.19	€ 7.75	€ 7.37
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	154%	153%	154%	153%	156%	155%
110x11.45X3.5	198%	194%	186%	181%	201%	197%
86x9.5x2.5	178%	174%	163%	159%	179%	174%
+ 1 length step	104%	104%	108%	109%	104%	105%
- 1 length step	107%	106%	105%	104%	107%	106%
+ 1 beam step	no data	no data	no data	no data	no data	no data
- 1 beam step	106%	106%	104%	104%	107%	106%
+ 1 draught step	117%	117%	117%	117%	118%	117%
- 1 draught step	107%	107%	107%	107%	109%	108%

sailing regime	B		B	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x25x2	135x25x2	135x25x2	135x25x2
required ship rate (€/T)	€ 8.86	€ 8.48	€ 9.33	€ 8.95
optimal	100%	100%	100%	100%
135x15x3.5	152%	151%	153%	153%
110x11.45X3.5	195%	192%	195%	192%
86x9.5x2.5	178%	173%	174%	170%
+ 1 length step	103%	104%	104%	105%
- 1 length step	107%	107%	106%	106%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	106%	106%	106%	105%
+ 1 draught step	117%	117%	117%	117%
- 1 draught step	107%	106%	107%	107%

Rotterdam – Nijmegen (136 km) – Tank vessels

Water depth 5 m (Tmax = 4.5 m)

sailing regime	B		A1		A1	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	135x25x4.5	135x25x4.5	135x20x4.5	135x20x4.5	135x20x4.5	135x20x4.5
Required ship rate (€/T)	€ 3.26	€ 3.14	€ 3.09	€ 2.99	€ 2.90	€ 2.78
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	124%	122%	115%	113%	114%	113%
110x11.45X3.5	155%	150%	134%	130%	132%	128%
86x9.5x2.5	211%	203%	177%	172%	176%	171%
+ 1 length step	103%	104%	106%	107%	107%	108%
- 1 length step	103%	103%	101%	100%	100%	100%
+ 1 beam step	no data	no data	101%	101%	101%	102%
- 1 beam step	102%	101%	105%	104%	104%	105%
+ 1 draught step	no data	no data	no data	no data	no data	no data
- 1 draught step	111%	111%	108%	108%	108%	108%

sailing regime	A1		A1	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x20x4.5	135x20x4.5	135x20x4.5	135x20x4.5
required ship rate (€/T)	€ 3.28	€ 3.18	€ 3.62	€ 3.51
optimal	100%	100%	100%	100%
135x15x3.5	116%	114%	114%	113%
110x11.45X3.5	135%	132%	132%	129%
86x9.5x2.5	179%	174%	175%	170%
+ 1 length step	106%	107%	107%	107%
- 1 length step	102%	101%	100%	100%
+ 1 beam step	101%	101%	101%	102%
- 1 beam step	105%	105%	104%	105%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step	109%	108%	108%	108%

Water depth 3.3 m (Tmax = 2.8 m)

sailing regime	B		A1		A1	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	135x25x3	135x25x3	135x25x3	135x25x3	135x25x3	135x25x3
required ship rate (€/T)	€ 4.47	€ 4.29	€ 4.23	€ 4.09	€ 3.94	€ 3.81
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	126%	124%	119%	118%	120%	118%
110x11.45X3.5	158%	154%	140%	136%	139%	134%
86x9.5x2.5	159%	153%	137%	133%	137%	132%
+ 1 length step	101%	102%	105%	105%	105%	106%
- 1 length step	105%	104%	102%	102%	102%	101%
+ 1 beam step	no data	no data	no data	no data	no data	no data
- 1 beam step	105%	104%	103%	102%	103%	102%
+ 1 draught step	110%	110%	111%	111%	111%	112%
- 1 draught step	104%	104%	102%	102%	103%	102%

sailing regime	A1		A1	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x25x3	135x25x3	135x25x3	135x25x3
required ship rate (€/T)	€ 4.51	€ 4.37	€ 4.95	€ 4.81
optimal	100%	100%	100%	100%
135x15x3.5	119%	118%	119%	117%
110x11.45X3.5	141%	137%	138%	135%
86x9.5x2.5	137%	133%	135%	131%
+ 1 length step	104%	105%	105%	105%
- 1 length step	103%	103%	102%	101%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	103%	103%	102%	102%
+ 1 draught step	111%	111%	111%	112%
- 1 draught step	102%	102%	102%	102%

Water depth 2.25 m (Tmax = 1.75)

sailing regime	B		A1		A1	
depreciation time	30/15		30/15		30/15	
fuel price	700		700		400	
crew cost	full	reduced	full	reduced	full	reduced
optimal dimensions	135x25x2	135x25x2	135x25x2	135x25x2	135x25x2	135x25x2
required ship rate (€/T)	€ 6.81	€ 6.47	€ 6.38	€ 6.12	€ 6.08	€ 5.81
optimal	100%	100%	100%	100%	100%	100%
135x15x3.5	153%	153%	152%	151%	154%	152%
110x11.45X3.5	196%	192%	182%	177%	183%	178%
86x9.5x2.5	174%	170%	156%	152%	156%	152%
+ 1 length step	104%	105%	109%	109%	109%	110%
- 1 length step	106%	105%	103%	102%	103%	102%
+ 1 beam step	no data	no data	no data	no data	no data	no data
- 1 beam step	106%	105%	103%	103%	103%	103%
+ 1 draught step	111%	111%	113%	113%	113%	113%
- 1 draught step	108%	107%	107%	106%	107%	107%

sailing regime	A1		A1	
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x25x2	135x25x2	135x25x2	135x25x2
required ship rate (€/T)	€ 6.69	€ 6.42	€ 7.49	€ 7.22
optimal	100%	100%	100%	100%
135x15x3.5	151%	150%	153%	152%
110x11.45X3.5	180%	176%	181%	177%
86x9.5x2.5	157%	153%	155%	151%
+ 1 length step	108%	109%	109%	109%
- 1 length step	104%	103%	103%	102%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	103%	103%	103%	102%
+ 1 draught step	112%	112%	113%	113%
- 1 draught step	106%	106%	107%	107%

Rotterdam – Dordrecht (45 km) – Tank vessels

water depth 5 m (Tmax = 4.5 m)

sailing regime	A1			
depreciation time	30/15		30/15	
fuel price	700		400	
crew cost	full	reduced	full	reduced
optimal dimensions	110x20x4.5	110x20x4.5	110x20x4.5	110x20x4.5
required ship rate (€/T)	€ 2.32	€ 2.22	€ 2.25	€ 2.15
optimal	100%	100%	100%	100%
135x15x3.5	114%	114%	115%	113%
110x11.45X3.5	130%	127%	129%	126%
86x9.5x2.5	169%	165%	169%	165%
+ 1 length step	101%	102%	102%	103%
- 1 length step	106%	105%	105%	105%
+ 1 beam step	103%	104%	103%	104%
- 1 beam step	107%	106%	107%	107%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step	111%	111%	111%	111%

sailing regime	A1			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	110x20x4.5	110x20x4.5	110x20x4.5	110x20x4.5
required ship rate (€/T)	€ 2.39	€ 2.29	€ 2.75	€ 2.65
optimal	100%	100%	100%	100%
135x15x3.5	114%	114%	114%	113%
110x11.45X3.5	131%	127%	129%	126%
86x9.5x2.5	170%	165%	167%	163%
+ 1 length step	101%	102%	102%	103%
- 1 length step	105%	105%	105%	105%
+ 1 beam step	103%	103%	103%	104%
- 1 beam step	107%	107%	107%	107%
+ 1 draught step	no data	no data	no data	no data
- 1 draught step	111%	111%	111%	111%

Water depth 3.3 m (Tmax = 2.8 m)

sailing regime	A1			
depreciation time	30/15		30/15	
fuel price	700		400	
crew cost	full	reduced	full	reduced
optimal dimensions	110x25x3	135x17.5x3	110x25x3	135x17.5x3
required ship rate (€/T)	€ 3.12	€ 2.97	€ 3.01	€ 2.88
optimal	100%	100%	100%	100%
135x15x3.5	118%	118%	119%	117%
110x11.45X3.5	135%	132%	135%	131%
86x9.5x2.5	129%	126%	130%	126%
+ 1 length step	100%	104%	100%	104%
- 1 length step	no data	106%	no data	106%
+ 1 beam step	no data	101%	no data	101%
- 1 beam step	107%	104%	108%	104%
+ 1 draught step	110%	113%	110%	113%
- 1 draught step	104%	107%	104%	107%

sailing regime	A1			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x25x3	135x17.5x3	135x17.5x3	135x17.5x3
required ship rate (€/T)	€ 3.21	€ 3.07	€ 3.70	€ 3.54
optimal	100%	100%	100%	100%
135x15x3.5	118%	117%	118%	118%
110x11.45X3.5	136%	133%	134%	132%
86x9.5x2.5	130%	126%	128%	125%
+ 1 length step	105%	104%	103%	104%
- 1 length step	100%	106%	106%	106%
+ 1 beam step	no data	102%	101%	102%
- 1 beam step	101%	104%	105%	104%
+ 1 draught step	112%	113%	112%	113%
- 1 draught step	103%	107%	108%	108%

Water depth 2.25 m (Tmax = 1.75 m)

sailing regime	A1			
depreciation time	30/15		30/15	
fuel price	700		400	
crew cost	full	reduced	full	reduced
optimal dimensions	135x25x2	135x25x2	135x25x2	110x25x2
required ship rate (€/T)	€ 4.62	€ 4.41	€ 4.52	€ 4.31
optimal	100%	100%	100%	100%
135x15x3.5	150%	149%	151%	150%
110x11.45X3.5	175%	170%	175%	171%
86x9.5x2.5	147%	143%	146%	142%
+ 1 length step	110%	110%	110%	100%
- 1 length step	101%	100%	101%	106%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	102%	101%	102%	107%
+ 1 draught step	114%	114%	114%	114%
- 1 draught step	106%	106%	107%	113%

sailing regime	A1			
depreciation time	30/15		20/10	
fuel price	1000		700	
crew cost	full	reduced	full	reduced
optimal dimensions	135x25x2	135x25x2	135x25x2	135x25x2
required ship rate (€/T)	€ 4.73	€ 4.51	€ 5.49	€ 5.28
optimal	100%	100%	100%	100%
135x15x3.5	149%	149%	150%	149%
110x11.45X3.5	174%	170%	174%	170%
86x9.5x2.5	147%	143%	145%	141%
+ 1 length step	109%	110%	109%	110%
- 1 length step	101%	101%	101%	100%
+ 1 beam step	no data	no data	no data	no data
- 1 beam step	102%	101%	102%	101%
+ 1 draught step	113%	114%	114%	114%
- 1 draught step	106%	106%	106%	106%

Samenvatting

Binnenvaartschepen voor efficiënte transportketens

De binnenvaartsector speelt een belangrijke rol in het vervoer van goederen van en naar een aantal van de belangrijkste zeehavens van Europa, waarbij jaarlijks meer dan 400 miljoen ton lading wordt vervoerd. Dit transport wordt uitgevoerd door ongeveer 14.000 schepen die hoofdzakelijk worden geëxploiteerd door kapitein-eigenaars met een enkel schip. Deze kleine ondernemers hebben weinig tot geen invloed op de markt waarin ze opereren en hebben slechts een klein aantal mogelijkheden om een concurrentievoordeel te verkrijgen ten opzichte van andere vervoerders. In dit proefschrift wordt een van de veelbelovende mogelijkheden om zo'n concurrentievoordeel te behalen onderzocht.

Kapitein-eigenaars kunnen hun concurrentiepositie niet verbeteren door een significante toename van hun marktaandeel tenzij ze samenwerken met een groot aantal andere vervoerders. Daarnaast zorgt de grote concurrentie op de primaire markt er voor dat zij bovendien hun marge slechts kunnen vergroten door kosten te verlagen, hun service te verbeteren of een nichemarkt te vinden. Toetreden tot een nichemarkt blijkt in de praktijk lastig voor kapitein-eigenaars. Ook zijn de opties die een kapitein-eigenaar heeft om zijn dienstverlening te verbeteren beperkt. Zijn kosten kan hij echter wel op verschillende manieren beïnvloeden, bijvoorbeeld door de manier waarop hij zijn schip financiert, door de intensiteit van operaties, door de snelheid waarmee hij vaart of door de vaste en variabele kosten te beïnvloeden middels het ontwerp van zijn schip.

Diverse andere manieren om de concurrentiepositie van binnenvaartondernemers te verbeteren vereisen actie van beleidsmakers, bijvoorbeeld door bemanningsreglementen aan te passen, de wettelijk toegestane wachttijden in havens te veranderen of door belastingen te wijzigen. Deze maatregelen versterken echter vooral de concurrentiepositie van een modaliteit ten opzichte van andere modaliteiten in plaats van de concurrentiepositie van een binnenvaartondernemer ten opzichte van een andere binnenvaartondernemer te verbeteren. Bovendien hebben individuele vervoerders over het algemeen onvoldoende invloed om zulke beleidswijzigingen te bewerkstelligen.

In dit proefschrift wordt geanalyseerd hoe individuele kapitein-eigenaars die in het stroomgebied van de Rijn opereren, dwz. het merendeel van de ondernemers in de Europese binnenvaartsector, in staat kunnen worden gesteld om hun concurrentiepositie te verbeteren zonder daarbij afhankelijk te zijn van anderen. Dit impliceert dat de aanpak die gevolgd moet worden om hun positie te verbeteren gericht dient te zijn op kostenreductie. Omdat het ontwerp van een schip een grote invloed heeft op de kosten van transport en er nog veel onbekend is over de relatie tussen het scheepsontwerp en de transportkosten, richt het onderzoek in dit proefschrift zich op kostenreductie door aanpassingen van het ontwerp van binnenvaartschepen.

Hoofdvraag

Er zijn verschillende manieren waarop een kostenreductie middels het ontwerp van een schip bereikt kan worden, waaronder een lichtere constructie, vergroting van de hoofdafmetingen en het verbeteren van de efficiëntie van de voortstuwing. De verbetering die na een eerste evaluatie de grootste besparingen lijkt mogelijk te maken is het vergroten van de hoofdafmetingen van het schip en daarom is het onderzoek in dit proefschrift hier op gericht.

Hoewel verwacht wordt dat het vergroten van de hoofdafmetingen van binnenvaartschepen zal leiden tot kostenreducties, brengt het ook een aantal nadelen met zich mee, aangezien grotere schepen een beperktere geografische flexibiliteit en langere overslagtijden hebben. Bovendien kan het zo zijn dat de grotere ladingpakketten die gepaard gaan met grotere schepen, leiden tot een toename van de voorraadkosten van verladers. In dat geval zal een groot schip niet competitief zijn als het vervoer kan aanbieden tegen dezelfde prijs als een kleiner schip, maar zal een lagere prijs moeten worden aangeboden. Als gevolg van het bovenstaande is het niet alleen nodig om te bepalen in welke mate veranderingen in de hoofdafmetingen van schepen leiden tot kostenreducties voor de vervoerder, maar ook om de invloed van scheepsafmetingen op de geografische flexibiliteit en de totale logistieke kosten van een verlader te analyseren.

De bovenstaande overwegingen leiden tot de formulering van een hoofdvraag en vier deelvragen. De hoofdvraag luidt:

Welke lengte, breedte en ontwerpdiepgang van een binnenvaartschip leiden tot de beste concurrentiepositie van kapitein-eigenaars?

Deze vraag kan alleen beantwoord worden als de volgende vier deelvragen beantwoord worden:

1) *wat zijn de praktische bovengrenzen voor de afmetingen van binnenvaartschepen?*

Het beantwoorden van deze vraag geeft inzicht in de infrastructuur- en marktgerelateerde grenzen van het onderzoek en voorkomt dat er valse optima gevonden worden in de vorm van schepen die weliswaar tegen zeer lage kosten kunnen opereren, maar niet voldoende lading kunnen aantrekken om succesvol te zijn, bijvoorbeeld doordat ze slechts in een beperkt geografisch gebied met een beperkte vraag naar vervoer kunnen varen.

2) *Hoe beïnvloeden de hoofdafmetingen van een binnenvaartschip haar bouwkosten en die technische eigenschappen die de kosten van vervoer beïnvloeden?*

Als deze vraag beantwoord is, komen ontbrekende data beschikbaar die nodig zijn voor een goede analyse van de kosten en baten van het vervoeren van lading met een schip met een willekeurige combinatie van lengte, breedte en ontwerpdiepgang.

3) *Hoe beïnvloeden de hoofdafmetingen van een binnenvaartschip de kosten van het gebruik van dit schip?*

De gemiddelde kosten van de vervoerder en de vervoersprijzen liggen in een zeer competitieve markt als de binnenvaartmarkt in de rijncorridor over een langere periode dicht bij elkaar. Daardoor maakt beantwoording van deelvraag 3 het mogelijk om te bepalen in welke mate een vervoerder zijn diensten tegen een lagere prijs kan gaan aanbieden. Het antwoord op deze vraag is niet alleen afhankelijk van de eigenschappen van het schip en de lading, maar wordt mede bepaald door de eigenschappen van de transportroute en de tijd die het schip in de haven doorbrengt.

4) *Hoe beïnvloeden de hoofdafmetingen van een binnenvaartschip de totale logistieke kosten van een verlader?*

Hoewel de prijs die een verlader moet bepalen voor vervoer een belangrijke rol speelt in zijn keuze voor een vervoerder, betekenen grotere schepen mogelijk ook grotere partijen, die zijn voorraadkosten zullen beïnvloeden. Hierdoor zal een verlader niet altijd de voorkeur geven aan de goedkoopste vervoersmodus, maar zal hij streven naar minimale totale logistieke kosten. Als gevolg hiervan moet deelvraag 4 beantwoord worden om te kunnen bepalen welke hoofdafmetingen tot de beste concurrentiepositie voor de binnenvaartondernemer leiden. Buiten de variabelen die van belang zijn voor deelvraag 3 worden hier ook de waarde van de vervoerde goederen en het jaarlijks benodigde volume van de verlader van belang.

Als deelvraag vier beantwoord is, is de hoofdvraag dat ook. Als gevolg hiervan is het mogelijk om vast te stellen wat de optimale afmetingen van een binnenvaartschip zijn als functie van de eigenschappen van de vaarroute, de waarde van de vervoerde goederen en het jaarlijks benodigde volume van de verlader.

Aanpak

De eerste deelvraag wordt beantwoord door een analyse van de infrastructurele beperkingen en van de mate waarin bepaalde scheepsafmetingen de toegang tot de markt beperken. De volgende stappen in het onderzoek maken het mogelijk om de relevante eigenschappen van schepen vast te stellen als functie van lengte, breedte en ontwerpdiepgang. Deze eigenschappen zijn de hoeveelheid lading die een schip per keer kan vervoeren, de bouwkosten van het schip en de operationele kosten.

Door een analyse van bestaande literatuur is vastgesteld dat noch de benodigde data, noch de benodigde methodes beschikbaar zijn om deze eigenschappen vast te kunnen stellen voor binnenvaartschepen met niet-standaard (combinaties van) lengte, breedte en/of ontwerpdiepgang.

Als gevolg het ontbreken van deze data en methodes en omdat alle drie de eigenschappen een complexe en directe relatie hebben met het ontwerp van een schip, is er een model ontwikkeld waarmee het mogelijk is om grote series conceptontwerpen van binnenschepen te maken waarin lengte, breedte en ontwerpdiepgang systematisch worden gevarieerd. Voor deze ontwerpen worden de bouwkosten bepaald, evenals de technische eigenschappen die van belang zijn bij het berekenen van het brandstofverbruik en de hoeveelheid lading die vervoerd kan worden. Als een laatste stap met betrekking tot de bepaling van de technische eigenschappen van een schip zijn er vuistregels opgesteld voor het schatten van het gewicht en de bouwkosten van binnenschepen.

Hierdoor is een aantal cruciale gaten in de kennis gevuld, maar is het nog niet mogelijk om de hier boven genoemde eigenschappen te bepalen. De hoeveelheid lading die een schip mee kan nemen wordt namelijk niet alleen bepaald wordt door de specificaties van het schip en de lading, maar kan ook beïnvloed worden door de waterdiepte en de hoogte van bruggen. Bovendien beïnvloeden waterdiepte en stroomsnelheid het brandstofverbruik van een schip en daarmee de kosten. Ook beïnvloeden de lengte van de route en de hoeveelheid tijd die in havens worden doorgebracht het aantal rondreizen dat in een jaar gemaakt kan worden, wat op zijn beurt weer de benodigde vrachtprijs per eenheid vervoerde lading beïnvloedt.

Om deze zaken aan te pakken is een tweede model ontwikkeld waarmee de benodigde vrachtprijs per eenheid vervoerde lading bepaald kan worden als functie van de scheepsafmetingen en de eigenschappen van de route. Tevens maakt dit model het mogelijk om het effect van internalisering van externe kosten te berekenen en om een vergelijk te maken tussen vervoer over water, gecombineerd vervoer en vervoer over de weg. Daarnaast is het mogelijk om met het model de totale logistieke kosten te berekenen, waardoor het mogelijk wordt om ook de laatste deelvraag te beantwoorden.

Als een laatste stap in het onderzoek wordt een aantal case studies uitgewerkt waarin de optimale afmetingen worden bepaald voor droge lading schepen, tankschepen en containerschepen op vier routes (Rotterdam naar Dordrecht, Nijmegen, Duisburg of Koblenz) voor drie verschillende waterstanden. In elk van deze gevallen zijn de beoordelingscriteria (A) de benodigde vrachtprijs en

(B) de totale logistieke kosten. Om de analyse compleet te maken is ook bekeken in welke mate het internaliseren van de relevante externe kosten de optimale afmetingen beïnvloedt en in welke gevallen schepen wel of niet kunnen concurreren met weg- en spoorvervoer.

Conclusies

De praktische bovengrenzen van de afmetingen van binnenvaartschepen die gebruikt worden in het stroomgebied van de Rijn liggen bij een lengte van 186.5 meter en een breedte van 22.9 meter. Dit zijn de grootste afmetingen die een binnenvaartschip toestaan om de zeehavens van Amsterdam, Antwerpen, Vlissingen, Gent en Terneuzen aan te doen, evenals het grootste deel van de binnenhavens langs de Rijn. Ondanks het feit dat de CCNR stelt dat de maximale lengte van ondeelbare schepen 135 meter is, worden de bovengenoemde maximale afmetingen van 165.5 x 22.9 meter gebruikt als de bovengrens in alle analyses. De gedachte hierachter is dat het de moeite waard is om vast te stellen of het significante voordelen oplevert om schepen te gebruiken die langer zijn dan 135 meter. Als dit het geval zou zijn, zou met de CCNR bediscussieerd moeten worden of de lengtegrens verhoogd kan worden of er zou een technische oplossing gevonden moeten worden om een langer schip deelbaar te maken.

De case studies tonen echter aan dat de optimale lengte van binnenvaartschepen meestal niet of nauwelijks groter is dan de maximale lengte van bestaande schepen. Hun breedte is meestal wel groter dan die van dan bestaande schepen en ze hebben vrijwel altijd een ontwerpdiepgang die overeen komt met de maximale diepgang bij normale waterniveaus op de route. De uitzondering hierop wordt gevormd door containerschepen, waarvan de optimale ontwerpdiepgang nooit groter is dan 3.5 meter.

Welke afmetingen optimaal zijn hangt echter sterk af van de eigenschappen van de route en de logistieke keten. Goederen met een lage waarde gecombineerd met een grote vraag van de verlader leiden tot een voorkeur voor schepen met een groot laadvermogen. Goederen met een hoge waarde en/of een kleine jaarlijkse vraag van een verlader leiden daarentegen tot een voorkeur voor schepen met een kleiner laadvermogen. Lage waterstanden leiden tot lage diepgangen, waardoor de optimale lengte en breedte toenemen. Ook doen de lange wachttijden die toegestaan zijn in havens een groot deel van het voordeel teniet dat kleine schepen kunnen behalen ten opzichte van hun grotere tegenhangers door een kortere omlooptijd als ze direct geladen en gelost worden.

Internalisering van externe kosten en wijzigingen in de kostenelementen die de vereiste vrachtprijs bepalen (brandstofkosten, bemanningskosten, afschrijvingstermijn,….) leiden doorgaans niet tot grote wijzigingen in de optimale scheepsafmetingen aangezien zij alle schepen op een soortgelijke manier beïnvloeden. Zij hebben echter wel een sterke en directe invloed op de absolute waarde van de vereiste vrachtprijs.

Met betrekking tot de relatie tussen scheepsafmetingen, laadvermogen, overige technische specificaties en bouwkosten van binnenvaartschepen wordt geconcludeerd dat bestaande methoden ontoereikend zijn om deze relatie met voldoende nauwkeurigheid vast te stellen. Het onderzoek dat in dit proefschrift is uitgevoerd dicht daardoor een cruciaal gat in de beschikbare kennis, terwijl de opgestelde vuistregels voor gewicht en kosten op een zinvolle manier bijdragen aan de toegankelijkheid van deze ontwikkelde kennis over de kapitaalskosten, capaciteiten en vrachtprijs van binnenvaartschepen.

Met betrekking tot kostenstudies van binnenvaart en intermodaal transport toont dit onderzoek aan dat de technische eigenschappen, bouwkosten en operationele kosten van binnenvaartschepen over het algemeen in sterke mate worden vereenvoudigd. Het onderzoek toont ook aan dat de daadwerkelijke benodigde vrachtprijs van een schip in hoge mate afhankelijk is van de kostenstructuur, de route waarop gevaren wordt en de tijd die in havens wordt doorgebracht. Hierdoor kan het vereenvoudigen van de beschrijving van het schip en zijn operatie een negatief effect hebben op de kwaliteit van een analyse. Dit benadrukt het belang van een voldoende gedetailleerde representatie van een schip en de manier waarop het wordt gebruikt wanneer de transportkosten en/of de concurrentiepositie van een binnenvaartschip ten opzichte van andere modaliteiten worden geanalyseerd.

Curriculum vitae

Robert Hekkenberg was born In Hilversum, the Netherlands, on May 4th 1979. After completing his secondary education at the Sint Vituscollege in Bussum in 1997, he started his study Marine Technology which he completed with honors in 2004.

Subsequently he was employed as a researcher at Delft University of Technology, department of Marine Technology & Transport Technology, section Ship Design, Production & Operation. During this time he performed research in the field of inland shipping as well as in the field of ship production. For his work on modeling of inland waterway transport, he received the 'VNSI-Timmersprijs' in 2006.

The appointment to the position of assistant professor at Delft University of Technology, department of Marine Technology & Transport Technology, section Ship Design, Production & Operation in 2007 marked the start of his PhD project, which was executed in parallel to teaching activities, research in the field of ship production and research in the field of ship design.

After the completion of his PhD, Robert Hekkenberg will continue his work at Delft University of Technology.