Development of a pushed barge with optimum performance on shallow draughts

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Development of a pushed barge with optimum performance on shallow draught

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ABSTRACT

The volume of goods traffic across Europe has significantly increased over the years, due to the continuing internationalization of trade and production. The demand for freight transport across Europe is met largely by inland waterway transport which is characterized by a high level of cost effectiveness and efficiency. However, these inland waterways are been faced with numerous navigational challenges one of which is either the seasonal or protracted low water period which often manifests to an interruption in the logistics chains and causes significant economic losses as only a comparatively low volume of transport can be achieved within these periods. In such cases, inland cargo vessels would normally sail with a lower draught and higher unit cost but there are, however, periods when navigation is completely impossible. Studies also reveals that the frequency of the low water periods are projected to even increase in the future leading to a question of how to strengthen the resilience of inland navigation transport ahead of these phenomena.

This study investigates the possibility for improvement of cargo transport within the European inland water ways by exploring the design and optimization of a specific type of cargo vessel capable of coping with the events of shallow water while also maintaining a plausible solution in normal water conditions. The proposed vessel is a pushed barge designed and optimized for high flexibility in operation and cargo type transport in shallow and normal water conditions. The traditional ship design principles are been applied for the initial design and realization of the proposed vessel while various tools available for the optimization of the design are implemented ahead of the water level restrictions. The proposed vessel is optimized with the aim of minimizing the overall light ship weight through structural weight reduction by a careful assessment of the vessel's main dimensions and hull structure while conforming to structural, economic and production constraints. Considerable reduction in structural weight was realized through the application of design bending moments obtained by direct calculations as opposed to traditional rule-based design bending moments. Proof of structural strength for the optimized structure is then performed through analytical longitudinal strength analysis and subsequently validated through global finite element analysis of the hull structure. The design performance at various operating conditions is then evaluated and compared to existing concepts.

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List of Abbreviations and Symbols

CAD – Computer Aided Design

CAE – Computer Aided Engineering

CAM – Computer Aided Manufacturing

CCNR - Central Commission for the Navigation of the Rhine

CEMT - Conférence Européenne des Ministres des Transports

DNV – Det Norske Veritas

ES-TRIN – European Standard laying down Technical Requirements for Inland Navigation Vessels

FEM – Finite Element Method

GL – Germanischer Lloyd

IWT – Inland Water Transport

IWW – Inland Water Way

LR – Lloyd‘s Register

PMB – Parallel Middle Body

TEU – Twenty-foot Equivalent Unit

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1. INTRODUCTION

1.1. Background and Motivation

The volume of goods traffic across Europe has been rising steadily and sometimes rapidly over the years and a shift of freight from road to water is one of the European strategies to curb the adverse effects of the growing transport volume. Marine transport has increased significantly, due to the continuing internationalization of trade and production, and consequently more cargo is transported via waterways. Various sectors rely on low-cost and consistent freight transport. This applies both to sectors whose main focus is on bulk cargo, for instance the energy, coal and steel, and chemical industries, and to the transport of containers (KLIWAS, 2016).

The demand for freight transport is met largely by inland waterway transport especially in the Rhine corridor because of its good infrastructure conditions and is often characterized by a high level of cost effectiveness and efficiency. However, these inland waterways are been faced with numerous navigational challenges one of which is either the permanent, seasonal or protracted low water period which often manifests to an interruption in the logistics chains and causes significant economic losses as only a comparatively low volume of transport can be achieved on the inland water ways within these periods (Hendrickx & Breemersch, 2012). In such cases, inland cargo vessels would normally sail with a lower draught and higher unit cost in an inefficient regime due to falling load factor and speed but there are, however, periods when navigation is completely impossible, even for the smaller vessels.

An examination of historical data on low water levels in the past (CCNR, 2019a) revealed that years with a high frequency of low-water days were also a very common occurrence at the beginning of the 20th century, in the 1940s and in the 1970s. These historical data demonstrate that marked fluctuations in navigational conditions are highly likely to recur in future. Also, in a research study on climate change effects on inland water transport (KLIWAS, 2016), it seems that the frequency of low water periods could even increase in the future.

Furthermore, a report published by the Central Commission for the Navigation of the Rhine (CCNR, 2019a) shows that the prolonged period of low water over the years especially in the second half of 2018 which was particularly pronounced on the Rhine, on its tributaries, on the Upper and Middle Danube, and on the Upper and Middle Elbe had led to a sharp decline in the inland freight transport and had significantly impacted the freight traffic, industrial production and freight rates. Major logistical chains, notably for the delivery of raw materials (iron ore, coal) and for the delivery of final products of the chemical and petrochemical industry, were heavily affected.

Figure 1 shows the monthly goods transport on the Rhine between January 2000 and December 2018 together with a 6-month moving average. Low-water periods are shaded in blue and are recognizable as V-shaped reductions of cargo traffic. The major part of the financial crisis (in 2008, 2009 and 2010) is shaded in yellow.

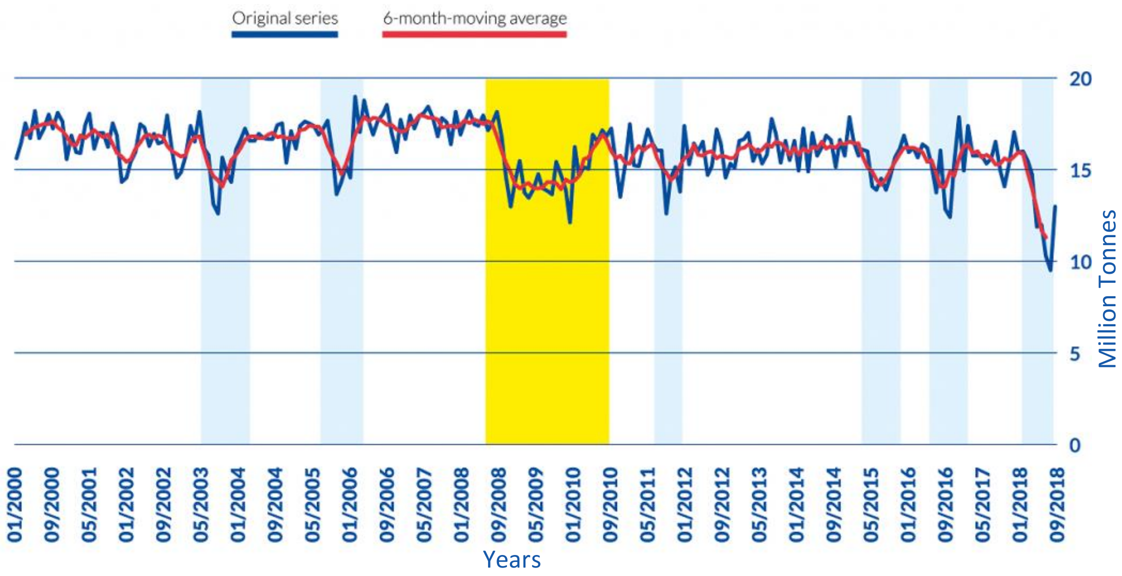

Figure 1: Monthly goods Transport on the Traditional Rhine (In Million Tonnes, 01/2000 – 12/2018), Financial crisis and low-water periods (CCNR, 2019a)

As shown in Figure 1, the low water period in the second half of 2018 had a stronger effect on goods transport than the previous years and had materialized to a drastic increase in freight rate for different dry cargo segments. The freight rate was estimated to have increased by 2.5 times higher than normal in October and November 2018 (CCNR, 2019a). The decline in the current effective carrying capacity was so severe that German companies faced serious supply bottlenecks and production problems. The water levels are seen to get lower each year and extra flotation equipment is needed to support vessels to cross certain parts of the waterway. The drop in the waterway capacity had millions of tons of goods switched to road and rail transport leading to another wave of severe bottlenecks in shipping as road and rail capacity in Europe is unable to support the volume being redirected (Gonen, 2019).

In view of this phenomena, a question of how to strengthen the resilience of inland navigation transport had certainly been an important question to be addressed. They also point to the necessity of a partial rethink and modification of the existing inland water way logistical concepts and infrastructures. Some of the proposed solutions are targeted towards waterway managers with view of adapting existing infrastructures to some degree in order to limit or to avoid water level decreases. The upgrading of these waterways to a higher capacity is planned at long term but often restricted by technical, environmental and / or for budgetary reasons. In addition to regular maintenance, improvement of the navigability could require realization of major infrastructural projects aimed at increase of the river depth; these are, however, often met with disputes over concerns of the effects of such activities on the natural habitat of the river (WWF, 2009).

On the other hand, the standard self-propelled inland vessels are typically designed for “deep” draughts, that are more suitable for the “regular” water levels (Bačkalov, et al., 2016). However, in low water periods, as only small ships with relatively high unit cost can be serviced. A possible solution can be to use barge types, which are adjusted to specific navigable conditions to increase efficiency and or loading capacity compared to standard self-propelled inland vessel (Johan , et al., 2018). Motivated by this context, various concepts are been implemented most of which tends to depart from the well-established design of the European inland cargo vessels in an attempt to put forward a concept that would be able to cope with the present-day navigation conditions, that is, in case that the large-scale upgrade of infrastructure does not take place in foreseeable future.

1.2. Aims and Objectives

With regards to the afore mentioned challenges posed by the effects of shallow water on European inland water transport, the main aims of this thesis are as follows:

- To design a cargo vessel taking into account the design dimensions suitable to obtain an optimum draught to tonnage relation capable to cope with events of shallow water and also plausible in normal water conditions.
- To implement a structural optimization technique for the optimization of the designed vessel with the aim of obtaining a light weight structure which can then be translated into meaningful payload for normal operating conditions and also tackle the reduced draft requirements in extreme conditions of shallow water.
- To design a vessel with high flexibility in configuration with different vessels types and barges and also, high flexibility in cargo type (container, dry bulk, project cargo,

tank) as well as ability to transport dangerous good in limited amount (ADN Container).

1.3. Scope and Limitations

Although the European inland water ways and transport is characterized by a number of water ways (The Rhine, the Danube, the Elbe etc.) and serviced by a number of different types of vessels (Multi-purpose dry cargo vessels, Tankers vessels, Container vessel, Roll-on/Roll-off-vessels etc.) differing in sizes and tonnage capacities tailored to meet the various demands and transport volume based on the types and shapes of cargo, this study however, focuses on the development and optimization of a particular type of vessel (push-barge) utilized for dry bulk cargo and container transport. This type of barge offers many advantaged over the standard self-propelled motor vessels, one of which is the flexible and robust operating possibilities. This type of barge could be operated in combination with other barges, motor vessels or push boats depending on the current demand or the adaption to waterway requirements. Larger number of interlinked barges are also possible with flexible operation in relations with several ports of call and also, the possibility to leave behind or picking up of individual barges as compared to self-propelled.

On the other hand, reports (Johan , et al., 2018) shows that that the main part of the European inland water vessel fleet is based in the Rhine basin. This is on one side related to the higher nautical standards on this river basin and on the other hand due to the strong economic centers located along these river basins and subsequently with the generally higher transport demand. Hence, this study targets to present a plausible solution to meet the large transport demands in the Rhine basin through the development of the specified vessel type with view of the afore mentioned challenges. The solution is thus focused but not limited to the Rhine basin. Of course, the solution proposed could also be implemented in other parts of the European inland water ways which shares similar characteristics.

1.4. Methodology

The method employed within the context of this study is the application of the traditional ship building practices to the design and realization of a cargo vessel capable of tackling the transport and navigational challenges mentioned in 1.1 above. The design is realized by taking an initial turn in the ship design spiral which often entails the collection of the basic requirements and vessel specifications and proceeds to making a first approximation of the components forming the base for the preliminary design actualization of the vessel. Some of the bottle necks actualized within this context are the main proportioning and arrangements of the proposed vessel, hull form and hydrostatics, structural idealization and strength analysis, weight estimations, intact stability, preliminary powering and cost estimates as required by designed vessel.

The study proceeds to implement and apply optimization techniques toward the structural optimization of the designed vessel which is aimed at minimizing the overall light ship weight through structural weight reduction and taking advantage of the various existing tools/ techniques already established for structural optimization and testing of ships at the early-stage of the design. The problem of structural optimization becomes complex if several methods are considered in one algorithm (Sekulski, 2009), therefore in this thesis, the emphasis is on size optimization (scantling optimization), by modifying the thickness of the plates and structural members and also material optimization, with the main objective on reducing the lightweight of the designed vessel. The main optimization technique is first applied to the midship section of the vessel and then validated by the finite element analysis with respect to the various strength requirements. This is achieved by a realistic modeling of the load due to light ship weight, deadweight and hydrostatic pressure while taking into consideration, the necessary extreme operating and loading conditions the ship might encounter in her operating cycle. The minimum structural weight is made the optimization objective, and the material yield strength requirements, buckling strength requirements and rule requirements are taken as constraints.

A number of tools and software are utilized for design of the specified vessel type and for the implementation of the optimization methods. Each software served a different purpose and are interlinked to the other. The software utilized for this study are presented in 1.6 below. The methodology for the execution of thesis work is done considering the various established design and optimization techniques while taking advantage of the feature offered by these tools and software.

1.5. Structure of Report

The objective of this thesis has been explored within various contexts and consequently divided into different sections forming the structure of this report. The major sections utilized within the framework of this report are as follows:

- **Chapter 2** – This chapter offers an overall overview on the inland cargo vessels operated within the major European inland water ways and also explores the various techniques employed by different establishments in optimization of these vessels in view of tackling the issues associated with shallow water restriction. This chapter also offers a theoretical approach to the various structural optimization techniques most commonly used in the early ship design phase and thus defines the method employed for the actualization of this project. This also provides an insight on the various plausible objective, constraints and design variables to be considered in structural optimization of such vessel as well as the necessary checks performed as regards the validation the obtained solution.
- **Chapter 3 –** This chapter dives into to the design aspect of the proposed vessel. Here, the results from the various segments such as the owner's requirements and specifications, general arrangement plan, hull form and lines plan, structural arrangement and steel plan, Weight distribution and Tank plan, basic out fittings and the demonstration of structural strength which constitutes the preliminary design of the proposed vessel are presented. Hence, an initial design of the proposed barge is been presented within this chapter.
- **Chapter 4** – In this chapter, the initially designed vessel is been optimized by employing the various optimization techniques outline within the context of this report. The details of the method, tools, assumptions and justifications of the various parameters such as load cases, boundary conditions etc. utilized in the actualization of the optimization process is been conveyed within this chapter.
- **Chapter 5 –** Here the results obtained from the structural optimization with respect to the considered load cases are been presented along with an evaluation of the design performance with respect to the design objectives and in comparison, with similar vessels.
- **Chapter 6** – Presents the conclusions from the analysis of the design.

1.6. Software Used

1.6.1. *Siemens NX*

Siemens NX is an advanced high-end CAD/CAM/CAE software which offers variety of tools, for the Design (e.g., parametric and direct solid/surface modelling), Engineering analysis (e.g., statics and dynamics, using the finite element method) and also for the Manufacturing finished design by using included machining modules. The software is made up of different applications some of which were utilized for the actualization of this thesis. The application modules used within the context of this thesis are the Modelling application which was used to model the required hull form and basic exterior components of the proposed designs, the Ship Basic Design application which was used to model the structural components of the vessel, the Pre/Post which comprises of the CAE preparation tool, FEM and Simulation tools used for the finite element analysis of the optimized structure considering different load cases and boundary conditions specified by the designer. The inputs from the designer are the various shells required to shape the structure, the structural component grid definition and assignment, the various loads and boundary conditions while the outputs are the resulting structural weight of the vessel and the global or local strength analysis.

1.6.2. *MAXSURF – Modeler and stability module*

MAXSURF software which provides integrated tools for hull modelling and optimization, comprehensive stability, motions & resistance prediction, structural modelling and structural analysis, was utilized within the frame work of this study. The MAXSURF modeler was first used to perform the initial hydrostatic analysis of the designed hull form which was then used as input in the MAXSURF stability module for the weight distribution, total weight estimation and consequently generate the bending moments and shear forces required for the longitudinal strength analysis of the design vessel. The stability module as the name implies was also used to perform the necessary stability checks on the designed vessel with respect to the criteria set by the user.

1.6.3. *AUTOCAD*

The AUTOCAD which is usually used for designing and drafting allows a user to conceptualize ideas, product designs and drawings to the required level of technical accuracy, perform rapid design calculations and simulations. The software was used had in hand with the siemens NX software for the actualization of the ship's main structure and dimensioning. The results from this software are the general arrangement plan and steel plan showing the various divisions and dimensions of the ship structure along with the auxiliary equipment allocations which was then used as an input for the structural modelling of the ship in the siemens NX software.

1.6.4. *Microsoft Excel*

Microsoft excel software provides various features that makes bulk data analysis very easy. The software was used to generate the various inputs such as the weight distribution of the vessel components required for the longitudinal strength calculation which yields the maximum bending moments and shear forces required for the assignment of loads for the Finite element analysis of the structure in Siemens NX.

The software was also utilized for the development of the code required for the structural strength assessment through the traditional midship section analysis specified in accordance with the class rules. The excel code generated which contains options for various structural element sizes, orientations and stiffening types was also used to create a first run of the structural optimization of the vessel by altering various plate and profile thicknesses within the midship section assigned while setting their limits before proceeding to validate the results by finite element analysis.

2. LITERATURE REVIEW

2.1. Overview of the European Inland Water Transport

2.1.1. *Effects of climate change on the European water level*

Inland water ways transport (IWT) is generally characterized by a high degree of reliability and safety compared to other transport modes. However, against the background of the climate change, new concerns are starting to raise attention. IWT is expected to be more sensitive to climate change aspects than other transport modes, e.g., in terms of water level fluctuations and resulting effects on cost and reliability (Hendrickx & Breemersch, 2012). Climate effects are influencing inland navigation throughout a variety of issues (Radojčić, et al., 2021): low-water level conditions, high-water level conditions, and ice conditions. For IWT the low-water level conditions are more disruptive than high-water level conditions from the economic and navigation point of view. Consequently, by far the most important topic is the low-water level condition as it significantly affects the IW vessel design primarily by limiting its draught (ECCONET, 2012a). This limits the capabilities of IW transport and results in increased freight rate, prolonged delivery periods and subsequently decline in the demand for inland water transport.

2.1.2. *Water level and prediction method for Inland Water Transport*

KLIWAS (2016) predicted prolonged dry summer periods with an increase of the air temperature for the Danube and the Rhine area. Amongst the conclusions is that the maintenance strategies due to river bed elevation and sediment balance could have more influence on the water depth than the lower precipitation. Figure 2 shows a diagram presented by (CCNR, 2019a) with a purpose to illustrate the reoccurrence of low waters in the future. The illustration shows the low-water level recordings for the Rhine in the past 200 years. The limited number of prolonged low water periods years before 2018 in the Rhine might have also contributed to the increase-in-scale trend and optimization of the new-buildings according to high water level conditions and as a consequence, larger vessels, even empty, were unable to reach their destination in November 2018. That led to the conclusion to reconsider the vessel design and to optimize them for low water conditions too (CCNR, 2019a).

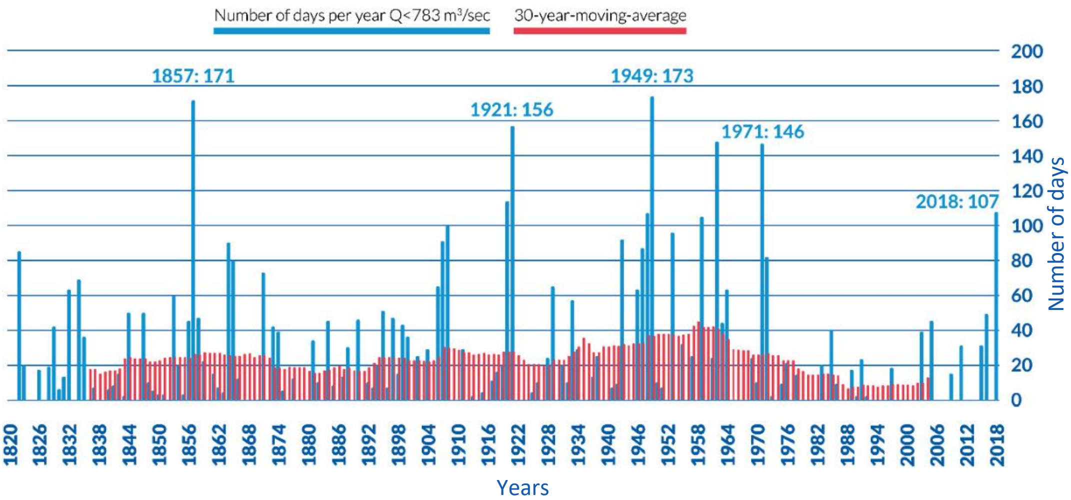

Figure 2: Number of low water days per year at Middle Rhine. Source (CCNR, 2019a)

The abovementioned year 2018 was bad for IW shipping and consequently, initiated several studies targeted toward estimating the effects of changing water depths on the capacity of inland ships and developing possible models to tackle the challenges posed by these effects.

The water level prediction methods on the other hand, plays an important role in the European inland water navigation as without knowledge of the water level and available draughts it will be difficult for vessels to load and navigate efficiently. In order to ensure that cargo vessels carry an optimum load which is also safe, present water levels along the route need be known before loading takes place. To this effect, various measuring stations (gauges) have been installed along the Rhine and its tributaries. These gauges give daily equivalent water level, possible draught and safe load for vessels at different regions.

For the Rhine water way, there are 3 most important gauges which are the Kaub, Duisburg and Emmerich gauges (CCNR, 2021). The Waterway and Shipping Administration endeavors to achieve a minimum navigation channel depth for each gauge station, also under critical low water conditions. This minimum depth is represented by the vertical distance below a critical low water level. The critical low water level is known as equivalent water level. It is normally exceeded on at least 95% of all days per year.

For the design of a new vessel or modification of an existing vessel with view of tackling the shallow water situation, an insight into the history of the water level along the specified route and how they are assessed is a very important aspect to be considered. Kaub gauge however, is often used as the key parameter for shipping on the Upper and Middle Rhine as water levels around the measuring point are some of the lowest along the course of the Upper and Middle Rhine (CCNR, 2021).

With a focus on Kaub, an equivalent water level (78 cm) and method for estimation of minimum depth of navigation channel is established. The available draught for a vessel at a certain gauge station is calculated as:

Possible or available draught = Minimum navigation channel depth + (actual water level – equivalent water level) - under keel clearance. Eq (1)

As illustrated in Figure 3, with the actual the actual water level specified in the illustration, applying the formula, we get an available draught of 319 cm. However, in times of extreme low water conditions, with an actual water level of about 25 cm at Kaub for example, which is the regarded as the lowest known water level (ELWIS, 2021), the available draught could only be realized as 105 cm.

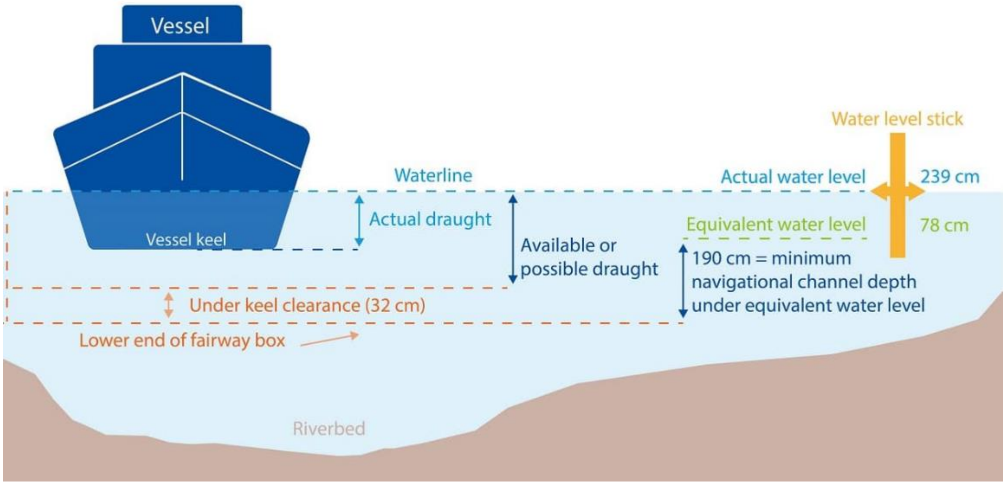

Figure 3: Actual water level, actual draught, equivalent water level, minimum navigation channel depth and possible or available draught at Kaub/middle Rhine (CCNR, 2021).

2.2. Overview of Representative Ship Types

The European inland fleet is characterized by its great array of vessel types which are designed to meet the demands for the varieties of cargo transported within the continent. There are a great number of parameters that could be used to describe and classify them. However, the target group here are cargo vessels and these can be further distinguished by the kind of commodity, most generally into dry-cargo ships and tankers.

The two main types of cargo vessels which are used in varieties of sizes and specifications on the European waterways are the self-propelled motor freight vessel (MV) and the pushing unit ([PU] consisting of a push tug and non-motorized barge). As such they could be classified based on the propulsion technology on the one hand and vessel type (container, dry cargo, liquid cargo etc.) on the other hand (Johan , et al., 2018). Besides a division in self-propelled vessels and convoys consisting of unpropelled barges pushed by another ship, they can also be classified by ship types based on their main dimensions. These ship types are identified as generalized ships representing a group of ships with similar size, load carrying capacity, and hydrodynamic properties (Zigic, et al., 2012).

The class of a waterway is determined by the horizontal dimensions of the vessels or pushed units, especially by their width. On the Rhine River common ship types are besides the Gustav-Koenigs and the Johann-Welker class the large cargo vessels. They are operated stand-alone as well as so-called coupled convoys. Most pushed convoys are operated with 4 barges, although 6-barge trains are also possible at the Duisburg-Rotterdam track. Hence, the main ship types and their sizes as well as their advantages in terms of maneuverability, in different traffic situation and environmental conditions are described in the subsequent sections.

2.2.1. *Motor Cargo Vessel*

In general, the Motor Cargo Vessel (or self-propelled vessels) is a single-hull ship type often equipped with a motor drive and cargo hold suitable for various types of cargo: Liquids, bulk products, containers or special cargo. They can be subdivided into dry cargo vessels, motor tankers, container and Ro-Ro vessels. There is a wide variety in sizes ranging from a small 38-40m long “Peniche/Spitz class” having a cargo capacity of only about 300 t at 2.5 m draught to a large 135m long and up to 17m wide river ship with on average about 3500t capacity at the same draught (Interreg, 2019). The “large motor cargo vessel” acts as the so called “lead ship” for the dimensioning of the extension and construction of canals. It offers many advantages (Johan , et al., 2018) some of which are summarized as follows:

- The possibility for the usage in vessel types with commodity-specific auxiliary equipment (i.e., pump system),
- The depiction of the right speed and maneuverability when used on free-flowing rivers with higher stream velocities and favorable fuel consumption in connection to relevant vessel types,
- Minimal crew concept, for example it can be operated by only a 2-man team.

An overview of some of the basic type of motor vessel types typical for the Rhine along with their main dimensions and corresponding cargo capacities are given in Table 1 below.

Table 1: Vessel types typical for the river Rhine and main dimensions (L, B, Tmax and Tmin) with the corresponding cargo capacities (Zigic, et al., 2012)

Vessel type	Dimensions (LxB)	Tonnage capacity at different draughts
JOWI-type (containership)	135 x 16.80 m	Payload about 5.200 t at 3.50 m and 1.300 t at 1.60 m
Large cargo vessel (GMS-type, 135m)	135 x 11.40/11.45 m	Payload about 3.800 t at 3.50 m and 670 t at 1.60 m
Large cargo vessel (GMS-type, 110m)	110 x 11.40/11.45 m	Payload about 2.900 t at 3.50 m and 400 t at 1.60 m
Johann Welker-type (Extended version or Europe-type)	85 x 9.50 m	Payload about 1.400 t at 2.60 m and 300 t at 1.20 m
Gustav Koenigs-type (extended version)	80 x 8.20 m	Payload about 1.100t at 2.50 m and 250 t at 1.10 m

2.2.2. *Pushed Convoys*

Pushed convoys are often referred to units consisting of a pusher (motorized vessel used for pushing) and one or more non-motorized pushed lighters or pushed barges that are firmly attached to the pushing unit. Depending on the waterway prospects, diverse formations are possible. On the Lower Rhine, on the ARA port relations (Amsterdam, Rotterdam, and Antwerp) and the Ruhr area, up to 6 European barges can be connected. On the Middle and Lower Danube, a pushing unit with up to 9 interlinked barges can be used (Johan , et al., 2018).

The term coupled formation or pushed-coupled convoy are often used when a motor cargo vessel is used for propelling the formation or convoy instead of a pusher. A coupled formation consists of one motor cargo vessel and lighters or barges. Often the barge’s aft is fitted adapted to the ship’s bow shape. The barge in front is equipped with a pump jet to assist maneuvering. Whereas a pushed-coupled convoy has one to two lighters or barges coupled to the motor cargo vessel on its sides with additional lighters or barges placed in front of it (Interreg, 2019). In this case the merits of the self-propelled motor vessel are combined with those of the pushed tow system increasing the possibility to individually control the capacity, depending on demand and relation, which would not be possible in that manner with single, self-propelled motor vessels.

Boats that are not transporting cargo themselves and are pushing one or more barges are referred to as push boats. Push boats on the river Rhine are built with a size of up to 40 x 15 meters with a draft of about 1.90m. The big push boats, which can carry up to six barges, are mostly equipped with diesel engines with a total power of about 4000 kW. A voyage from Rotterdam to Duisburg and loaded with 10,000 tons of ore, takes 26 hours. The empty downstream 12 hours. These push boats are operating 24/7 (Johan , et al., 2018).

Some of the key advantages of the pushed convoys over the single self-propelled vessel types are highlighted as follows:

- Variability of pushed tow systems depending on the current demand or the adaption to waterway requirements, representation of very large tow systems on demand and on major waterways.
- Flexible operation on relations with several ports of call and the possibility to leave behind or picking up of individual barges
- It allows the simultaneous transport of different cargo types as each barge in the formation may load different cargo. In addition, barges may be replaced by others at each port called or have different destinations during a single voyage.
- Larger number of interlinked barges possible compared to self-propelled vessels, also due to the possibility of decoupling the barges in locks (however, this is associated with loss of time and higher personnel expenses)

This is offset by system-specific disadvantages such as higher traction resistance, difficulty in maneuverability under certain circumstances (weather conditions, bottlenecks) and the increased number of personnel required (one additional person needed for the coupling and decoupling of the barges). These factors have to be considered when deciding which system to use (Johan , et al., 2018).

An overview of the typical barge types and the possible pushed convoy formations utilized within the European inland water ways along with their resulting dimensions and tonnage capacity are presented in Table 2 below:

Table 2: Barge types and the possible pushed convoy formations utilized within the European inland water ways along with their resulting tonnage capacity (Zigic, et al., 2012)

Vessel type	**Dimensions (LxB)**	**Tonnage capacity at various draughts**
Europe II barge (E II-barge) (to be combined with pushing unit)	76.5 x 11.4/11.45 m	Payload about 2.750t at 4m, 2.300t at 3.5m and 600t at 1.35m
Danube-Europe II Barge (DE II-barge, to be combined with pushing unit)	76.5 x 11 m	Payload about 1.100t at 2.50m
Coupled convoy consisting of GMS-110 + 1 E II-barge	186.5 x 11.4/11.45 m	Payload about 5.200 at 3.50m and 1000t at 1.35m
Coupled convoy consisting of GMS-95 + 1 DE II-barge	171.5 x 11.0/11.40 m	Payload about 3.200 at 2.5m and 930t at 1.35m
Pushed convoy consisting of push boat + 2 x 2 DE II-barges	153 x 22.00 m	Payload about 4 x 1.550 = 6.200t at 4.0m and 4x 865 = 3.450t at 1.60m

Some other specific inland freighters explicitly built to operate as a coupled formation consisting of one motor cargo vessel and one pushed barge with unusual dimensions specially utilized for container transport are also highlighted as shown in Figure 4 and Figure 5 below:

Figure 4: Coupled formation: Contargo1; L: 97.55m - B: 11.40m – D: 3.51m-T: 2848/176TEU Contargo X; L: 83.10m - B: 11.45m – D: 3.67m -T: 2673/172TEU Available from http://www.daribv.com/en/our-fleet/freighters/contargo-i-contargo-x [Accessed 12 Jul 2021]

Figure 5: Coupled formation: Company; L: 94.90m - B: 11.45m – D: 3.65m-T: 2765/160TEU Barge Mystery; L: 76.46m - B: 11.43m – D: 3.85m -T: 2665/160TEU. Available from http://www.daribv.com/en/our-fleet/freighters/company-mystery [Accessed 12 Jul 2021]

Special attention is been paid to the vessel’s main dimensions, hull shape, carrying capacity and container arrangements as this will serve as a basis in combination with the owner’s requirements for the dimensioning, partitioning and design of the proposed vessel type in the preliminary design stage.

2.3. Review of IW Vessel Shallow Draught Concepts

As a rule, a ship design study is based on the similar vessels of the existing fleet. Usually, a successful vessel is adopted as a prototype and modified so as to fulfil particular requirements. However, if the operational conditions and desired performance of the new design considerably deviates from those used in the development of the vessels considered, the ship will most likely represent a “paradigm shift” (Bačkalov, et al., 2014). These operating conditions such as the extreme shallow water condition defined in 1.11.1 are thus converted into design constraints in the early design stage of such vessels. These constrains are sometimes obvious, but could also greatly impact the vessel design in an unexpected way. The task of the designer is to anticipate and fulfill these limitations together with the owner’s requirements, and achieve a “good vessel” that complies with the best of engineering logic (Hofman, 2006).

In view of the effect of climate change on the water level and Inland Water Transport (IWT), various adaptative measure has been evaluated in function of their cost-effectiveness, given the expected impact of climate change on the navigation conditions. Some of the adaptation strategy identified and analyzed by the EC funded ECCONET project (Zigic, et al., 2012) are the adaptation of the technical aspect of fleets which refers to options such as increasing the payload of a ship keeping the main dimensions (L x B x T) unchanged (lightweight structures), adding adjustable tunnel (retractable tunnel aprons) or employing flat hulls (multi screw push boats). The solution proposed by the study towards the realization of a lighter ship structure are either the use of high tensile steel instead of mild steel (reduced scantlings and plate thickness), reduced frame and/or longitudinal spacing enabling hull construction with thinner plates and lighter stiffeners or applying a different concept solution for the midship section in the range of the cargo hold. Results from the application of the proposed concept solution for the midship section of an existing Rhine vessel in the range of the cargo hold as shown in Figure 6, shows that a significant amount of weight saving on the cargo hold weight was achieved consequently leading to an increase of the payload at the same draught while applying the same material (mild steel) and maintaining the same stress limits as for the conventional solution.

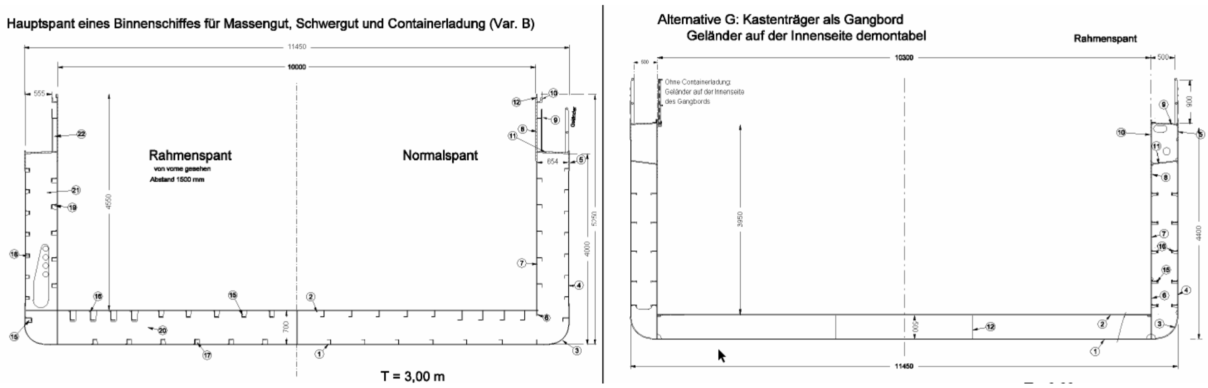

Figure 6: A conventional midship section of a large Rhine motorship (left) and an alternative solution with box girder as gangway (right) Source: (Zigic, et al., 2012)

Such methods of lightening the hull can be applied to new buildings as well as to reconstructions of existing ships, for instance by replacing the parallel middle section by a new, light-weight structure (Zigic, et al., 2012). Other solutions such the reduction of the frame spacing and consequently the savings on plate thickness are also demonstrated. However, this is often offset by the higher labor-related building costs and also, thicker plates may be required for the cargo hold, inner bottom and side walls of bulk cargo vessels in cases where grapples are used for reloading of bulk.

Another design suited particularly for operation in shallow waters is an inland ship with retractable side buoyancy bodies (blisters); their application alters the ship breadth from 9 to 12.6 m enabling the draught reduction without reducing the cargo quantity. Side bodies are supposed to be operated by hydraulic cylinders, Figure 7. There is a series of other technical solutions that are based on the same principle (e.g., inflatable and steel blisters). Expected effects and installation costs for various ship types are discussed in (ECCONET , 2012b)

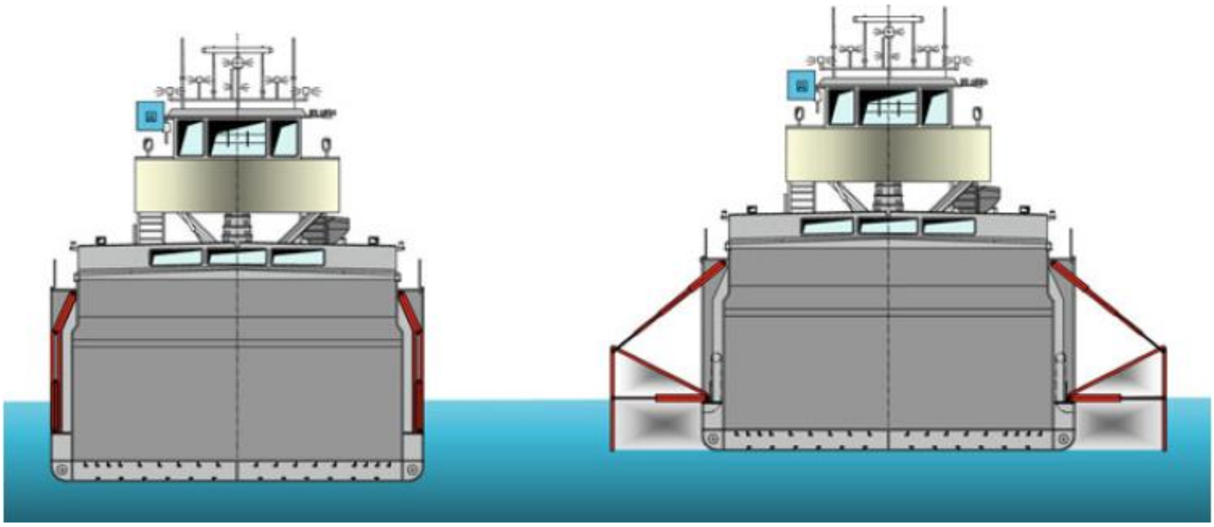

Figure 7: Cross-section of the IW ship with laterally extractable buoyancy elements. Source: (Müller, 2003)

Bačkalov, et al. (2016) proposed a solution pointed towards the optimization of the main dimensions of existing vessel types resulting in an innovative and unconventional container vessel design. The study demonstrated that improvements in that respect could be achieved already in the preliminary design phase, by careful selection of main dimensions. The proposed design differs from standard European inland ships of the same capacity by reduced depth, increased breadth and consequently shallow draught. It was demonstrated that such vessel would be less susceptible than the standard vessels to the weather phenomena (low water levels and strong winds) along with an extension of operation throughout the year while increasing the cargo capacity in comparison to existing, deeper draught vessels. In the same time, the cargo capacity in terms of number of TEUs carried by such vessel would be increased. In addition to conventional methods, the study employs direct calculations to examine the structural strength and numerical experiments based on ship dynamics to assess the stability and safety of the vessel exposed to gusting wind. Overall, the results indicate the advantage of the shallow-draught vessels in the present-day navigation conditions.

Also, in a study that dealt with the design of the extremely shallow draught bulk carrier for the Lower Danube (Bačkalov, et al., 2014), it was indicated that the challenges related to the navigation in limited water depth could be successfully tackled by altering the main dimensions of the typical European inland ships.

In the same vein, other possible solutions directed towards the development of constructive material and technological solutions to reduce the dead weight of inland cargo vessels have been put forward by various researchers, one of which is the use sandwich plate system (SPS). The analysis of the possible weight reduction that could be gained by the application of SPS in building a complete ship hull structure of a conventional inland barges (general cargo, bulk carrier and container barge) (Momčilović & Motok, 2009) shows a reduction in weight up to 15% and the application of Al-foam sandwich and GRP-Pur sandwich element by means of numerical solution (Kaufmann & Hipke, 2012) resulted in approx. 27% weight reduction for the hull. However, these are rather theoretical approach which are subject to further investigations.

Among the various adaptive measures outlined and analyzed by various studies towards the maximization of the carrying capacity of the inland cargo vessels in shallow or extreme water conditions, the ship main dimension and hull structure weight saving offers a more realistic and cost-effective solution (Zigic, et al., 2012) and (Bačkalov, et al., 2016). Hence, the application of the various means for the realization of a light weight structure through proper dimensioning and structural optimization at the preliminary design phase of a vessel is thus explored within this context. However, these methods are often subjected to structural strength analysis with particular emphasis on the longitudinal strength issues as the designer must consider stress analysis, material behavior as well as failure methods during the design process, keeping good structural integrity.

2.4. Structural optimization of ship structure

Structural optimization can be expressed as finding the optimal objective function subject to design constraints. It plays an important role in the design process of engineering structures as various optimization methods have been integrated into software to ease the realization of more accurate results (Haftka & Sobieszczanski-Sobieski, 2009).

Depending on the design variables, structural optimization can be defined via four main methods (Sekulski, 2009):

- Topological optimization,
- Shape optimization,

- Size (scantling) optimization and
- Material Optimization (Choice and distribution of materials).

The problem of structural optimization is complex if all four methods are considered in one algorithm (Sekulski, 2009). However, specifying the right objective function and design variables points the designer in the right direction as regards the choice of method to apply. A certain number of design variables (e.g., thickness, shape or cross section area of a structure) has to be determined in a way that the objective function (e.g., minimal weight of a construction) is best fulfilled in compliance with the state variables (e.g., strength, stiffness or production) (Lindemann & Kaeding, 2010).

In the industry of shipbuilding, structural optimization represents a challenge, especially in the global structural optimization of a vessel. It is considered that the most suitable objective function in the optimization of ship structure is the weight. Minimizing weight is of particular importance in deadweight carriers, in ships required to have limited draft, and in fast fine lines ships, such as passenger vessels (Rigo & Rizzuto, 2003). With regard to the objective function, one has to carefully consider the various design variables and constraints that could be assigned and hence, the method of optimization to be applied. In aerospace and automobile industry, topology optimization has proven to be most efficient in weight minimization, unlike the shipbuilding industry where the majority of the lightship weight is comprised of continuous panels that form the hull shape and the internal main structural members such as decks or transversal and longitudinal bulkheads, that cannot be optimized using topology optimization due to the necessity of keeping the hull watertight and providing water and weather-tight compartments inside the ship to maintain the integrity and safety of the structure (Bendsoe & Sigmund, 2004).

Size (scantling) optimization on the other hand, has proven more viable results in the domain of ship building. The main design variable considered within the domain of size optimization in ship structures (Rigo, 2001) are: Plate thickness, Longitudinal members (stiffeners, crossbars, longitudinals, girders, etc.) and Transverse members (frames, transverse stiffeners etc.). Web heights and thickness, flange width and spacing between two transverse or longitudinal members are also considered within this context.

Just as structural optimization is of great importance especially at the very beginning of the preliminary design and calculation for a ship, the structural integrity of the optimized structure must be also ensured. Therefore, precision must be achieved in the stress and displacement computation of the optimized structure. Various analytical and numerical techniques have been developed with the aims of enhancing the investigation of the structural integrity of optimized structures. Depending on the strength requirement of the ship structure, various parameters such as the material yield strength, buckling strength, fatigue, etc. could be investigated. For yield strength, the stress is sufficiently calculated directly by the FEM models (Yu, et al., 2010) and (Lindemann & Kaeding, 2010). A combination of structural optimization using mathematical algorithms and strength assessment using FEM is also feasible (Amrane , et al., 2012).

An insight into the likely failure modes of the proposed design is also beneficial in structural strength analysis as it gives an idea of what is expected and consequently, the possible orientations or specification of the design variables and constraints with respect to the specified objective function. In attempt to systematically investigate the collapse behavior of modern inland cargo vessel, Meinken & Schluter (2001) in their study, applied the finite element method towards the investigation of the structural strength of a push-barge. The structural failure was found to be dominant around the midship region. The detailed view of the stress distribution in the components, deformations of particular structural members as well as recommendations for the improvement of the structural strength was presented. This will serve as a basis for the assessment of the structural strength of the proposed design.

2.5. Finite Element Analysis and Its Application to Ship Structures

Finite element analysis (FEA) is a widely used computer-based method of numerically solving a range of boundary problems (Ashcroft & Mubashar, 2018). The Finite Element Method (FEM) is explained (Stolarski, et al., 2018) as a mathematical technique used for solving systems of partial differential (or integral) equations. The FEM is formulated using two main methods: one based on the direct variational method – e.g., Rayleigh-Ritz method – and one based on the weighted residuals method – e.g., Galerkin's method. According to Thompson & Thompson (2017), FEM is used in engineering, to divide a system whose behavior cannot be predicted through closed-form equations into small pieces, or elements, whose solution can be approximated. In the method, a continuum is subdivided into a number of well-defined elements that are joined at nodes, a process known as discretization. A continuous field parameter, such as displacement or temperature, is now characterized by its value at the nodes, with the values between the nodes determined from polynomial interpolation. The nodal values are determined by the solution of an array of simultaneous equations using computational matrix methods and the solution to these equations represents the behavior of the system (Ashcroft & Mubashar, 2018).

The accuracy of the results is dependent on the discretization, the accuracy of the assumed interpolation form, and the accuracy of the computation solution methods. A finite element model approaches a perfect representation of the system as the number of elements becomes infinite. This could be likened to the case of a regular polygon which approaches a perfect circle as the number of sides increases. Hence, finite element method produces an exact solution to an approximation of the problem and as the number of elements becomes sufficiently large, the approximation becomes good enough for engineering analysis but this comes with a cost increase in terms of computation time and manpower assigned to interpret the results. However, it still outweighs the option of calculating these equations manually (Thompson & Thompson, 2017). The benefit of the method is based on its ability to model many classes of problem regardless of geometry, boundary conditions, and loading and the ability to solve arbitrarily complex problems for which analytical solutions are not available or which would be too expensive to solve by hand.

2.5.1. *Basic FEM analysis Procedure*

The basic steps in any finite element analysis as described by (Ashcroft & Mubashar, 2018) and (Thompson & Thompson, 2017) are divided into three main stages, which are termed preprocessing, processing/solution, and post-processing.

2.5.1.1. Pre-Processing stage:

In the preprocessing stage, the geometric model is created, and material parameters, loads, boundary conditions, and analysis controls are defined. The geometric model is discretized by meshing with elements. The necessary data file containing all the necessary information in a format required for the finite element processor are created as a result of the process. The preprocessing is incorporated into sophisticated graphical interfaces with the options of modifying the date files for example; modifying or refining the mesh to improve the accuracy of the solution. Many of the commercial graphical preprocessors are capable of preparing data files in a format suitable for a number of different processors.

2.5.1.2. Processing or Solution stage:

In the processing stage, the solver solves the problem and creates output files with the results of the analysis process such as nodal deflections, element stresses, etc. This normally involves the solution of many thousands of equations and can involve the creation of large temporary files. Processing is generally controlled by the software package most of which allows for monitoring the progress of the analysis and enables the user observe progress toward convergence of the solution against a selected convergence criterion. With the advent of multicore processors and HPCs, a solution can be solved using multiple processor cores. This decreases the time required to solve a problem by dividing the problem domain into several smaller domains and sending each smaller domain to a single processor core (Ashcroft & Mubashar, 2018).

2.5.1.3. Post processing stage:

At the stage, the results are plotted, viewed, and exported. The user can view an analysis log giving details of the analysis process and search for status messages created by the software to indicate possible errors in the analysis. With the tendency toward larger models, sifting through large text files can be laborious, and it is now more common to view results in graphical mode. The results are usually compared to first-order estimates, closed-form solutions, mathematical models, or experimental results to ensure that the output of the program is reasonable and as expected (Thompson & Thompson, 2017).

Graphic postprocessors are capable of presenting results in many different formats. One of the most useful plots to look at initially is the deformed mesh. Any major errors should be obvious from the deformed shape. If the scale of the deformation is being assessed from this plot, the magnification factor must be set to 1 (Ashcroft & Mubashar, 2018). Contour plots can then be used to show the distribution of stresses, strains, displacements, or other parameters through the structure.

The steps mentioned above could be applied in differing order and it is also possible to omit some for example the options of automated meshing option exist to ease the task of choosing element types and sizes for complex structures. Also, for some simple analysis type, the default solution type is often sufficient. Similarly, the load and boundary conditions can be defined in either order.

In ship design and ship structural optimization, finite element analysis (FEA) tools are typically used in ship structural assessment (Amrane , et al., 2012). It is used extensively in ship structural strength analysis with respect to the set criteria either by the classification society or with respected to the material properties to assess stresses such as yield stress, fatigue, buckling stress etc. depending on the analysis requirement.

August and Carlos (2003) specified that by describing the whole ship structure in its primary, secondary and tertiary parts: Hull Girder, Frames and Plating, respectively, and by incorporating FEM analysis to a ship-like structure optimization a significant capability of reducing the weight of the structural components can be achieved, in an amount impossible to be reached by other means, since, by computer, the "best design" can be selected among thousands of different and feasible ones.

In a bid to analyze the structural behavior of a General Cargo Vessels Parunov, Uroda and Senjanović (2010) Employed the finite element analysis to a complete ship model (CSM). The global strength assessment was performed using "coarse mesh" finite element model, while the areas where stress concentrations occur are further analyzed by the fine mesh analysis and checked with the BV criteria for yielding and buckling failure modes. The loading and boundary conditions were specified to depict the actual cases of still and wave water scenarios. The study demonstrates how 3D FEM (Finite Element Method) analysis may be employed as a tool for improving structural safety of general cargo ships as thus enables reinforcement of the critical areas.

The application of FEM to floating structures requires a special consideration of the structure modelling, loading and boundary conditions as this greatly influences the accuracy of the result produced.

2.5.2. *FE Modeling and Analysis of Ship Structures*

The development in the construction of unconventional ships and the implementation of lightweight materials have shown a large impulse towards finite element (FE) method, making it a general tool for ship design (Iqbal & Shifan, 2018). Finite element modeling of ship structures can be an expensive activity and number of questions must be asked before modeling commences. The most important of these are probably: Is finite element modeling necessary? What information is required from the analysis and to what degree of accuracy? And if an effective analytical solution has already been derived for the problem, then this will almost inevitably be a cheaper option. (Ashcroft & Mubashar, 2018). Many analytical methods have been developed to effectively assess the structural strength of ship structure, one of which is the traditional means been the mid-ship section analysis proposed approved by various classification societies. However, when it comes to the structural optimization which involves unconventional designing and deviation from the structural specifications of the class society, FEA becomes useful as it provides a more precise result especially in the global strength determination of ship structures.

Depending on the analysis requirements and the software available, various approaches are available for the modelling and analyzing ship structures. With the rapid adoption of FEA in the shipping industry, various classification societies have also developed guidelines describing the scope and methods required for structural analysis of ships and the background for how such analyses should be carried out. The class guidelines application is based on relevant Rules for Classification of Ships. Structural analyses carried out in accordance with the procedure outlined in the class guideline will normally be accepted as basis for plan approval. Any recognized finite element software may be utilized provided that all specifications on mesh size, element type, boundary conditions etc. can be achieved with this computer program. If wave loads are calculated from a hydrodynamic analysis, it is required to use recognized software (DNV-GL, 2020).

For the purpose of this study the guidelines specified by DNV-GL (DNV-GL, 2020) for the for finite element analyses and assessment of ship hull structures shall be employed. Calculation methods such as global direct strength analysis to assess the overall hull girder response, partial ship structural analysis to assess the strength of hull girder structural members, primary supporting structural members and bulkheads, local structure analysis to assess detailed stress levels in local structural details and fatigue assessment of ship structures are covered within the class guidelines.

2.5.3. *Boundary conditions*

The simulation of boundary conditions and other forms of restraint requires an understanding of the mechanics of the problem. As with other elements of the modeling procedure, the selection of boundary conditions will involve some simplification of the problem, which must be justifiable. An important consideration when applying constraints is to ensure that rigid body motion is prevented. In most structural applications, maximum stresses occur at a boundary. The choice of boundary conditions defines the extent of the model. In some cases, more than one constraining condition should be analyzed to provide upper and lower boundary values for the analysis (Ashcroft & Mubashar, 2018). The specifications for boundary conditions used for finite element analysis of ship structures are also defined by class societies depending on the analysis type. The boundary conditions define by (DNV-GL,

2020) guidelines for the global strength analysis of ship structure shall be considered in this study.

2.5.4. *Load applications*

In most software packages, loads can be applied to nodes, elements, or geometric features. For ship global strength determination, these loads could be applied as point force, uniformly distributed force, moments, pressures etc., depending on the analysis requirements. However, in all cases, the loads will be converted into equivalent nodal loads for the analysis. If stresses close to the point of loading are not critical, then the high stress concentrations under a point load can be ignored, as according to Saint-Venant's Principle, this will not affect the stress distribution in other parts of the structure. If the area of loading is important, then attention must be paid to the method of load application to ensure that the nodal loading is representative of the actual loading. One method to reduce stress concentrations close to the loading point is to use additional elements to transfer the loads. However, if the actual point of contact is important, a contact analysis may be required. Another way to apply a load is by the specification of a prescribed displacement (Ashcroft & Mubashar, 2018).

For global longitudinal strength analysis of ship hull structure where the ship vertical hull girder bending is investigated with the application maximum bending moments, typical beam theory method could be utilized to induce these bending moments by converting the bending moment to equivalent forces and applied at the appropriate geometric features corresponding longitudinal position of the maximum bending moment.

2.5.5. *Strength assessment*

Depending on the analysis requirements, various strength assessment methods are possible for the analysis of ship structures. However, for modern inland vessels which are characterized by open-top, with unusually large length-to-beam and length-to-height ratios, shallow draught and an extremely long cargo hold, longitudinal strength analysis often dominates the strength analysis of the structure. This analysis could be carried out either by direct calculations or by recommendations from the classification societies. For direct calculation method, yield and buckling check are typical for inland cargo vessels with criteria set by classification societies. These criteria are imposed for the prevention of yielding (in hull girder, frames, longitudinals, etc.), plate and stiffened plate buckling, plate and stiffened plate ultimate strength, ultimate strength of hull girder, fatigue, and many other types of failure particular to the type of vessel and operational scope (Rigo & Rizzuto, 2003).

2.5.5.1. Yield Strength Assessmnent

Various yield capacity assessment methods have been develop with respect to the minimum yield strength of the material used. DNV GL (2015) provides a set of checking criteria for assessment of the yield capacity of structural members either subjected to lateral pressure or contributing to the hull girder longitudinal strength and hull girder normal stresses. These criteria are applicable to structures analyzed through isolated beam model or through a three-dimensional structural model. The yielding check can also be carried out for structural members subjected to specific loads, such as concentrated loads. The checking criteria is as thus (DNV GL, 2015):

$$0.98 \cdot \frac{R_{eH}}{\gamma_R} \geq \sigma_{VM} \qquad \text{Eq (2)}$$

Where: γ_R is the resistance partial safety factor taken generally taken as 1.20 for coarse finite element model and 1.05 for fine finite element model (DNV GL, 2015), R_{eH} is the material minimum yield strength in [N/mm^2] and σ_{VM} is the equivalent Von Mises stress in [N/mm^2]. Stresses are generally calculated by the computer programs for each element. The values of these stresses are to be used for carrying out the checks required.

2.5.5.2. Buckling and Ultimate Strength of Ship Structure

Although this study focuses on hull girder global strength with respect to the hull girder vertical bending stresses, it is also seen that buckling and ultimate strength of plates and stiffened panels are fundamentally important to the local and global strength of the ship (Zhang, 2016) especially in ship structural optimization. Over the years, several researchers have widely investigated the concepts by employing analytical methods, experimental tests, empirical approaches and non-linear FEM simulations.

Zhang (2016) and Kim, et al. (2018) presents a comprehensive technical review on existing empirical formulations that predict the ultimate limit state (ULS) of a stiffened panel under longitudinal compression. The empirical formulations to predict the buckling and ultimate strength of plates and stiffened panels behavior are strongly related to two parameters which are plate slenderness ratio (β) and column (λ) slenderness ratio determined by the following expressions:

$$\frac{\sigma_{xu}}{\sigma_{Yeq}} = f(\beta, \lambda) \qquad \text{Eq (3)}$$

$$\beta = \frac{b_p}{t_p}\sqrt{\frac{\sigma_{Yp}}{E}} \qquad \text{Eq (4)}$$

$$\lambda = \frac{a}{\pi r}\sqrt{\frac{\sigma_{Yeq}}{E}} \qquad \text{Eq (5)}$$

Where σ_{xu} is the ultimate compressive strength in x-axis (under longitudinal compression), σ_{Yeq} is the equivalent yield strength of plate and stiffener, σ_{Yp} is the yield strength of plate, E is the Young's modulus; t_p and b_p are the plate thickness and width, r =√(I/A) is the radius of gyration of the stiffener including associated full width plating; and I and A are the moment of inertia and sectional area for the plate-stiffener combination respectively.

Following the basic format of the empirical formulations, illustrated in Eq (3), a number of empirical formulations have been proposed. Basically, there are several types of empirical formulations obtained via experimental testing or numerical simulations. In addition, there are also design formulas that are obtained using the analytical method. Details of existing empirical formulations and their technical reviews can be found in the research by Zhang (2016) and Kim, et al. (2018).

Approaches for assessing the ultimate strength of unstiffened plates have also been concentrated on four categories: analytical method, experimental model test, semi-empirical approach and non-linear finite element simulation. The classical elastic buckling stress for plates can be analytically determined from Eq (6) (Zhang, 2016):

$$\frac{\sigma_E}{\sigma_y} = \frac{\pi^2 E}{3(1-\nu^2)\sigma_y}\left(\frac{b}{t}\right)^2 \approx \frac{3.62}{\beta^2} \qquad \text{Eq (6)}$$

The method however, as seen in Eq (6) is considered not to give accurate results for relatively thick plates as the buckling stress becomes 3.6 times the yield stress when $\beta = 1$ for example.

Due to the complicated nature and high nonlinearity of the subject, analytical solutions for ultimate strength becomes difficult which led studies to focus on semi-analytical and empirical approaches for developing design equations (Zhang, 2016). Useful formulations have been developed by different authors but the Faulkner’s equation Eq (7) however, shows good agreement with extensive experimental data and with non-linear FEM simulations and has been widely accepted and used in the industry.

$$\frac{\sigma_{xu}}{\sigma_y} = \frac{2}{\beta} - \frac{1}{\beta^2} \qquad \text{Eq (7)}$$

The ultimate strength of unstiffened plates can be influenced by initial imperfections and Faulkner’s formulation is used for the average geometrical initial imperfections.

3. DESIGN ASPECT

As it is the case with every design process, the various design specifications, owner's requirements, design constraints as well as class requirements are been taken into consideration towards the realization of the design. The first step taken was to define a scope for the design. The requirements specified by the owner are collected and evaluated against the various constraints leading to a baseline concept of the design. Preliminary analysis is then carried on the concept design with respect to technical, operational as well as safety compliance. This section explains the various steps and assumptions as well as justification considered towards the realization of the preliminary design of the proposed vessel.

3.1. Design Objectives and Owner's Requirements

The key objective of this study as defined in the scope (see: Scope and Limitations) is to develop a push-barge optimized for performance on shallow draught. An investigation into the possible options available towards achieving the design objectives have been premeditated and weighed against each other leading to a final collection of the requirements for the proposed push-barge design. The requirements for the proposed design are as summarized in the following subsections:

3.1.1. *Main dimension fixing:*

The main dimensions were selected with respect to maximizing the carrying capacity of the push-barge with respect to the type of cargo transported and the existing infrastructural limitations such as lock sizes, height of bridges, available depth for vessel navigations in normal and extreme water levels. These parameters were then benchmarked against similar vessels operating within the same route and initial vessel particulars were decided. According to (Radojčić, et al., 2021), in the design of an optimal container ship, her main dimensions is directly influenced by the number of containers that should be transported onboard. Some essential expressions and design guidelines for the preliminary dimensioning of inland water vessel have also been established across the years. Procedures for estimating the main dimensions, steel weight, light ship weight and power predictions have also been developed within the study of (Radojčić, et al., 2021). Push-barge with a breadth of 11.45 m allows for transport of a 4 container rows and a pushed convoy of 2 barges side by side against the maximum allowable width with respect to the locks existing within the region and correspond to the upper limits of European class Va waterways (CEMT classification) recommendation for pushed convoy in this region (BAW Karlsruhe, 2016).

The length was selected with the objective of transporting a 12 bay TEU container leading to a cargo hold dimensions specified according to the length of standard 12 ISO containers with average clearance between them. Adding to the cargo hold length the fore and aft length were also determined leading to a final length specification.

The depth on the other hand is not directly connected to the maximal number of containers onboard, but is related to the other principal dimensions and influences significantly the quality of the vessel. The depth depends mainly on two factors, the freeboard requirements and longitudinal strength limitations (Radojčić, et al., 2021). An initial vessel depth was proposed with reference to similar vessel and as a first step to minimizing the structural weight of the vessel while traying to maintaining the limits for the longitudinal strength requirements specified by the class society ($L/H \leq 35$ stemming from the Lloyd’s Register, 2021, which when exceeded would require additional strength calculations). The initial design draught is assigned with respect to the free board requirements specified by the ES-TRIN (ES-TRIN, 2021).

The summary of the vessel’s main dimensions is presented in the Table 3 below:

Table 3: Vessel’s main particulars

Specification	**Dimension**	**Description**
Length	83 m	Based on similar vessels
Breadth	11.45 m	CMT class requirement for pushed convoy
Depth	2.8 m	Initial proposed based on similar vessels
Draught	2.6 m	According to freeboard requirements (ES-TRIN, 2021)
Cargo Hold Dimensions	73.632 m	Allows for 12-Bay and 4-Row container transports and Dimensions based on standard ISO containers (6.058m x 2.438m x 2.591m)
Cargo arrangement	144 - 192 TEU	3/4-Tier, 4-Row and 12-Bay container - Based on current route infrastructure and maximizing cargo carrying capacity

The present design aims to achieve the following objectives:

- A cargo/container vessel that should be able to provide a continuous year-round service, independent of environmental conditions as far as practicable

- Maximized capacity of the vessel in terms of deadweight and the number containers carried (Minimum steel weight)
- The capacity of the vessel in terms of the deadweight should be maximized
- High flexibility in configuration with different vessels types and barges and also, high flexibility in cargo type (container, dry bulk, project cargo, tank) as well as ability to transport dangerous good in limited amount (ADN Container).

3.2. General Arrangement plan

Following the preliminary dimensioning of the proposed vessel, the next step is to define the general arrangement plan for the vessel. This entails the allocation of volumes for all the crucial functions/operations, compartment and bulkhead arrangement of the vessel based on the definition of its spaces, definition of access and the location of equipment crucial to the operation of the ship (winches, loading gear, bow thruster etc.). This is achieved by an initial survey of the arrangement plans for similar vessels and the possible modifications with respect to the design requirements and ship's main dimensions. The various limits and sections for the main compartments were initially specified and later checked with the requirements of the ES-TRIN (ES-TRIN, 2021) and Lloyd's Register (Lloyd's Register, 2021) class requirements.

3.2.1. *General arrangement concept*

The main deck plan consists of the fore, mid and aft section of the vessel. Sufficient spaces are allocated for the various operational equipment such as the anchor windlass and coupling winches which are placed in the fore and aft of the cargo hold compartment. The Anchor windlasses placed at forward and aft of the cargo hold compartment enables for the securing of the fore and aft anchors while the winches placed on the port and starboard sides aids to secure the vessel either a port during loading and unloading or to other vessels in a pushed convoy. Bollards of different sizes are also placed at strategic positions of the main deck for also securing the vessel. Access to the possible machinery room (forward) and aft peak compartment are located on the main deck with sufficient dimensioning and water tight coverings while proper accessibility throughout vessel main deck is ensured by proper dimensioning of the deck spaces port and starboard of the cargo hold compartment. Depending on the owner's requirements or the maneuverability needs, bow thrusters with channels or pump jet may be placed in the compartment forward of the cargo hold compartment.

Figure 8 shows a cropped plan and profile view of the fore and aft section of the ship showing the major arrangement of the operational equipment while the typical layouts of the proposed vessel are shown in Figure 9.

Figure 8: Enlarged Profile and Plan View of the Proposed Forward and Aft general Arrangement Plan.

The cargo hold compartment consists of a parallel section with the capacity to house the specified container bay and rows along with hatch coamings around the cargo hold compartment. These hatch coamings are specified based on the minimum safety clearance designated by the class society (Lloyd's Register, 2021). A typical view of the cargo hold section is shown in the general arrangement plan displayed in Figure 9.

Figure 9: General Arrangement Plan for Proposed Push-Barge

3.3. Hull form Modelling

Successful barge hull design requires a combination of familiarity with operational problems, design experience, and extensive model testing. Over the years various design guidelines consist of schematic drawings, model test results, notes on specific design aspects and proposed limits for certain barge hull related parameters has been published. With the information available from various literatures, it is possible for a designer with relatively little experience to avoid the major pitfalls and to evolve a barge hull design which will be generally acceptable for the operating service (Taggart, 1983).

Hence, the choice of the hull type for this design is based on the reports and recommendations from various researches and publications which are dedicated to obtaining an optimum hull characteristic that satisfies the requirements for minimum resistance and possible hydrodynamic capabilities in relation to the inland navigational characteristics. There are two important aspects to consider in designing a barge hull form which are, the bow and stern forms.

3.3.1. *Bow region*

Considering the design of the ship bow, several bow shape types are available depending on the design requirements. Over the years, a variety of bow forms have been applied to inland ships. According to (Heuser, 1986), there are four major bow shapes employed for the inland cargo vessels namely;

- U-shaped bow sections,
- V-shaped bow sections,
- Wedged-shape and
- Pontoon bow.

The U-shaped bow section is characterized by its high displacement and deadweight tonnage but offer s higher resistance as compared to the V-shaped which is better for higher speed as it requires less propulsion power. The V-shaped bow is convenient for the self-propelled vessels designed to push additional barges. The pontoon-shaped and the wedge-framed bow on the other hand, are mainly used for barges, due to the simple construction and lower building cost. This bow type requires more power for the same speed, compared to U- and V-shaped bows (Radojčić, et al., 2021). According to (Interreg, 2019), the wedge frame bows was also developed to optimize the flow conditions of pushed boat behind the barges.

Heuser (1986) presents a set of guidelines to design the bow in more detail as well. These guidelines correspond to the bow region length ($L_{WL\text{-}B}$) as well as the bow region block coefficient ($C_{B\text{-}B}$) while Taggart (1983) following a series of different hull form tests, recommended an optimum line development for barges with a wedged shape bow and a "straight-element" rake end. These recommendations are then adopted for the actualization of the hull form design. However, this hull is subject to validation and further optimization if necessary.

3.3.2. *Stern region*

Unlike the bow form, much consideration is not given to the stern form since the intended design is for a non-motorized push-barge. Hence, issues such allowance for propulsion devices, tunnel geometry etc., are not the case here. However, some special stern designs exist for barges in coupled formation which is designed to fit the bow form of the pushing vessel. The stern region for this application is designed following the traditional Europe barge stern designs which are usually flat or slightly inclined forward towards the base with allowance for anchors. This stern is also compatible with pushing units.

3.3.3. *Parallel Middle Body*

A parallel middle body (PMB) similar to a cuboid with rounded bilges was maintained for the cargo hold mid region of the vessel. The full form of the PMB provides maximal volumetric displacement, i.e., cargo-carrying capacity. The length of the parallel middle body is usually up to 70% of LWL, with block coefficient of close to 0.995 (Radojčić, et al., 2021).

The hull form modelling was realized using the Siemens-NX modelling application while basic hull hydrostatics were calculated using MAXSURF Modeler application. A view an enlarged view of the bow shape lines plan is as shown in Figure 10 along with the hull hydrostatics characteristics shown in Table 4:

Figure 10: Enlarged View of the Bow Form Lines Plan

Table 4: Proposed Hull Hydrostatics

Excluded from public version

3.4. Structure Idealization

The structural idealization and arrangements for this study were determined on one hand by adoption of existing structural arrangements for similar ships while the scantling arrangements and various plate thicknesses on the other hand were checked with the requirements from the Lloyd’s Register Rules (Lloyd's Register, 2021). The overall structural response of the mid-ship region with respect to the hull section modulus and permissible stresses are also determined in according to the recommendations of the Lloyd’s Register rules (LR).

Following the specifications of the LR rules, the ship is been identified as belonging to a class termed “A1 I.W.W. Cargo/Container Barge” which is defined as a non-propelled ship (barge) towed and/pushed or carried alongside another ship and designed primarily for the carriage of either general dry cargo, containers or bulk heavy dry cargo in holds. The applicability of the structural requirements from the rules for the midship region of the ship are limited to ships having a length not exceeding 135 m, a ratio of length to depth generally not exceeding 35 and a ratio of breadth to depth not exceeding 5. Hence, the rules are applicable to the proposed design as the ship particulars are within the specified limits. The structural arrangements and scantlings for the forward and aft region of the ship are also adopted and checked with the requirements from Pt 3, Ch 5 (Fore and At End Structure) of the rules.

3.4.1. *Structural Configuration*

The hull structure is characterized by a single deck hull with wide hatch openings and continuous hatch side coamings, a double skin arrangement in way of cargo space, and a double bottom arrangement. The hull of the vessel is longitudinally framed (See Figure 11) and the spacing between transverse primary members are governed by the ADN rule on one hand and container positioning, on the other hand. A centerline and side girders are placed running through entire length of the vessel. The side girders are also aligned to support the container positioning.

A frame spacing of 511.16mm is maintained within the cargo hold compartment due to the container positioning while a spacing of 500mm was maintained on the aft and the fore peak region of the ship. Web frames and plate floors are placed at every 3rd frame (i.e., spaced of 1533.48mm) and a water tight frame at every 8th web frame position defining the major compartments of the double bottom and wing passage. Longitudinal stiffeners are evenly distributed along the width of the vessel with centerline and side girders running throughout the length of the ship. The scantlings and various plate thicknesses were checked with the requirements from part 3 (Ship structure - general) and 4 (Ship structure - ship type) of the LR rules (Lloyd's Register, 2021). A cross-section of the scantling arrangement at the mid ship section is as shown in Figure 11

Figure 11: Midship Section of Designed Vessel

This study focuses on the structural configuration of the midship region which is the highly stressed region as regards the longitudinal strength of the ship and the structural optimization technique is also intended to be applied to the midship region. Subsequently, longitudinal strength assessment of the structure is been carried out. A summary of the basic criteria as per the rules (Lloyd's Register, 2021) for the plate thicknesses comprising the midship region is as defined in Table 5.

The structural configuration utilized for the initial structure as seen in Table 5 is corresponding to the adapted configuration of existing similar vessels. The thicknesses are seen to vary from the rule prescribed thicknesses mostly towards the upper end of the structure. This is often results from the structural assessments. The thicknesses are seen to be greatly increased at the hatch coamings, deck and sheer strake corresponding to the regions farther away from the neutral axis which are usually the highly stressed regions for such ship configurations. Also, it is a common practice that ship owners tend to extend the life of cargo vessels by increasing inner bottom and cargo hold bulkhead thicknesses by 2 or 3 mm in comparison to calculated ones having in mind wear and tear that might result from the cargo handlings. However, this practice is not based on any kind of structural assessment, and as such might not be necessary depending on the application (Bačkalov, et al., 2016).

Table 5: Plate thickness requirement and specification at the midship region

Item and Parameter	Requirements	Min. Values
Deck thickness	The greater of: $t = (5.6 + 0.039L)\sqrt{s}$ mm $t = 10s$ mm	6.2
Hatch coaming minimum thickness	The greater of: $t = 0.042(L_1 + 200)\ d_c$ mm $t = (6 + 0.06L)\sqrt{d_c}$ mm	12.9
Bottom plating thickness	$t_b = (5.6 + 0.054L)\sqrt{s}$ mm	7.1
Bilge plating thickness	$t = t_b + 2$ mm	9.1
Side shell plating thickness	The greater of: $t = (5.6 + 0.054L)\sqrt{s}$ $t = 10s$	7.0
Sheer strake thickness	t = side shell thickness + 5 mm	12.1
Double bottom minimum depth at center line	$d_f = 35B$ mm	400
Center and side girder thickness	The greater of: $t = 0.008d_f + 3.0$ mm $t = 8.0$ mm	8.0
Floor thickness	The greater of: $t = 0.009d_f + 2.0$ mm $t = 8.0$ mm	8.0
Water tight floor thickness	The greater of: $t = 0.0085d_f + 2.0$ mm $t = 8.0$ mm	8.0
Inner bottom plating	The greater of: $t = 12s$ mm $t = 6$ mm	6.0

Where:

- L, D and s are Length, Depth and spacing of secondary stiffeners, i.e., frames, beams or stiffeners, in meters
- d_c = vertical distance, in meters, between deck and horizontal stiffener on coaming or between horizontal stiffener
- S = distance between coaming stiffeners, in meters
- L_1 = L but to be taken not less than 40 m
- I_s = upper hatch coaming stiffener inertia
- t_b = thickness of bottom plating

The corresponding stiffener profiles, aft and forward structures are also specified and checked with respect to the requirements from the rules.

3.4.2. *Material Specification*

The material considered for the most part of the hull structure design is the Grade A – Mild steel (S235). However, depending on the prospective structural strength analysis, higher tensile steel Grade AH (S355) or higher may be applied to highly stressed areas depending on the material thickness and stress pattern associated with these regions in view of weight minimization. The assessment of stresses where higher tensile steel is used are determined by taking into account the material factor k_L. The basic properties of the steel used (DNVGL, 2015) are as outlined in Table 6.

Table 6: Basic Mechanical Properties of Steel Grade

Steel	**Minimum Yield Stress R_{eH} (N/mm^2)**	**Ultimate Minimum Tensile Strength (N/mm^2)**	k_L
Mild Steel	235	400 - 520	1.0
Higher Tensile Steel	355	490 - 630	0.72

3.5. Longitudinal Strength

The longitudinal strength analysis of ships in this category is governed by the hull section modulus calculation of the midship section. The hull section modulus is calculated considering the moment of inertia of the hull structure midship section, while the maximum bending stress is determined considering the maximum bending moment obtained either by rule based or direct calculations. The maximum bending stress is then checked with the maximum permissible stresses specified by the rules. This section explains the procedures taken for the analysis of the hull structure section modulus in relation to the longitudinal strength of the ship.

3.5.1. *Hull Section Modulus*

All continuous longitudinal structural members are included in the calculation of the inertia and hull section modulus of the midship section. The lever y is measured vertically from the neutral axis to the top of keel and to the effective height of the hatch coaming, i.e., molded deck line at side amidships plus height of hatch coaming including camber. The section modulus at any point of a hull transverse section is obtained [cm^3] from the following formula (DNV GL, 2015):

$$\boldsymbol{Z} = \frac{I_Y}{100 \cdot |\ z - N\ |} \qquad \text{Eq (8)}$$

Where, I_Y – is the moment of inertia [cm^4] about the horizontal neutral axis of the hull girder transverse section, N – z co-ordinate [m] of the center of gravity of the hull transverse section and z = z co-ordinate [m] of the calculation point of a structural element.

The hull girder normal stresses induced by vertical bending moments are obtained [N/mm^2] from the following formulae:

3.5.2. *Design Bending moment*

The design bending moments in relation to longitudinal strength category are determined for non-propelled ships sailing in Zone 3, as specified by Pt 1, Ch 2, 2.1 of the rules (Lloyd's Register, 2021). The bending moments and shear forces are calculated for the still water condition only, neglecting the wave bending moments and wave shear forces as per rules. The loading conditions covered by the calculation of design bending moments as per Pt 3, Ch 4, 2.1 of the rules are;

- **Light condition** - Ship completely equipped, fresh water tanks, fuel tanks and lubricating oil tanks full, crew and stores on board and tanks partly filled or full with water ballast if intended to be carried in this condition).
- **Fully loaded condition** - Ship as in light condition and loaded with cargo, as evenly distributed as is practicable in the cargo compartment space, to the maximum allowable draught on even keel.
- **Others -** Any other loading condition of the ship giving higher values of bending moments or shear forces, caused by loading and discharging sequences and/or unusual or non-uniform cargo distribution, depending on the ship type.

The design bending moments, sagging and hogging, are the maximum moments occurring when the ship is in any of the loading conditions. The loading sequence considered for the condition considered is the loading/Discharging in one run (Category ‘O’ as per LR-rules). Table 7 summarizes the rule-based analysis of the design bending moments considered.

Table 7: Design Bending Moments Considered

Moments	**Specified Formula**	**Value (ton-f.m)**
MH_O	$(0.0166 – 0.0088C_b)\ L^2BT \times (3.97r – 2.414)$	1844.90
MS_O	$(0,091C_b – 0.068)\ L^2BT \times (4.18 – 3.7r)$	2888.05
MH_T	$(2.23 - 1.67C_b)\ MH_O$	1128.65
MS_T	$(2C_b – 1.08)\ MS_O$	2477.94

Where;

- MH_O and MS_O are the hogging and sagging moments of the ship with loading sequence ‘O’ as per Pt 3, Ch 4, 2.1 of the Rules

- MH_T and MS_T are the hogging and sagging moments of the ship with loading sequence 'T' as per Pt 3, Ch 4, 2.1 of the Rules
- r is the ratio of Lc/L
- Lc is the length of the hold for dry cargo ships

The maximum bending moment obtained was for sagging condition which generally induces compressive stresses at the region above the neutral axis while tensile stresses are induced at the region below the neutral axis.

3.5.3. *Bending Stress Calculation and Permissible Hull Vertical Bending Stresses*

Applying the maximum bending moment obtained from the rule calculation, the normal stresses induced by vertical bending moments are obtained according to the following expressions.

$$\sigma = \frac{M_{Max}}{Z} 10^3 \qquad \text{Eq (9)}$$

Where: σ is the bending normal stress [N/mm^2], M_{Max} is the design maximum bending moment [KNm] in hogging or sagging condition and Z is the section modulus [cm^3] at designated points. The maximum stress obtained are checked with the criteria specified the rules (Lloyd's Register, 2021). The general criterion for the permissible combined stress for hull vertical bending within the midship region is given as:

$$\sigma = \frac{175}{k_L} N/mm^2 \qquad \text{Eq (10)}$$

Where K_L is the material factor defined in 3.4.2.

The values obtained with respect to the criteria are well below the minimum defined. The details of the section modulus calculations are given in Appendix 1 of this report. Table 8, however, gives a summary of the values of the stresses obtained at different positions as regards the midship section analysis with the maximum design bending moment calculated in accordance with the rule specification.

Table 8: Stress Values Obtained at Midship Section

Designation	**Stress value [Mpa]**
With max sagging moment MS_O	
Top of hatch coaming	127.22
Deck	75.13
Bottom	46.42
With max hogging moment MH_O	
Top of hatch coaming	81.26
Deck	47.99
Bottom	29.65

As seen in Table 8, the peak stress is found at the top of the hatch coaming subjected to bending moment in sagging condition. The tensile stress in the deck and hatch coaming as well as the compressive stress values obtained are seen to meet the prescribed permissible stress values earlier defined.

3.6. Weight estimation

Calculating of weights is done by implementing several different methods. Structure and light ship weight were primarily calculated using approximations based on the ship main dimensions but is after replaced by more accurate calculation provided from structural 3d model made in Siemens NX and MAXSURF. Most of other weights are calculated using Excel spreadsheets where weights of separate elements, their number and coordinates are defined.

The vessel's geometry and loads are defined with respect to the following right-hand co-ordinate system

- Origin: at the intersection among the longitudinal plane of symmetry of vessel, the aft end of L and the baseline
- X axis: longitudinal axis, positive forwards
- Y axis: transverse axis, positive towards portside
- Z axis: vertical axis, positive upwards.

3.6.1. *Lightweight*

Ship lightweight includes steel weight mass and other "local" masses, such as wheelhouse, winches, masts, outfitting, etc. The items included in the lightship are permanently integrated into the vessel structure, and form part of the displacement of the vessel for any loading condition. (Heuser, 1986) and (Hofman, 2006) presents mathematical models for the estimation of steel weight, lightweight, and some other local masses, for conventional self-propelled IW vessels based on the vessel's main dimensions and a range of design drafts with distinctions made between longitudinally and transversely framed hulls, dry bulk and container vessels. These equations provide an estimate of the various components of the ship's lightweight. Applying the ship lightweight formula Eq (13) proposed by Hofman (2006), an initial ship lightweight was estimated and later validated by the actual ship lightweight estimation. A deviation of only about 7% was found.

$$W_{lightweight} = -4.44 * 10^{-6}(LBD)^2 + 0.195(LBD) \qquad \text{Eq (11)}$$

The actual steel weight which is a very important aspect of this study is obtained by careful modelling of the entire ship structure in Siemens NX (Ship structure basic design application) software. The procedure involves the modelling and transfer of the ship hull structure outer shell components from the modeling application to the ship structure basic design application. To achieve this, a ship hull container is defined as the extremities of the ship hull structure within which the different structural components are to be contained. The hull is then created by importing the various parts making up the hull and the outer shell structure of the ship from the modelling application and assigning the corresponding thicknesses. Grid lines are then defined dividing the ship into longitudinal, transverse and vertical sections corresponding to the structural divisions of the hull structure. The estimated structural components (Bulkheads, Decks, Stiffeners, Floors, Web-frames etc.) are then assigned to these grid lines forming a complete ship structure model. The steel weight and corresponding center of gravity hull structure is then exported into Excel and sorted out. Figure 12 shows the complete ship structure model with a cross section of the midship section. The estimated steel weight is as shown in Table 9

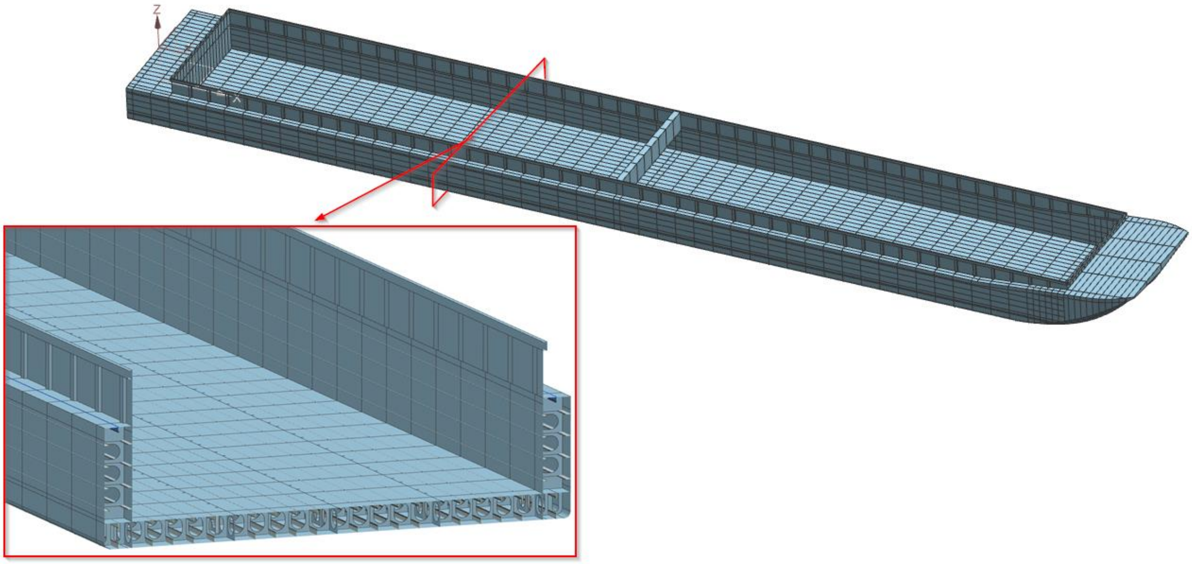

Figure 12: Ship hull structure model in Siemens NX

Table 9: Hull Structure Steel Weight (Maxsurf)

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The estimation of other major systems comprising the lightweight of the ship are also estimated and tabulated with respect to their locations and center of gravities on board. Table 10 gives a summary of the major groupings of the components comprising the lightweight of the ship with their corresponding center of gravities. The details of the various components within each group are given in the 0 of this report.

Table 10: Total Light Ship Weight

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With the detail of the ship's lightweight and hull displacement, it is possible to estimate the payload capacity of the ship corresponding to different draughts. MAXSURF stability module was utilized for detailed modeling of the ship's loading conditions. Various hold and tank capacities are modeled within the hull while specifying the types and limits of cargo transported within these holds. The payload capacity could then be accessed in terms of tonnage capacity as well as number of TEU containers possible at specified draughts. The longitudinal strength of the vessel is also accessed with respect to the bending moments and shear forces corresponding to these loading conditions. Details of the loading conditions and payload estimation are explained in the subsequent section of this report.

4. STRUCTURAL OPTIMIZATION AND GLOBAL FE ANALYSIS OF PROPOSED VESSEL

Ship hull structures realized by conventional design are often characterized by heavy structures as a result of the strict compliance to the class rules and the cost of design optimizations. However, at the early design stage of vessel structural optimization plays a very important role towards the actualization of lighter structures while maintaining the strength requirement of the structure. Various techniques towards the structural optimization of ships have been implemented and could be adopted at the preliminary design stage of a vessel. This approach often tagged as direct calculations, allows the designer to determine an optimum hull structure by a realistic modeling of the load due to light ship weight, deadweight and hydrostatic pressure while taking into consideration, the necessary extreme operating and loading conditions the ship might encounter in her operating cycle. These often results in lighter structures with limited strength capabilities which must be verified through structural strength analysis. The proof of structural strength could then be carried out through analytical or numerical methods (Finite element analysis). Setting the structural weight as the objective function, the study explores various design variables such as plate thicknesses, profile scantling etc. while considering the structural strength requirement as design constraints.

Having employed the traditional/rule-based approach to the determination of the designed hull structure for the proposed vessel, a full ship model comprising of the various structural members making up the hull structure is been developed. The hull structural strength is then investigated by applying the maximum bending moments obtained by direct calculation thus, leaving room for possible optimization of the hull structural components with the maximum permissible stresses as constraints. The ultimate target is to establish a link between the standard design tools (hull form, hydrostatics curves, steel structure CAD, weight estimation, strength analysis, etc.) with a rational optimization design module and a minimum weight objective function.

The procedure followed through for the hull structure optimization is as thus:

- **Design bending moments calculation:** This entails the direct calculation of the design bending moments by detailed weight distribution at different loading conditions.

- **Analysis of the structure:** The maximum bending moments obtained are then applied to the hull structure midship section. The longitudinal strength of the ship is then analyzed through the section modulus calculation at the midship section.
- **Optimization of the structure:** Here the structure is been optimized by careful reduction of various plate and profile thicknesses while ensuring the compliance to the maximum permissible stresses. In other words, the design variables (plate and profile thicknesses) are been modified with respect to various design constraints (technological, geometrical and structural constraints) while trying to attain the specified objective function (weight reduction). This is achieved by setting up and analyzing the hull structure through an excel code containing details of the structural components of the midship region. Hence, the analysis of the hull section modulus is the key approach within this section.
- **FE Analysis of the structure:** Here, the structure obtained after the structural optimization is then analyzed through global finite element analysis. The entire hull structure is been modelled and analyzed through FEM by applying the necessary load and boundary conditions while assessing the maximum stresses in critical areas of the structure.

This present chapter provides details on the procedures for:

- Direct calculation of the load cases and design bending moments
- Optimization of the structure with respect to the calculated design bending moments
- Finite element analysis of the hull structure with respect to maximum permissible stresses

4.1. Design Bending Moments - Direct Calculations

For the direct calculation of the design bending moments, MAXSURF stability module was utilized. The longitudinal strength analysis within the software lets you determine the bending moments and shear forces created along the length of the hull due to the forces applied from the loads and the buoyancy forces. The analysis can be carried out in still water or in a waveform. The actual light weight of the ship and its distribution over the ship length were defined while the details of cargo weights and their centers of gravity (Longitudinal, transverse and vertical center of gravity) were defined for different loading conditions. Direct longitudinal strength analysis is then performed yielding the longitudinal loading, shear force and bending moment for the evaluation of hull-girder stresses. Different loading conditions were evaluated corresponding to the conditions prescribed in the (Lloyd's Register, 2021) rules. Additional loading conditions were also evaluated representing extreme loading cases which may be expected during the ship service. The maximum bending moment realized within these loading conditions is then applied to the ship in order to assess hull girder bending stress as defined in 3.5.3. The procedures followed through for the direct calculation of the design bending moments is described in the subsequent subsections.

4.1.1. *Compartment and Tank Definitions*

With the finalized hull form imported into MAXSURF stability module, the major compartments and tanks comprised in the designed hull were modelled. As defined in 3.4, the hull structure is divided into several water tight compartments by bulkheads, water tight floors and web frames. The wing structure could be utilized for possible ballast while the fuel and lube oil tanks are located within the double bottom structure. This could also serve as a base for the stability analysis of the vessel. The details of the tank and compartment definitions are shown in 0.

4.1.2. *Load Cases*

Corresponding to the possible loading conditions as described in 3.5.2, the different load cases considered are as thus:

- Load Case 1 (LC01) – Light ship condition
- Load Case 2 (LC02) – Fully loaded condition (100% Cargos)
- Load Case 3 (LC03) – 50% Cargo
- Load Case 4 (LC04) – Fully loaded with 10% supplies
- Load Case 5 (LC05) – Light ship 50% ballast
- Load Case 6 (LC06) – Light ship 100% supplies
- Load Case 7 (LC07) – Extreme loading case 1
- Load Case (LC08) – Extreme loading case 2

Load Case 1 – 4 considers the light ship and possible uniform distribution of cargo load and supplies (Diesel oil, lube oil, used oil etc.) within the hold. For this loading conditions, equal mass of containers (Average mass of loaded 20TEU taken as 14tonnes while the average mass of empty 20TEU taken as 2.5tonnes) was considered and distributed as evenly as possible within the cargo hold. These are not critical cases for the structure but useful for verifying the model. The critical cases which generate the maximum hogging and sagging moments are load cases 7 and 8. These are found by distributing unequal mass of containers along the hold which is a most likely situation in real practice. Table 11 shows the maximum bending moments obtained for each loading cases and their corresponding longitudinal positions.

Table 11: Maximum Bending Moments for All loading Cases with Corresponding Longitudinal Positions

As shown in Table 11, the negative bending moments represents the sagging case while the positive moments represent the hogging case. It can also be seen that the maximum bending moment obtained even at extreme loading condition is about 37% less than the rule-based design bending moment. This implies that designing the ship based on the rule-based bending moment will yield heavier structures consisting of thicker plates and profiles. Although the rule-based design bending moment was used for cross sectional property evaluation and initial scantling determination, application of the direct bending moment obtained by direct calculation allows for possible structural weight saving. The latter is then used for the finite element analysis of the structure with respect to the global strength of the ship.

Furthermore, in as much as the bending moment distribution differs for every load case, their maximums are however, found around the mid ship region as seen in Figure 13. This justifies the earlier described failure modes for such vessels as well as the focus of the study on the global strength of the ship with respect to the stresses obtained at midship region. The detail of the longitudinal strength analysis for the extreme conditions is shown in Appendix 4.

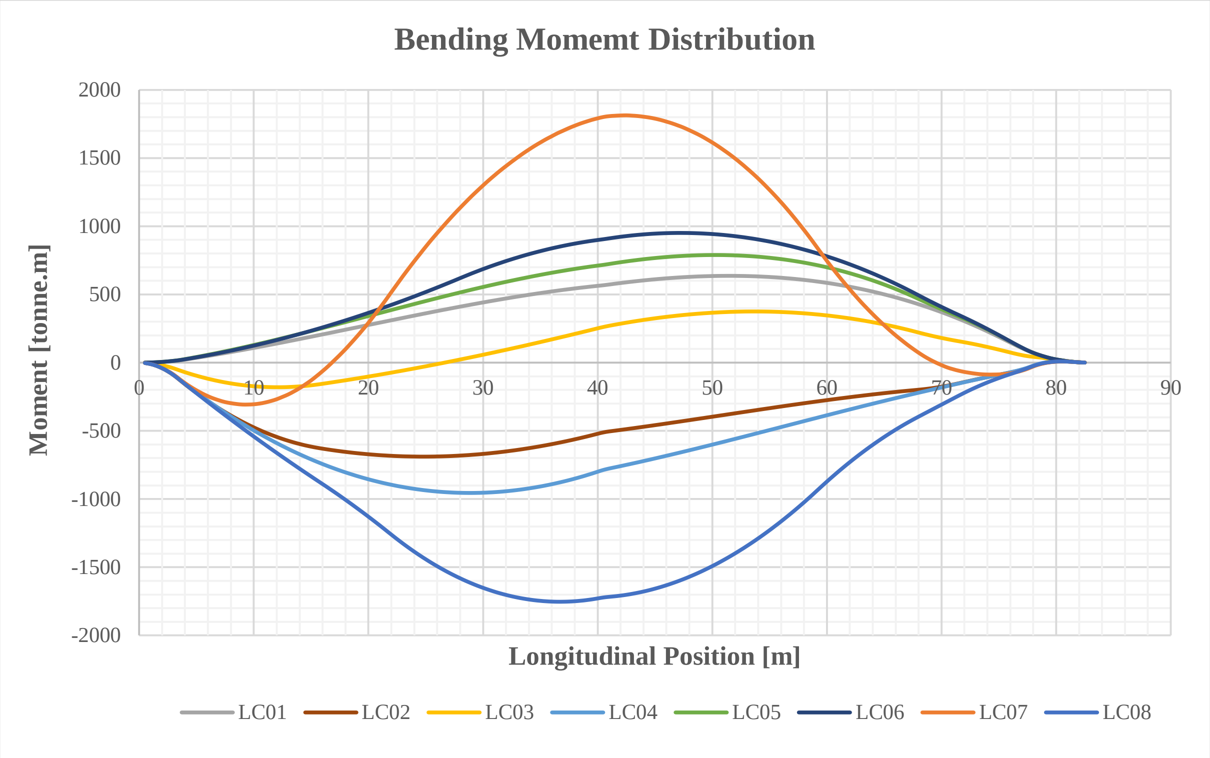

Figure 13: Bending moment distribution for all load cases

4.1.3. *Structure Optimization Technique*

Having obtained the actual bending moment by direct application of the ship weight, loads and buoyancy, the structure is then reassessed with respect to the maxim bending moment obtained by direct calculation. The vertical hull bending stress are then obtained with the actual bending moment according to the midship section analysis performed in 3.5.3 keeping the structural details the same for the first analysis. The results obtained for the hull girder bending stress are then assessed leaving room for the possible optimization of the structure with respect weight reduction.

Two cases were considered for the optimization of the structure assessed through the midship region with respect to the objective function (Weight reduction). The first case been a form of size optimization, reduces the plate and profile thicknesses keeping the technological and geometrical limits while the second case targets a possible geometry optimization by decreasing the overall depth of the vessel (Height of sides). Utilizing the excel program developed for the mid ship section analysis, the two cases of optimization were implemented with the maximum permissible stresses defined in 3.5.3 as limits while the design variables (Profile thicknesses and Height of side) were modified to attain optimum stress values. Finite element global strength analysis is then performed for the optimized structures to further validate the hull girder bending stress with respect to the plate yield and permissible stress requirements defined in 2.5.5.

4.1.3.1. Design Variables

The design variables assigned for optimization are the various panel thicknesses and dimensions comprising the hull structure assessed through the midship section. These thicknesses and stiffener dimensions were carefully adjusted to reach an optimum stress distribution with respect to the set constraints. Table 12 shows the design variables as defined in 3.4.1 Structural Configuration and in Figure 11: Midship Section of Designed Vessel.

Table 12: Design variables

Items	**Item Description**
1	Outer bottom plate thickness
2	Outer bottom longitudinals (8 x HP)
3	Reinforcement outer bottom at wing tank (HP)
4	Center and side girders - double bottom
5	Bilge plate thickness
6	Inner bottom/cargo deck plate thickness
7	Hull - outer side shell thickness
8	Hull outer side shell reinforcement (4 x HP)
9	Mountain plate/sheer strake
10	Weather deck/main deck plate
11	Inner wall – cargo hold long. bulkhead
12	4 x Reinforcement inner wall (HP)
13	Hatch coamings
14	Hatch coaming reinforcement (U-profile)
15	Weather deck reinforcement (1 x HP)
16	Inner bottom reinforcement (8 x HP)
17	Inner bottom reinforcement at wing tanks (HP)
18	Vessel overall depth/height of sides

4.1.3.2. Design Constraints

With respect to the design variables, various constraints were set. As described in 3.5.3 the main design constraints are the allowable stresses assessed in various regions of the ship. Other constraints such as the minimum plate thickness at different regions as defined in 3.4.1 are also applied. To ensure weldability between web and attached plates, minimum web plating thickness in relation to the connected plating shown in Table 13 are established and also applied as a geometric constraint in the optimization process. Plates which are not exposed to extreme loading and environmental conditions and do not contribute significantly to the hull girder strength are drastically reduced while the minimum plate thicknesses are maintained for critical parts. This is however, considered as a side constraint in the process. The stress constraints are considered in two ways; first, with respect to the allowable stress defined by the class rules assessed through the hull section modulus analysis and secondly, with respect to the material yield criterion assessed through von-misses stresses obtained from finite element analysis.

Table 13: Applied Geometric Constraints - Minimum web plating thickness in relation to the connected plating

Plating thickness	Web thickness
6 - 7 mm	5 mm
8 - 9 mm	6 mm
above 9 mm	7 mm

4.2. FE Global Strength Analysis of Structure

The objective of the FE global strength analysis is to calculate and assess the global stresses and deformations of hull girder members. The global analysis is generally based on load combinations that are representative with respect to the responses and examined failure modes, e.g.: yield, buckling and fatigue. Different load concepts and boundary conditions are used for the global strength analysis, depending on the ship type and analysis objectives.

The entire modelling, calculations and post-treatments in the present study are carried out using software Siemens NX.

4.2.1. *Model Description*

In order to satisfactorily represent the global stiffness with respect to the analysis objectives, a 3-D shell FE model of the complete ship length was utilized. The model extends over the full breadth and depth of the ship and represent the actual geometric shape of the hull. The entire ship was modelled including all effective longitudinal material as well as all transverse primary structures (i.e., watertight bulkheads, open bulkheads (mid-hold support structure), web frames and cross-deck structures) Figure 14 and Figure 15. All primary longitudinal and transverse structural members, i.e., shell plates, deck plates, bulkhead plates, stringers and girders and transverse webs, are modelled by shell or beam elements. However, the model is based on the basic design of the structure, meaning that small secondary components or structures such as brackets at frames not contributing substantially to the global strength and have no influence on stresses in the evaluation area of the vessel are disregarded.

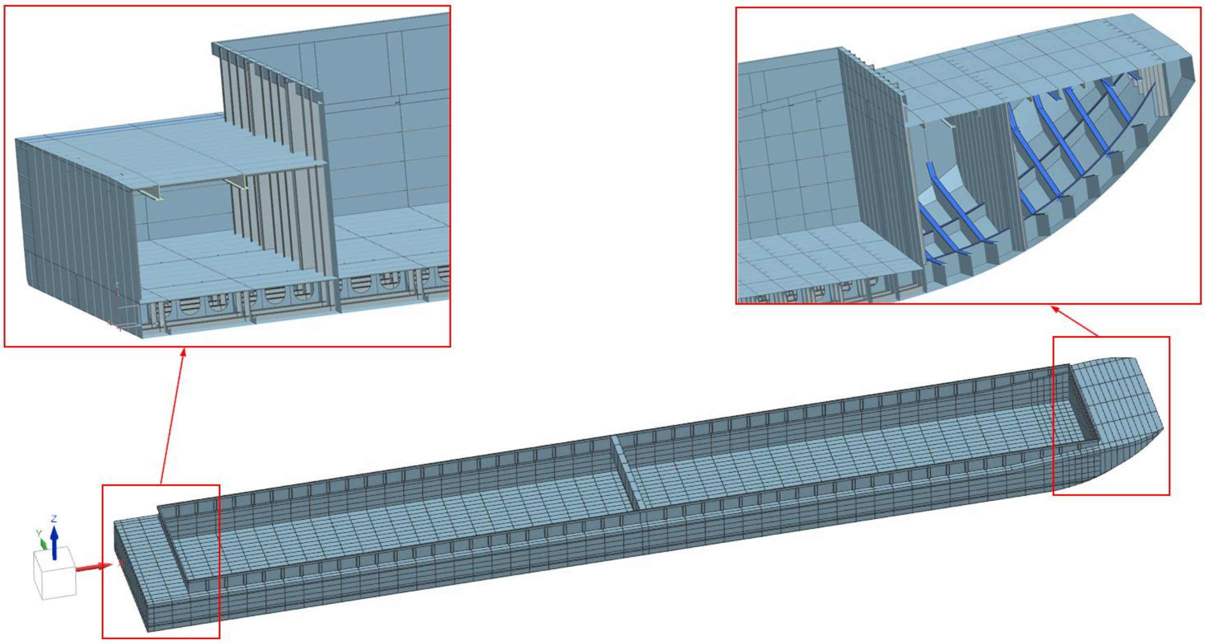

Figure 14: Complete Ship Model Showing Forward and Aft Ends

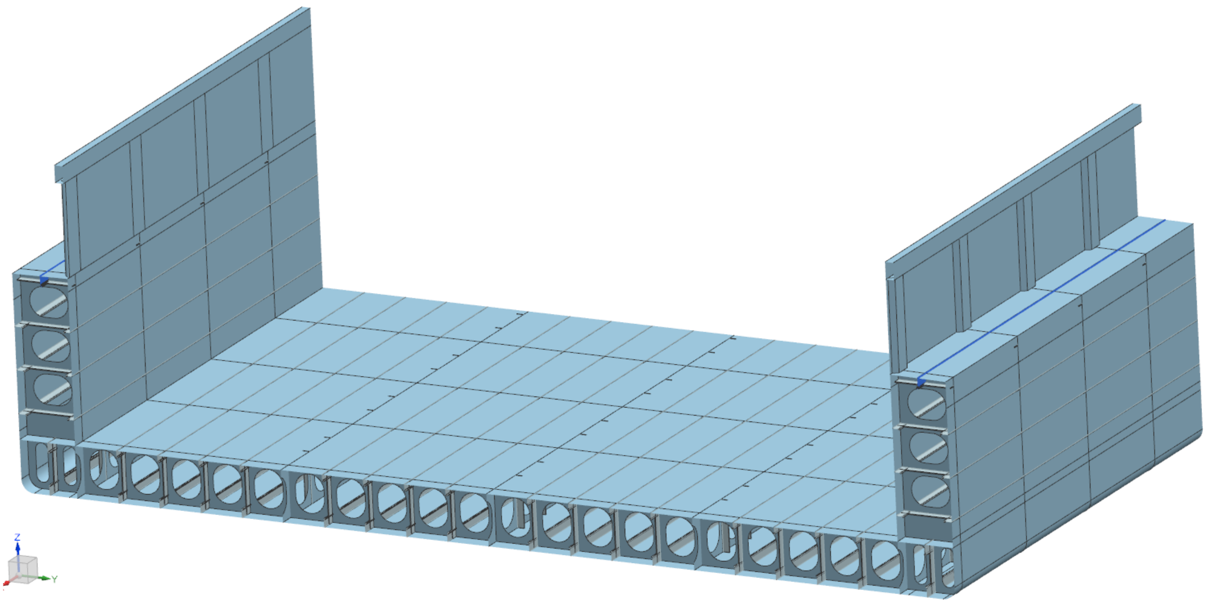

Figure 15: Mid Structure of Complete Ship Model

4.2.2. *Structure Meshing and material specification*

Prior to the meshing of the structure, all faces and edges of the structural members comprising the model were merged and stitched so as to ensure that all structural members are rigidly fixed in their place and deflects as whole structure. Utilizing the software's automated ship meshing tool, the entire structure was meshed. The automated ship meshing allows for easy meshing and grouping of all structural members by creating a mesh collector for all elements with respect to their types and thicknesses. The plate structure is meshed with a 2-D mesh primarily consisting of quadrilateral cells while stiffeners are meshed as 1D-Elements. The meshing is considered as the so-called coarse mesh with sizes automatically adjusted by the software for optimum performance. The material used is as specified as in 3.4.2.

4.2.3. *Boundary conditions*

The boundary conditions for the global structural model were assigned to reflect simple supports specified to prevent rigid body motions. The fixation points are generally located away from areas of interest (Midship region), as the applied loads or moments may lead to imbalance in the model. Hence, the fixation points are applied at the centerline close to the aft and the forward ends of the vessel.

For this study, the global model is supported in three positions, one in the waterline and centerline at the A.P (transverse bulkhead in the aft ship), fixed for translation along all three axes, one at the uppermost continuous deck; fixed in transverse direction and one in the waterline and centerline at the collision bulkhead in the fore ship; fixed in vertical and transverse direction as shown in Table 14.

Table 14: Applied Boundary Conditions

Boundary Conditions	**Loction**	**Displacement in Directions**		
		X	**Y**	**Z**
Aft End	At the A.P on the centerline and waterline	Fixed	Fixed	Fixed
	At the deck on the centerline at the A.P.	Free	Fixed	Free
Forward End	Collision bulkhead on the centerline and waterline	Free	Fixed	Fixed

Schematic representation of the boundary conditions is shown in Figure 16

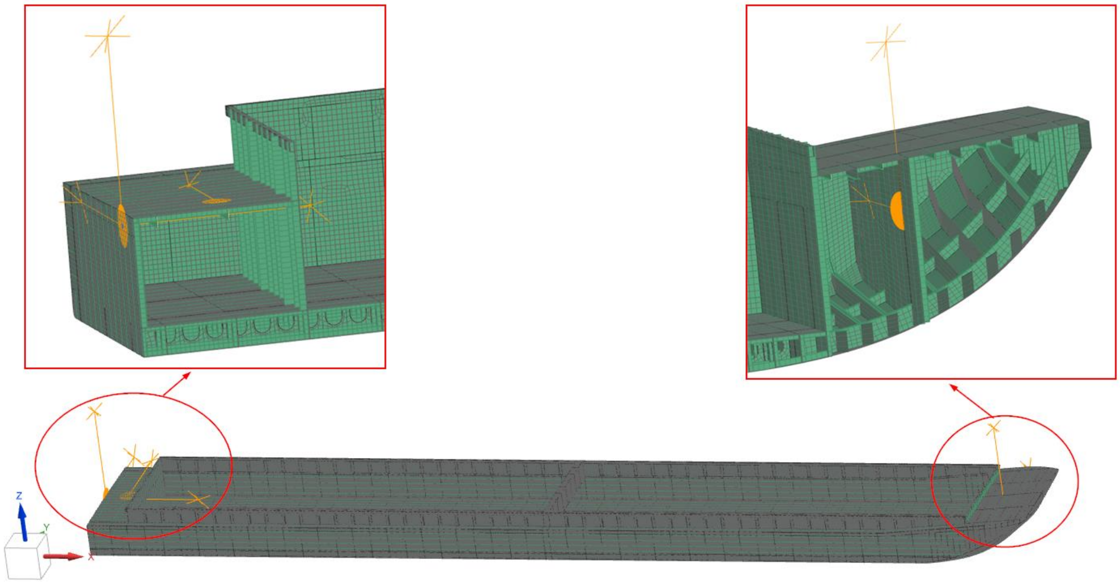

Figure 16: Boundary conditions of the complete ship model

4.2.4. *Load Application*

Various load application methods are possible within this method. However, the loads considered for this study are the maximum hogging and sagging bending moments determined from the load cases defined in 4.1. From the maximum bending moments obtained, the forces required to induce these moments are then calculated and applied as described in 2.5.4. The bending moment is assumed to increase linearly from one end of the vessel till it reaches the maximum and then decreases to the other end as shown in Figure 17. This assumption is valid as the maximum bending moment is well represented at the point of focus.

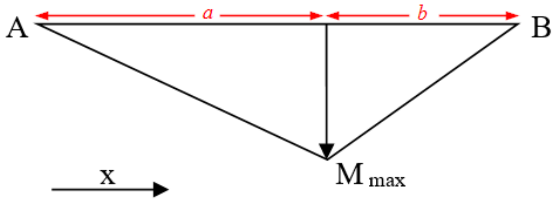

Figure 17: Bending Moment Behavior

Hence, applying Eq (12Eq (12), the maximum bending moment is then converted to the equivalent maximum bending force and applied to the corresponding longitudinal position. Table 1 shows the calculated maximum bending forces (hogging and sagging) applied and their corresponding longitudinal positions. The forces are then applied to the appropriate geometric feature corresponding to the longitudinal position of the maximum bending moments.

$$F_{max} = M_{max} \cdot \frac{l}{a \cdot b} \qquad \text{Eq (12)}$$

Where F_{max} is the force corresponding to the maximum bending moment M_{max}, l represents the longitudinal extent of the ship or ship length, while a and b are parameters describing the longitudinal position of the maximum bending moment.

Table 15: Maximum Bending Forces Calculated

Excluded from public version

Different mode of application of the maximum bending force was examined for both the hogging and sagging conditions:

- Case 1: Maximum bending force applied to complete transversal structure (transversal plate floor and side web frame) at the determined longitudinal position Figure 18.
- Case 2: Maximum bending force applied to the bottom structure (transversal plate floor only) corresponding to the determined longitudinal position Figure 19.

Although the resulting stresses for both cases do not differ greatly, the loading orientation yielding higher stress values were considered for the analysis.

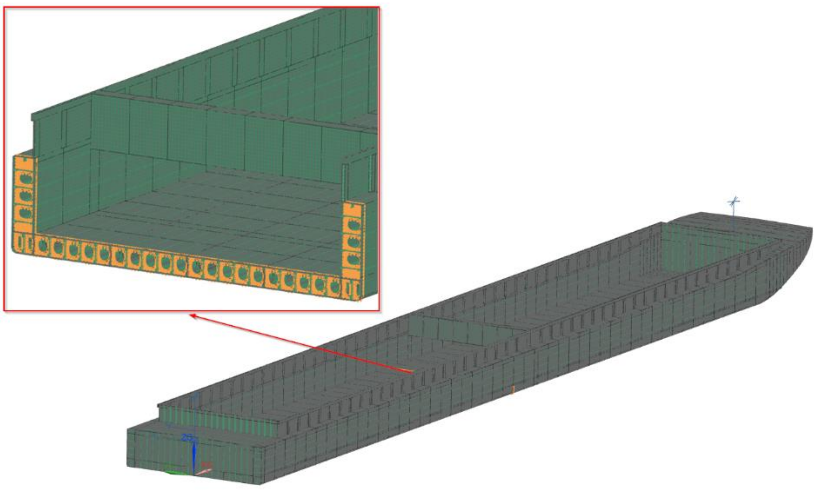

Figure 18: Max. Bending Force Applied at Complete Transverse Structure

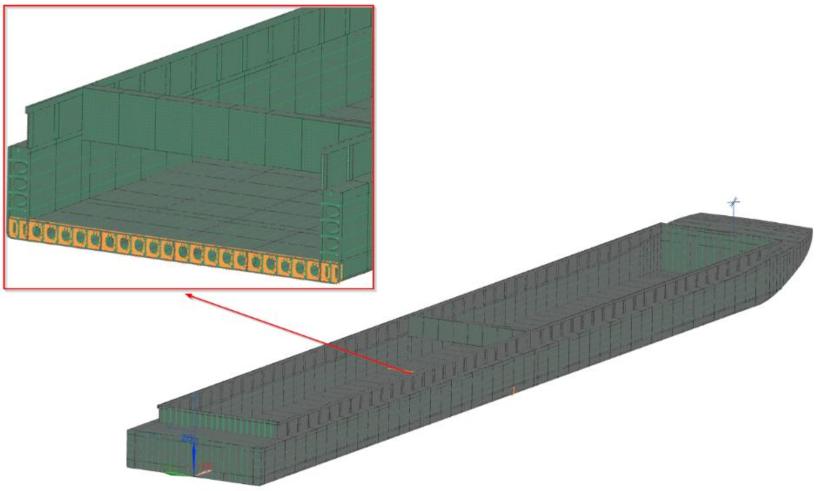

Figure 19: Max. Bending Force Applied at Transverse Bottom Structure

4.2.5. *Analysis and Solution Type*

The calculation is solved with NX Nastran solver structural analysis type. SOL 103 - Real Eigenvalues solution type was initially used to assess the global compactness of the structure i.e., to check if all the structural parts are fixed together and deflects as one global structure. This solution type induces different eigen modes on the structure in order to assess the structural rigidity with respect to the faces and edges of all structural members. Hence, any loose edges or faces can be easily seen from the analysis result. The structure is then solved with the SOL 101 Linear statics, global constraints solution type. Here, the boundary conditions and loads are assigned while the global structural response are then assessed in terms of stresses and displacements.

4.2.6. *Checking Criteria*

The yield criteria described in 2.5.5.1, will be applied in the stress assessment of the global structure. The yield criteria define the maximum allowable von-misses stress in the global structure depending on the material used. For this study the material utilized is mild steel with possibility of applying high tensile steel to highly stressed region depending on the analysis result (Properties described in 3.4.2). Applying Eq (2), the yield criteria for both materials are be calculated and presented in Table 16.

Table 16: Yield Criteria for Materials Used

Items	Item Description	Allowable Von-Misses Stress [N/mm^2]
1	Grade A - Mild Steel [S235]	192
2	Grade AH - High Tensile Steel [S355]	290

5. RESULTS AND DISCUSSION

Within the course of this study, different approaches have been investigated with the aim of minimizing the overall light ship weight of the designed vessel and to maximize the carrying capacity against the events of shallow waters. The concepts developed however, have been analyzed and a comparison is made between them. This section discusses the results realized and provides a general evaluation of the design with respect to the design objectives and operating conditions.

5.1. Structure Optimization (1st Iteration)

Following the procedures defined in 4.1.3, the structure is been optimized against weight. Starting from the size optimization method, the results of the analysis are presented showing how the various design variables (panel thicknesses) have been modified with respect to the specified constraints. Vital in the process of size (scantling) optimization, where the focus is on changing the thickness of the panels are the stress values. Hence, compliance to the longitudinal strength of the section is been ensured in the course of the optimization. The results from the stresses at different regions are also presented. Table 17 shows the results from the size optimization accessed through the midship section.

Table 17: Result from Hull Structure Midship Section Plate Thicknesses Reductions

Excluded from public version

The resulting steel weight, lightship weight and deadweight capacity at maximum draft for the corresponding structures are modeled and analyzed as described in 3.6. Results are displayed in Table 18.

Table 18: Steel weight calculated according to the optimized ship structure and corresponding lightship and mass of lightship and mass of deadweight at fully loaded drafts

Excluded from public version

As seen in Table 18, a 29% reduction in steel weight is realized. This results in significant reduction in light ship weight and can be translated into meaningful payload as the vessel can transport about 110 tons more cargo at same draft. Further analysis on the possible payload capacities at various drafts are investigated subsequently.

A preliminary investigation of the longitudinal strength of the optimized structure was performed as described in 3.5 considering the maximum bending moments obtained by direct calculation. The results are compared with the previous structure and checked with the permissible stress criteria defined in 3.5.3. The resulting stresses at the hatch coamings, deck and bottom structure are presented in the Table 19.

Table 19: Maximum Stress Values Obtained

Designation	**Initial Stress value [Mpa]**	**New Stress value [Mpa]**	**Permissible Stresses [Mpa]**	**Status**
Top of hatch coaming	127.22	138.46	175	
Deck	75.13	84.19	175	OK
Bottom	46.42	42.45	175	

5.1.1. *FE Analysis of Structure*

Having subjected the optimized structure to finite element analysis the global response is then studied with respect to the applied loads. The stresses and deformations at areas of interest were investigated giving an insight into the overall bending resistance of the hull structure and its compliance to various evaluated strength criteria. The model is been subject to forces inducing deformations in both hogging and sagging orientations as described in 4.2.4. The results realized are as presented as follows.

Table 20: Calculation Results

Loading Case	Max. Displacement	Max. Von-Mises-Stress	Material Yield Criteria [Mpa]	Status
LC07 (Hogging)	107.35 mm	167.10 N/mm^2	192	OK
LC08 (Sagging)	105.66 mm	166.88 N/mm^2	192	OK

5.1.2. *Stress Distribution*

Investigating the stress distribution across the analyzed model, the von-misses stresses are seen to be under the yield and permissible stress of the material at all areas of the structure. However, due to the boundary and load application methods, higher stresses were observed specifically around the boundary and the transverse extremities of the loaded frame in both loading conditions. These regions of higher stresses are identical for both loading conditions (Hogging and Sagging). Spherical plots, Figure 20 and Figure 21 are used to reveal these regions for further investigation.

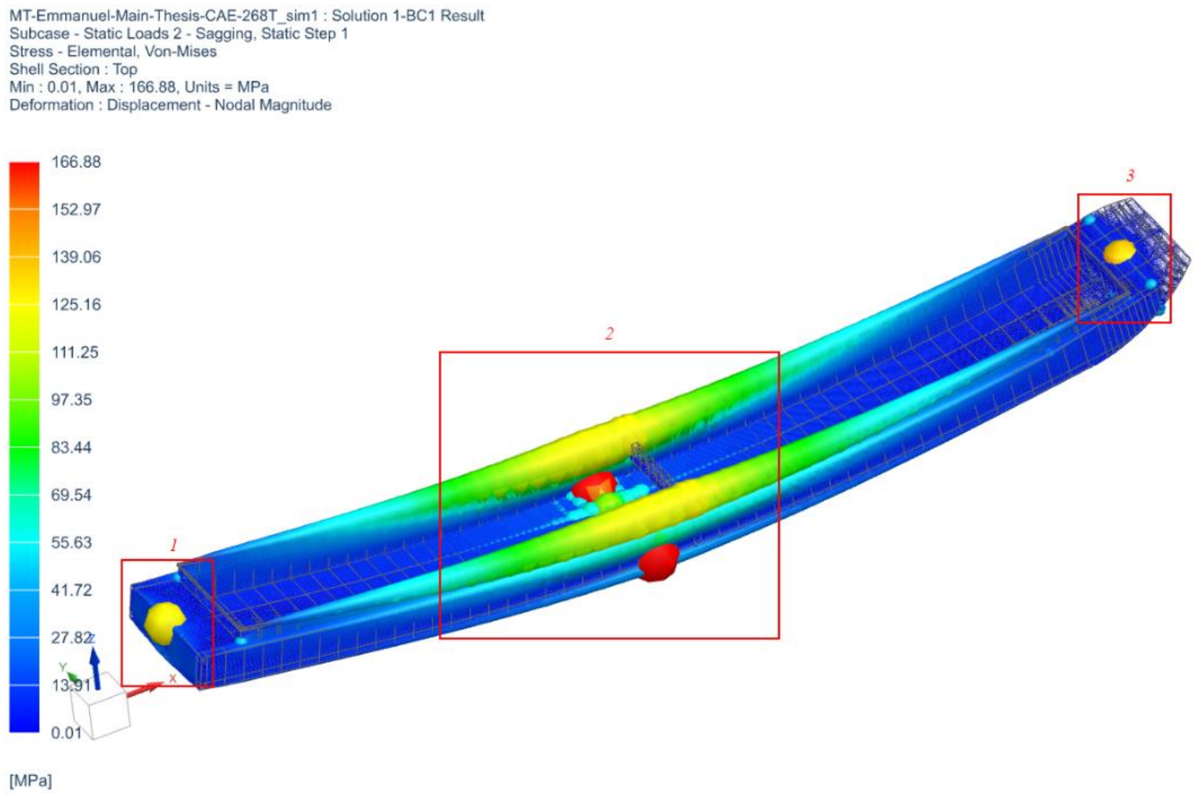

Figure 20: Higher Stress Region (Sagging Condition)

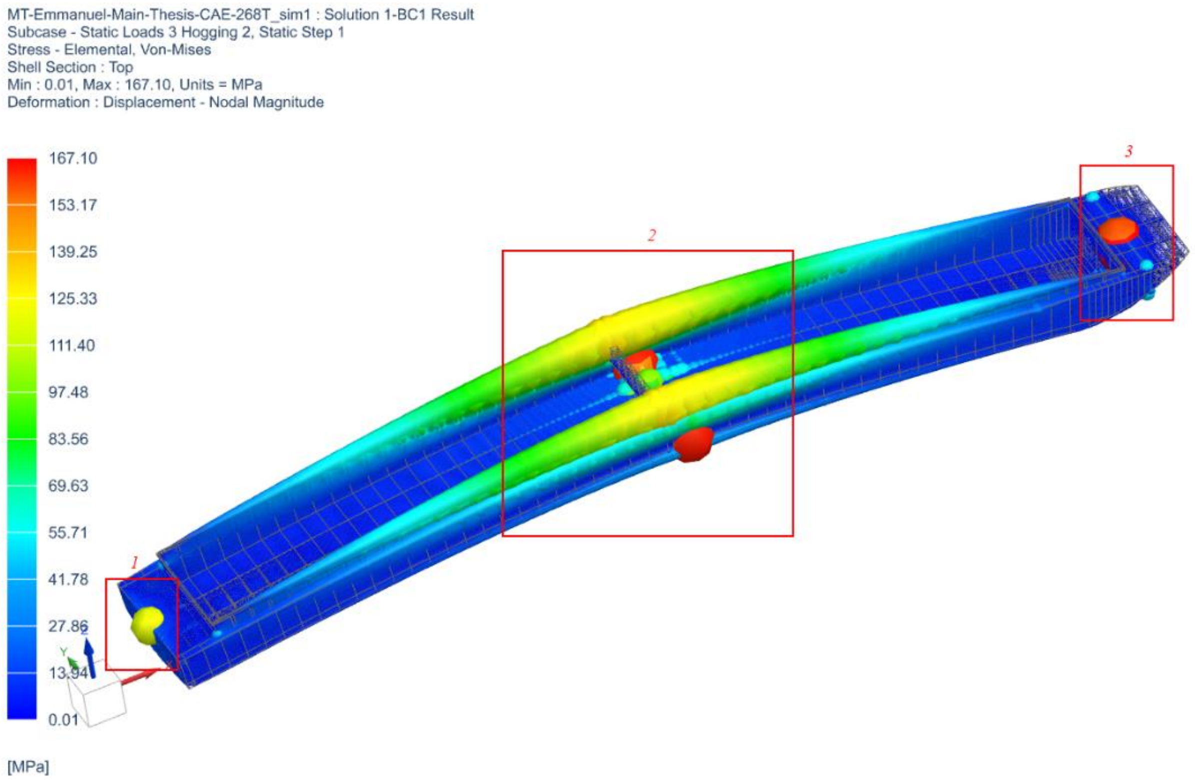

Figure 21: Higher Stress Region (Hogging Condition)

A closer examination of these regions pronounced by large red spheres shows a jump in stress values and are limited to a single cell or 2 adjacent cells where the point is in the line of transversal symmetry. This is an indication of singularities as the stress is concentrated within these regions. These points could be found in the forward and aft constraints Figure 22. The boundary conditions are however an idealization of a floating ship but without additional external constraints which makes the stress values in these regions overestimated. For the evaluation of the global strength of the ship, the stress values at these boundaries can be neglected.

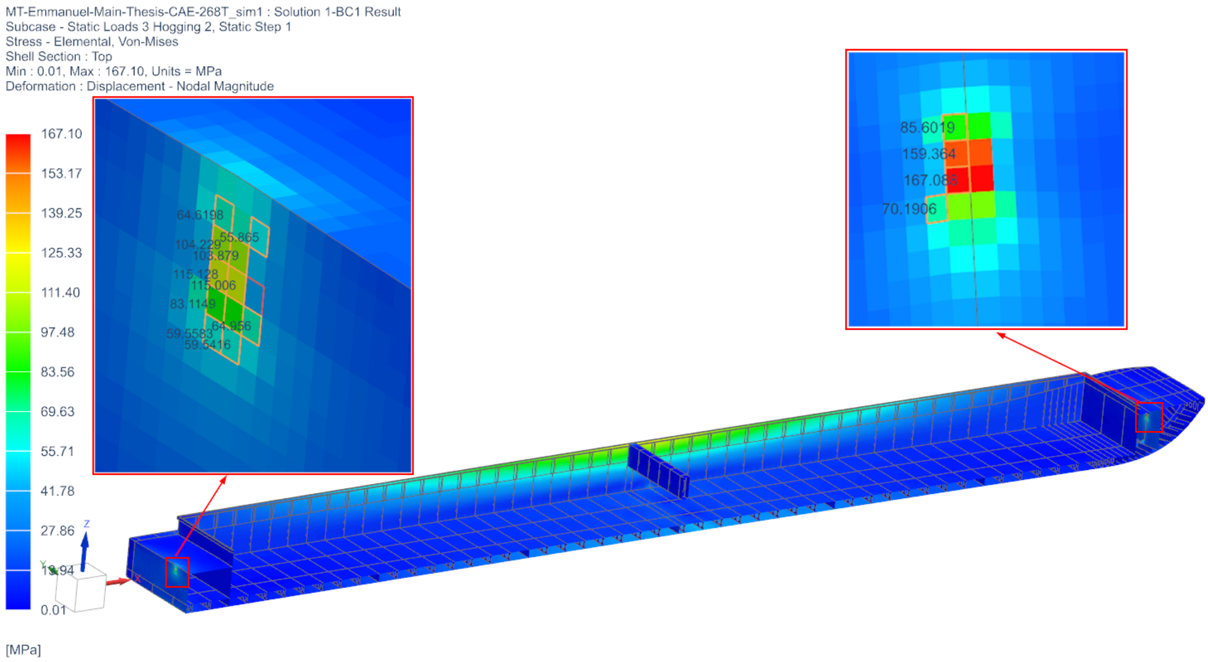

Figure 22: Peak Stresses at Aft and Forward Constraint

Another region of higher stress concentration is at the transverse extremities of the loaded frame shown in Figure 23. The stresses result from the occurrence of high transversal stiffness and due to the conspicuous orientation of the loading. The stress concentration in this region could be further analyzed by local analysis consisting of a finer mesh and a more detailed loading but however, this is not the case for the global strength analysis coupled with the fact that the allowable and material yield stress are no exceeded.

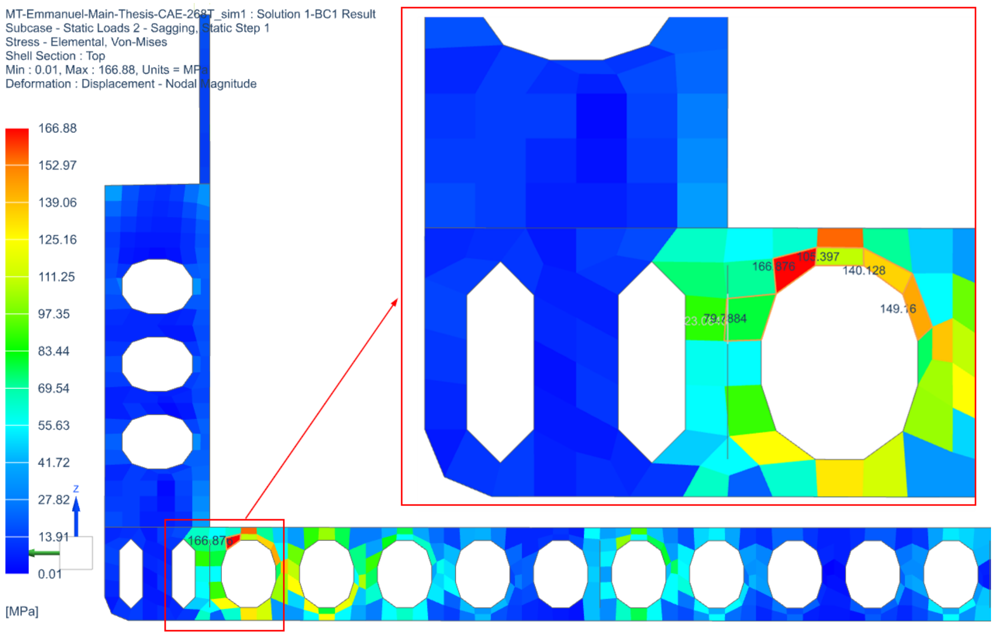

Figure 23: Higher Stress Concentration in the Loaded Frame

Furthermore, apart from the region characterized by red spheres as shown in Figure 20 and Figure 21, the stress distribution is seen to agree with the analytical solution as notable stress values are seen at the top of the hatch coamings and outer bottom around the midship ship region. The stress values are the highest at the top of the hatch coaming with maximum values conforming to analytically determined values. To access the maximum stress at these regions, a plot is generated along the path by highlighting a series of elements within the region. Figure 24 shows the highlighted region of notable stress along the hatch coaming while Figure 25 shows the corresponding stress along the path.

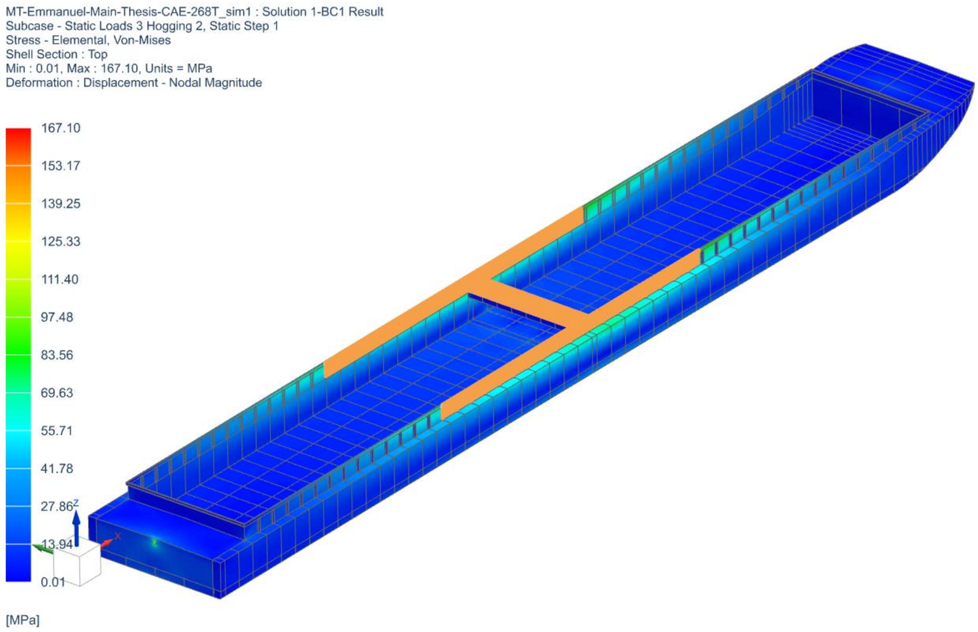

Figure 24: Highlighted region of notable stress

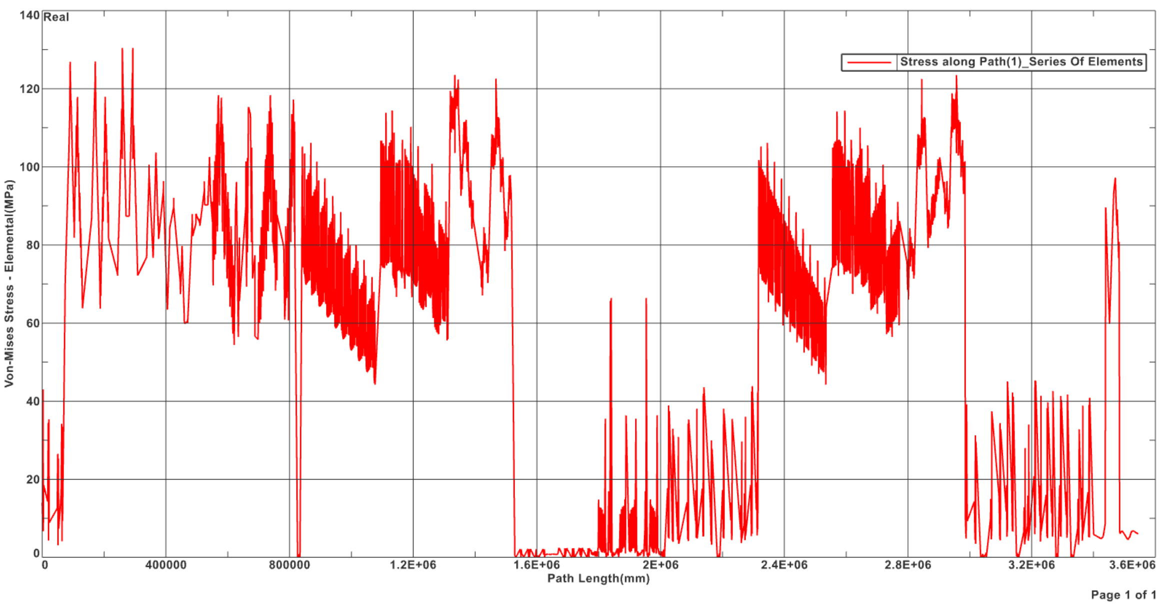

Figure 25: Stress Along the Hatch Coaming at Midship Region

As can be seen in Figure 25, the maximum von-misses stress obtained along the hatch coamings at the midship region are way below the allowable stress and conforms to the analytically results with maximum values below 140 Mpa.

5.1.3. *Displacement and Deformation of structure*

As expected, the structure deforms in the direction of the applied forces. As shown in Figure 26, the maximum displacement is obtained in hogging condition. However, the displacements for all cases are within reasonable ranges with values ranging from 108mm in sagging condition to 109 mm in hogging condition. In connection to the ship's dimensions the displacement in all cases is considered to be within allowable limits, especially as it corresponds to the extreme and partly concentrated loading and boundary conditions. Hence, the deformation will however, be less in reality.

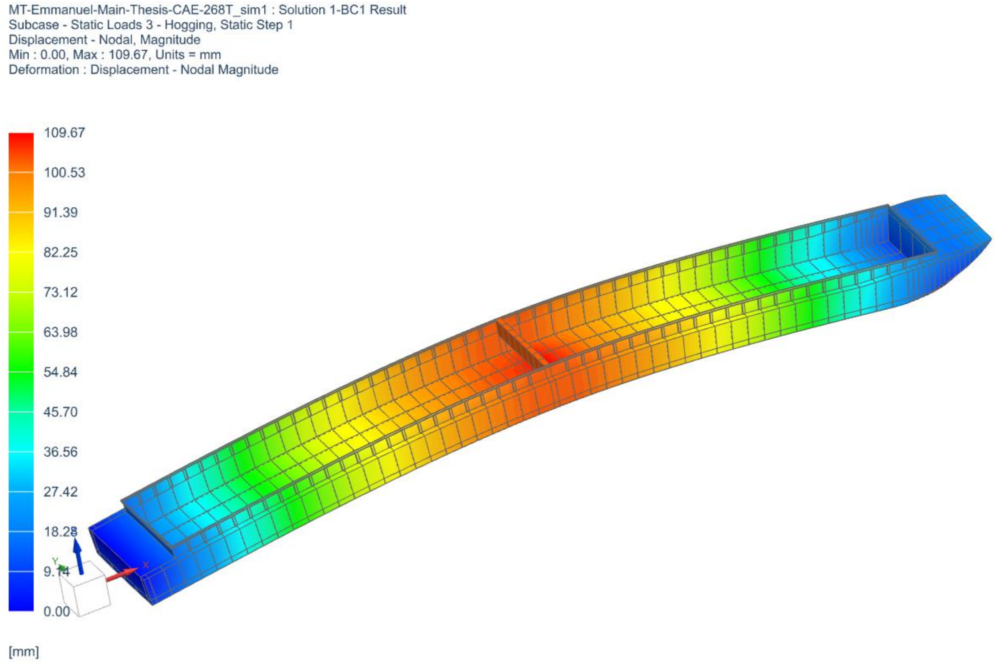

Figure 26: Maximum Deformation at Maximum Hogging Moment – LC07 (Scaled at 5% Model)

Generally, the results from the global strength analysis shows that the structure is able to withstand the bending moments for all load cases even in the extreme loading which rarely occur in reality. In as much as there are regions of high stresses due to the orientation of the loading and boundary conditions the structure is seen to maintain stress values below the allowable stresses and material yield stress.

5.2. Structure Optimization (2nd Iteration)

Here, the results from the 2nd iteration are been presented. An attempt to further reduce the structural weight is been made by reducing the overall depth of the vessel keeping the hull structural components (panel thicknesses and profile dimensions) the same as in the 1st iteration. The depth is reduced while considering the rule prescribed geometric constraints($L/D \leq 35$ & $B/D \leq 5$). The depth is reduced by 30cm i.e., from 2.8m to 2.5m and the influence on the overall structural strength and weight is been evaluated. Result from the weight estimation corresponding to the reduction in depth is as shown in Table 21:

Table 21: Steel weight for the optimized ship structure 2 and corresponding lightship and possible deadweight masses at fully loaded drafts

Excluded from public version

As seen in Table 21, there is no significant weight reduction realized from the depth reduction. This could be attributed to the geometric orientation of the vessel and also due to the careful selection of main dimensions in which the vessel depth had already been optimized as a first stage to the weight optimization at the earlier stage of the design. Not much material could be assessed within the optimized region as the vessel is characterized by open and extended cargo hold. Hence, only structural components vertically extending towards the maximum height of sides of the structure are affected.

Furthermore, a decrease in depth of the vessel also translates into a decrease in the vessel's draught and if the weight reduction realized are not within reasonable amount, the advantages of the reduced depth are then offset by the disadvantages associated with the vessel's limited operation in normal water conditions. In this case, only about 16 tons of weight saving could be realized by the reduction of the depth corresponding to a draft to 2.3m.

A preliminary investigation of the longitudinal strength of the vessel realized from the 2nd iteration is also performed and results obtained are presented in Table 22.

Table 22: Maximum Stress Values Obtained at Midship Section

Designation	**Stress value [Mpa]**	**Permissible Stresses [Mpa]**	**Status**
Top of hatch coaming	176.69	175	Exceeded
Deck	92.46	175	OK
Bottom	47.93	175	OK

As seen from Table 22, the stress values obtained from the longitudinal strength analysis at the midship section exceeds the permissible stress by a small margin at the top of the hatch coaming. This is normally improved by increasing the plate thickness at such regions but as the focus is on weight minimization, a form of material optimization could be employed. This entails the use of high-tensile steel at these regions. Since high stresses occurred at the upper end of the hatch coaming, the utilization of high-tensile steel for upper end of the coaming and the coaming longitudinal stiffener, would be useful. With the application of high-tensile steel, the material yield strength is improved leading to an increase in the permissible stress and the corresponding yield criterion (See Eq (10) and Table 16: Yield Criteria for Materials Used).

5.3. Evaluation of Design Performance

Each concept developed and investigated within the framework of this study provides a plausible solution towards tackling the earlier delineated bottlenecks. Each concept is developed with the aim of maximizing their cargo carrying capacities while maintaining a reasonable draught to payload ratio in low as well as normal water conditions. Table 23 gives an overview of the main properties of each solution obtained. The initial design was developed by careful consideration of the vessel main dimension as a first step to the optimization of the design while the second and third concept proceeds to further optimize the design by adjusting the properties of the initial design. However, in as much as the proposed solutions share similar characteristics, an evaluation of the different concepts as regards the design objective points out the various advantages of each concept over the other as well as their limitations.

Table 23: Main properties of vessel corresponding to the proposed concepts

Excluded from public version

As can be deduced from Table 23, each developed concept provides a plausible solution even though they differ in their carrying capacities. The light ship mass resulting from the 1st and 2nd iterations are seen to decrease by some 24% and 28% respectively from the initial design. This could contribute tremendously to the cost of production and cargo carrying capacities of the respective designs as less steel weight is needed. When compared to the other concepts, the results corresponding to the 1st iteration stands out as the it offers more advantages over the other designs in both normal and shallow water conditions. In normal water condition i.e., at draught above 2.3m, the design corresponding to the 1st iteration transports 110tons more cargo than the initial concept and 270 tons more than the 2nd iteration which is limited by its design draught. When analyzed at drafts below 2.3m the 2nd iteration transports 16tons more cargo than the 1st iteration. The advantages of the 2nd iteration at reduced draught could be easily offset by those of corresponding to the 1st iteration in normal water conditions.

In terms of TEUs transported, each concept is developed with a cargo hold capacity of transporting standard ISO TEUs in 4 row and 12 bay arrangements. When compared to each other, a maximum of 160 TEU can be transported by the optimized ship corresponding to the 1st iteration results when taking an average mass of 13tons per container. This means the vessel can be loaded up to 4 tiers. However, depending on the mass of containers loaded, the number of TEUs transported could be increased significantly. For example, when taking an average container mass of 10tons per container, the vessel will be capable of transporting 192 TEUs at 4 layers. The number could be reduced when the vessel is required to sail at lower draughts.

Furthermore, in order to assess the transport capabilities of respective designs, a simple parameter defined by (Bačkalov, et al., 2016) is introduced. Assuming that the proposed vessel operates fully laden 350 days a year, the “reference cargo” is calculated as:

$$R_C = m_{DWT} \cdot 350 = 691516\, t \qquad \text{Eq (13)}$$

Reference cargo may be described as the maximal annual cargo carrying capacity of the vessel. The reference mass of deadweight used is the one corresponding to the initial design. Knowing the deadweights of other analyzed concepts, it is possible to calculate the number of days required by each of the vessels to transport the same amount of cargo. Hence, analyzing the concept based on the reference cargo, the 1st iteration will require 18 days less to transport the reference cargo while the 2nd iteration will require about 1 month more. However, the deadweights given in Table 24 correspond to navigation in unrestricted water depth, i.e., in conditions that allow each vessel concepts to sail with her design draught. If the water levels drop, or vessels are supposed to sail through shallow-water sectors, the situation changes drastically. The cargo carrying capabilities of heavier and deep draught vessels sharply decrease and the time necessary to transport the reference cargo prolongs considerably. So, if the water level does not allow navigation with draught greater than 2.3, the initial design will require some 2 months more while the 1st and 2nd iteration will 1 month more to transport the reference cargo (see Figure 27). Hence, from these evaluations, the solution corresponding to the 1st iteration could be considered as the optimum design for this study as it offers better results with respect to the examined operating conditions.

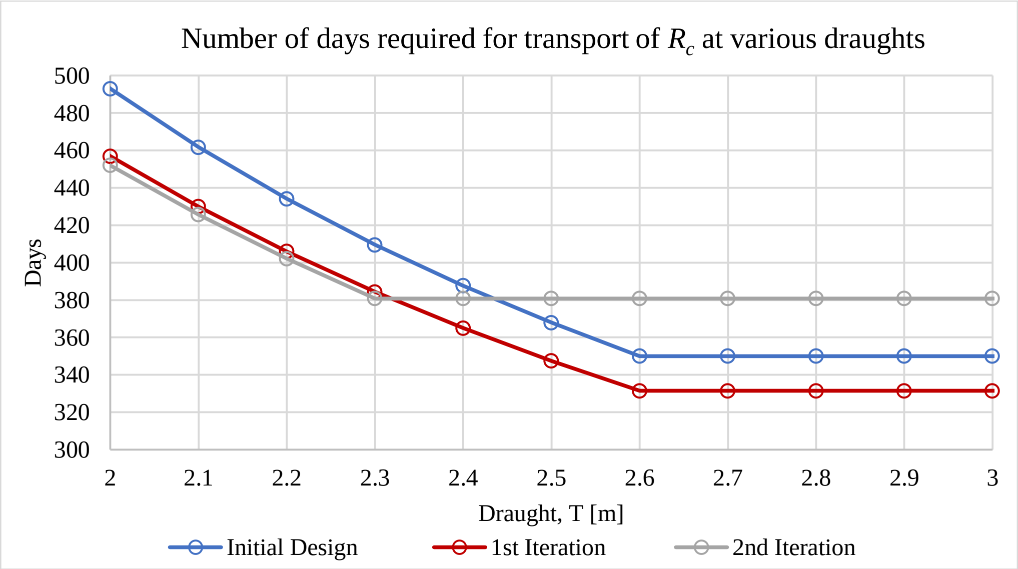

Figure 27: Number of days necessary to transport the reference cargo, *Rc* by each examined concepts, depending on possible draughts

Several concepts of general cargo and container vessels operating within the Rhine region and its tributaries have been developed over the years, most of which are self-propelled vessels designed to operate in normal water conditions although could also be utilized for lower draughts with lesser payload. However, several concepts for shallow water conditions have also been developed within the frame work of various researches most of which are directed towards the self-propelled vessel types.

The proposed vessel within the framework of this study is however, a push barge designed to operate in combination with a push boat or with a motor vessel in a pushed convoy. Hence, the design is benchmarked against other barge concepts within these regions. One of the most common river barges operating in a large scale within these regions are the EUROPE II barges. It is built as type II, II a and II b. The differences between these variations consist in different draughts and consequently different loading capacity. For the operation on a lower water depth (e.g., upper Rhine, Elbe) the type EUROPE II c was developed. It differs from the above called types by the lower molded depth (Müller, 2003). Other concepts also exist. Some of which covers a wide range of design draughts and main dimensions, while keeping the standard breadth the Rhine vessels.

The performance of the proposed optimum design would be benchmarked against these concepts whose main features are given in Table 24.

Table 24: Main Particulars of Existing Rhine Barge Concepts and the Proposed Design

Excluded from public version

Analyzing the proposed design against the listed barge concepts and applying the reference cargo idealization described in Eq (13) using the deadweight of the proposed concept as the reference mass, the Europa II and IIa concepts will require lesser number of days to transport the reference cargo at normal water conditions while the Europa IIc will require more. However, in limited water depths, none of the concepts can compete with the proposed design. The cargo capacity of the proposed design at draughts lower than 2.6m is marginally greater than those corresponding to the other concepts. Thanks to the weight saving realized from the structural optimization.

Still, a question of particular importance for inland navigation is which water depth could be considered as sufficient for a safe sailing with a specified draught? Taking the Kaub gauge as reference, low water levels are considered at Kaub gauge reading below 150cm and this corresponds to an allowable vessel draught of 2.3m considering an under-keel clearance of 32cm (see 2.1.2). At a Kaub gauge level of 40cm i.e., at an allowable draught of 1.2m, navigation may be considered as unreasonable. However, there is no official low water level at which Rhine traffic is stopped. The only limitation is the payload capacities of the cargo vessels at limited draughts. If the designed vessel offers a considerable amount of payload at limited draught, then navigation is possible. Table 25 shows the tonnage capacity of the proposed vessel at various draughts.

Table 25: Proposed vessel capacity at different gauge values (Kaub) and draughts

Excluded from public version

Depending on the draught requirements the proposed design could be loaded as specified in Table 25. The TEU capacities were calculated assuming an average container mass of 13tons for the lower limits and an average container mass of 10tons for the upper limits.

The number of low water days per year (i.e., at Kaub gauge ≤ 150cm) varies from year to year. Vessel operators therefore, have to rely on projections from analysis of previous trends and recommendations of climatologists while making cost related estimations. Taking the severe cases like in 2003, 2011 and 2018 for example, where there was low water for more than 150 days in the years, the proposed design offers a better solution. Hence, at Kaub guage value of 180cm and below, the proposed design performs better than most existing designs in terms of cargo capacity.

5.3.1. *Barge Train*

The main advantage of the proposed design over the standard self-propelled vessel type is the flexibility in operation and in reduced draught, a cost-effective navigation with partly loaded barges could be utilized. If navigation with a reduced draught would be required, then to substitute for reduced carrying capacity, the number of barges in a convoy might be increased. The proposed barge could be combined in a pushed convoy of 2-6 barges operated by a push boat or in combination with a motor vessel. Navigation is plausible at extreme water condition but limited to the draught capabilities of the pushing unit which cannot be reduced below a certain level. Hence, the transom and propeller of the pushing unit should be design for minimal draught.

In order to achieve a reasonable payload capacity at reduced draughts, a combination of the proposed barge with a low draught push boat would be more advantageous. Conventional push boats with power around 2000kW usually have draughts above 1.7m, however, a lower draught push boat with could be realized within same range of power will be sufficient to transport a push train of more than 4 fully loaded barges. A push boat with the following features proposed by Radojcic (2009) could be utilized:

- **Length, breadth and height (L x B x H)** – 30 x 11 x 2.5m. The length is chosen with conditions to provide enough space necessary for all machinery and crew. Although somewhat longer would be acceptable but with limitations based on possible length of convoy. The breadth is selected with the aim of maintaining somewhat same breath as a standard pushed barge although can be adjusted to have same breath as the proposed pushed barge for easier operation (e.g., Easier barge parking with similar breadth as push boat). The height is considered as minimal for fitting engines and other necessary machine-room equipment below the deck.
- **Draught (T)** – 1.4 maximum. With view of the low water operations, a draught of 1.4m is selected. A propeller in a nozzle with a diameter of 1.5m which would accept a power of up to 700kW could be installed. Hence, this makes a three-propeller installation feasible.
- **Propulsion** - Low emission Stage V diesel engines of 3 × 700 kW with exhaust gas after-treatment systems and relatively high power to weight ratio is proposed. Transmission of power to be via a conventional horizontal shaft line and a gearbox (i.e., diesel-direct). With an installed power of around 2000 kW, sailing with a push train of more than four fully loaded proposed barges at usual convoy speeds is possible during most of the navigable season. For propeller type, a triple-screw propulsion, (skewed) propellers in nozzles with a diameter (D) of 1.5m, located in a relatively shallow tunnel is proposed. With respect to the breadth and high-speed diesel engine, the propeller diameter is considered to be sufficient. Special attention should be paid to the design of tunnels, propellers and nozzles with the aim to increase thrust and reduce vibrations (model experiments and CFD analysis are recommended).
- **Ship form** – Optimized ship hull form with tunnels is proposed as relatively large power needs to be installed within an extremely shallow draught hull. Hence, the tunnels are of utmost importance. The transom and propellers should always have a draught of around 1.4m, while weight variations (due to fuel consumption) should change the bow draught only. Model experiments and CFD analysis are also recommended.
- **Weight** – Taking into account lightweight engines and other equipment and machinery, a weight of 270t is roughly estimated. A fully loaded push boat with fuel and other provisions should weigh around 350t (at a level draught of 1.4 m). Weight saving should also be considered wherever possible.

- **Steering** - Three fish-tail rudders located behind propellers (without flanking rudders) and a gondola type bow thruster, with an electric motor of around 300 kW, should be considered for easier maneuvering.
- **Wheelhouse and accommodation** – A wheel house with the possibility to be raised to increase visibility to at least 250 m ahead of the ship, as requested by statutory regulations. Accommodation premises in one-tier superstructure on the deck (comprising 4 single and 2 double cabins, although this depends on the shipowner's needs/request) is recommended. Living premises to be fully air-conditioned. Resiliently mounted superstructure (on pneumatic shock absorbers) for reduced vibrations, noise and increased comfort should also be considered.
- **Auxiliary equipment -** Shore-to-ship-power supply should be considered with the aim to reduce onboard diesel emissions. Electronics and computerization should be of the latest technology, providing one-man watch operation of the vessel with the engine and ship-system monitoring and recording, voyage optimization, etc. Provision for long range pushing is also recommended.

Although the proposed features are not optimum as various aspect are subject to scrutiny but this is however, considered as a base for the possible actualization of a push boat capable of coping with the low water conditions. Table 26 outlines the main particulars of the proposed push boat.

Table 26: Main particulars of proposed push boat (Radojcic, 2009)

Loa [m]	30.00
Boa [m]	11.00
H [m]	2.50
T [m]	1.40
Height above base line	6.00
P_B [kW]	3 x 700
Bow thruster [kW]	250-300
Crew capacity	8

The main advantage of the proposed push boat is its extremely low draught of only 1.4m compared to draught of above 1.7 m of similar conventional push boats. This enables navigation with partly loaded barges in low water condition. Utilizing the proposed design, at a draught of 1.4m the barges could be loaded up to half the maximum capacity (See Table 25) and a combination of 4 barges for example yields a total cargo capacity of about 4000tons. Other factors such as the application of the latest technologies that increases the efficiency, safety, comfort and cleanliness (for instance: the use of gondola-type bow thruster which enables enhanced maneuvering capabilities and clean engines) are also advantages of the proposed concept over existing ones. As a form of concept sketch, a general arrangement plan is shown in the Appendix 5 of this report.

Speed is normally deemed as one of the crucial parameters of vessel's profitability. In restricted waterways, the speed may be limited by the hydrodynamic effects related to navigation in shallow water. These "speed limits" may have to be applied not only in order to avoid drastic increase of ship resistance (that normally occurs at Fnh ≈ 0.7), but also to prevent contact with the river-bed and grounding, due to squat. Therefore, the speed may be limited due to safety requirements, which, in turn, may increase the transport costs.

6. CONCLUSION

In this study which examines the design and optimization of cargo vessels with focus on pushed barges capable of coping with the seasonal or protracted periods of low waters caused by the effects of climate change on the average water levels within the European inland water ways, several concepts have been investigated within this frame work while attempting to put forward a conceivable optimum solution with respect to the existing infrastructures and navigational conditions.

The study investigates the possibility of maximizing the cargo capacity of push barges through design and structural optimization carried out at different levels of the initial design phase of the vessel. The careful investigation and selection of the vessel main particulars during the conceptualization stage serves as a first step to the optimization process. Following the proposed concept, a plausible solution was first proposed by applying the traditional ship design principles towards the actualization of the initial concept design which was then evaluated against the design objectives. Subsequently, as a second step to the optimization process, an overall hull structure optimization which was aimed at minimizing the overall lightship weight was investigated and a considerable weight saving was realized. This was achieved by the application of design bending moments obtained by direct calculation towards the investigation of the longitudinal strength of the proposed design. As opposed to the rule-based design bending moments, the direct modeling of the load due to light ship weight, deadweight and hydrostatic pressure yielded a considerably lower design bending moments even at extreme loading conditions.

Taking advantage of the increased strength capabilities of the initial design with respect to the calculated bending moments, the possibility for considerable amount of hull structural weight saving became evident. This was then realized by first, performing a form of size and scantling optimization (reduction of the hull structure plate and profile thicknesses accessed through the midship section) and subsequently, attempting to adjust the main geometric features of the vessel (geometry optimization) while maintaining the prescribed longitudinal strength limits. The overall global strength of the optimized structure is then investigated by finite element analysis. The results from the global ship analysis showed that the optimized structure withstands the applied design loads with respect to the material yield stress criterion even at extreme loading conditions. Also, with respect to the investigated failure modes for such vessel configuration, the results from critical regions especially within the hatch coamings, main deck and double bottom structure at midship region were found to be way below the material yield stresses. The attempt to further optimize the structure by adjusting the geometric properties (reducing the height of sides) also yielded considerable results when compared to the initial design but however, not considered as the optimum due to draught and possible deadweight limitations when compared to the initial optimization results.

Furthermore, the evaluation of the design performance reveals the applicability of the proposed optimum design in both normal and low water conditions. In as much as the carrying capacity of the proposed design is limited due to the design draught, a considerable amount of cargo could still be realized in normal water conditions when compared to existing concepts. However, at periods of low water or where vessels are required to navigate with limited draughts, the proposed design stands out in terms of cargo carrying capacity and flexibility in operation. The cost advantages of the proposed design could be realized in terms of building cost as the reduced steel weight tremendously reduces the cost of production. While the increases cargo capacity at lower draught and the so-called low water surcharge associated with vessels operating at water low water levels could be an advantage in terms of operational cost. The high flexibility in cargo type and in configuration with other vessel types and barges are also eminent advantages of the proposed design. At extreme water conditions, the proposed barge could be pushed by the proposed shallow water push boat in combination with other barges which then increases the cargo capacities realized in these conditions.

7. FURTHER WORKS

In as much as the result proposed was considered as optimum with respect to the investigated objectives, there are still possibilities for improvement. Some of the possible aspects that could be investigated for further improvement of this study are:

- The global strength of the ship structure had been investigated but however, local analysis at different sectors of the hull structure could be investigate with aims of further reducing the structural weights especially at regions not actively contributing to the global strength or affected by extreme loadings.
- Innovative approach such as the application of light weight material could also be investigated. For example, the use sandwich plate or panel system (SPS). However, this must be checked with the necessary strength and possible cost implications as the technology is not trivial.

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10. APPENDICES

Appendix 1. **Moment of Inertia and Section Modulus Calculation**

Excluded from public version

Appendix 2. **Light Ship Weight Estimation (First Case)**

Excluded from public version

Appendix 3. **Tanks and Compartment Definition**

S/N	Name	Type	Intact Perm. %	Damaged Perm. %	Specific Gravity	Fluid Type	Aft [m]	Fore [m]	F.Port [m]	F.Stbd [m]	F.Top [m]	F.Bott. [m]
1	Aft Peak	Compartment	95	95			0.00	3.50	-7.00	7.00	5.00	0.00
2	Cargo Hold	Compartment	95	95			3.50	77.62	-7.00	7.00	5.00	0.00
3	Engine room	Compartment	95	95			77.62	79.50	-7.00	7.00	5.00	0.00
4	Fore Peak	Compartment	95	95			79.50	83.00	-7.00	7.00	5.00	0.00
5	Tank001 prt	Tank	98	95	1	Water Ballast	0.00	3.50	-7.50	-5.03	3.45	0.60
6	Tank 001 Mid	Tank	98	95	0.001	Dry	0.00	3.00	-7.00	7.00	0.60	0.00
7	Tank 001 Mid	Linked Tank	98	100	0.001	Dry	3.00	3.50	-7.00	-3.50	0.60	0.00
8	Tank 001 Mid	Linked Tank	98	100	0.001	Dry	3.00	3.50	0.00	7.00	0.60	0.00
9	Tank001 stb	Tank	98	95	1	Water Ballast	0.00	3.50	5.03	7.50	3.45	0.60
10	Tank002 prt	Tank	98	95	1	Water Ballast	3.50	15.77	-7.50	-5.03	3.45	0.60
11	Tank002 mid	Tank	98	95	0.001	Dry	3.50	15.77	-7.00	7.00	0.60	0.00
12	Tank002 stb	Tank	98	95	1	Water Ballast	3.50	15.77	5.03	7.50	3.45	0.60
13	Tank003 prt	Tank	98	95	1	Water Ballast	15.77	28.04	-7.50	-5.03	3.45	0.60
14	Tank003 mid	Tank	98	95	0.001	Dry	15.77	28.04	-7.00	7.00	0.60	0.00
15	Tank003 stb	Tank	98	95	1	Water Ballast	15.77	28.04	5.03	7.50	3.45	0.60
16	Tank004	Tank	98	95	1	Water	28.04	40.30	-7.50	-5.03	3.45	0.60

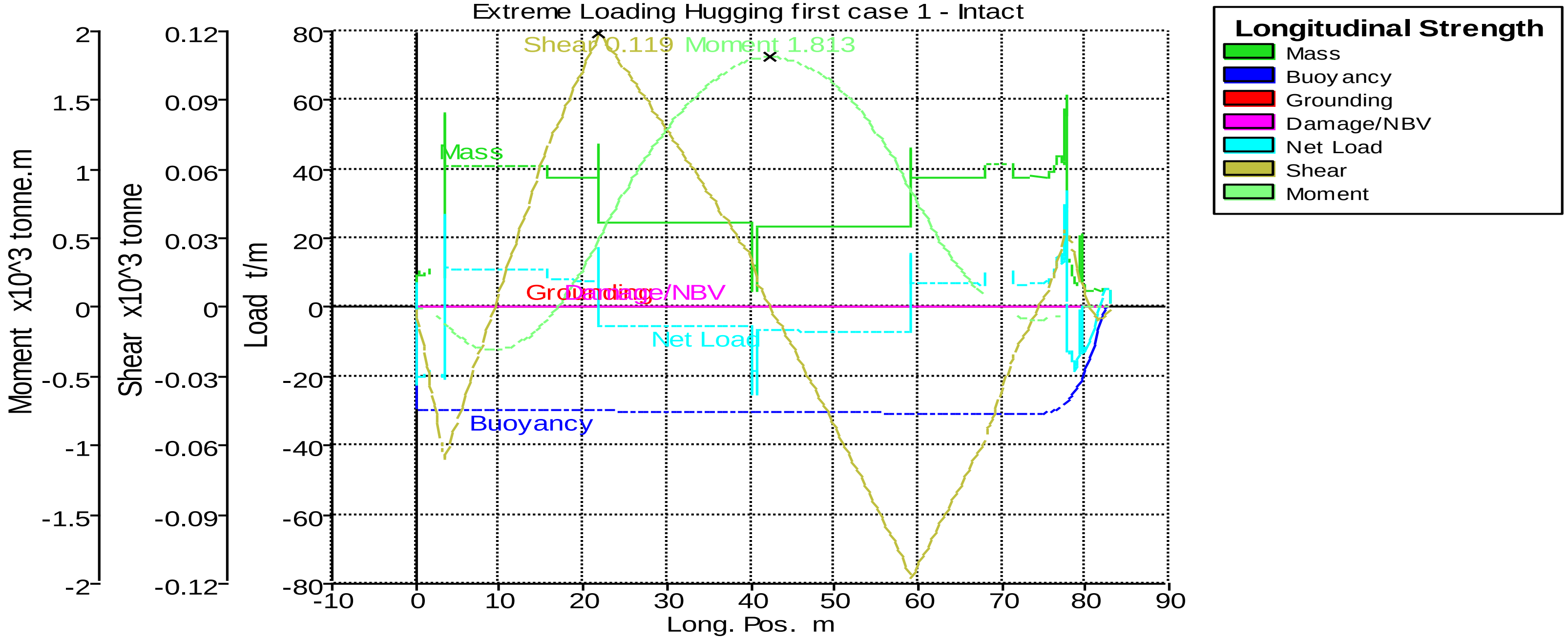
S/N	Name	Type	Intact Perm. %	Damaged Perm. %	Specific Gravity	Fluid Type	Aft [m]	Fore [m]	F.Port [m]	F.Stbd [m]	F.Top [m]	F.Bott. [m]
	prt					Ballast						
17	Tank004 mid	Tank	98	95	0.001	Dry	28.04	40.30	-7.00	7.00	0.60	0.00
18	Tank004 stb	Tank	98	95	1	Water Ballast	28.04	40.30	5.03	7.50	3.45	0.60
19	Mid Tank Sep Port	Tank	98	95	1	Water Ballast	40.30	40.82	-7.50	-5.03	3.45	0.60
20	Mid Tank Sep Mid	Tank	98	95	0.001	Dry	40.30	40.82	-7.00	7.00	0.60	0.00
21	Mid Tank Sep Stb	Tank	98	95	1	Water Ballast	40.30	40.82	5.03	7.50	3.45	0.60
22	Tank005 prt	Tank	98	95	1	Water Ballast	40.82	53.08	-7.50	-5.03	3.45	0.60
23	Tank005 mid	Tank	98	95	0.001	Dry	40.82	53.08	-7.00	7.00	0.60	0.00
24	Tank005 stb	Tank	98	95	1	Water Ballast	40.82	53.08	5.03	7.50	3.45	0.60
25	Tank006 prt	Tank	98	95	1	Water Ballast	53.08	65.35	-7.00	-5.03	3.45	0.60
26	Tank006 mid	Tank	98	95	0.001	Dry	53.08	65.35	-7.00	7.00	0.60	0.00
27	Tank006 stb	Tank	98	95	1	Water Ballast	53.08	65.35	5.03	7.00	3.45	0.60
28	Tank007 prt	Tank	98	95	1	Water Ballast	65.35	77.62	-7.50	-5.03	3.45	0.60
29	tank007 mid	Tank	98	95	0.001	Dry	67.91	77.62	-7.50	-4.00	0.60	0.00
30	tank007 mid	Linked Tank	98	95	0.001	Dry	67.91	77.62	4.00	7.50	0.60	0.00
31	tank007 mid	Linked Tank	98	95	0.001	Dry	65.35	67.91	-7.50	7.50	0.60	0.00
32	tank007	Linked Tank	98	95	0.001	Dry	71.48	77.62	-4.00	4.00	0.60	0.00

S/N	Name	Type	Intact Perm. %	Damaged Perm. %	Specific Gravity	Fluid Type	Aft [m]	Fore [m]	F.Port [m]	F.Stbd [m]	F.Top [m]	F.Bott. [m]
	mid											
33	Tank007 stb	Tank	98	95	1	Water Ballast	65.35	77.62	5.03	7.50	3.45	0.60
34	Tank008 mid	Tank	98	95	1	Custom 3	77.62	79.50	-7.50	1.50	0.60	0.00
35	Tank008 mid	Linked Tank	98	95	1	Custom 3	78.50	79.50	1.50	7.50	0.60	0.00
36	Tank008 prt	Tank	98	95	1	Custom 3	77.62	79.50	-7.00	-5.03	5.00	0.60
37	Tank008 stb	Tank	98	95	1	Custom 3	78.50	79.50	5.03	7.00	5.00	0.60
38	Tank008 stb	Linked Tank	98	95	1	Custom 3	78.00	78.50	5.03	7.00	5.00	1.10
39	Tank008 stb	Linked Tank	98	95	1	Custom 3	77.62	78.00	5.03	7.00	5.00	2.00
40	Diesel oil 1 M	Tank	98	95	0.84	Diesel	67.91	71.48	-4.00	4.00	0.60	0.00
41	Urea	Tank	98	95	1.039	Urea	77.62	78.50	-4.50	-2.50	2.50	0.80
42	Used oil fore ship	Tank	98	95	0.913	Slops	77.62	78.50	1.50	7.50	1.10	0.00
43	Used oil Aft ship	Tank	98	95	0.913	Slops	3.00	3.50	-3.50	0.00	0.60	0.00
44	Lube forecastle	Tank	98	95	0.92	Lube Oil	77.62	78.00	2.50	7.50	2.00	1.10

Appendix 4. **Longitudinal Strength calculation – MT-EM001-Push-Barge**

Stability 22.01.00.131, build: 131
Model file: T:\Student Emmanuel\Masther Thesis Main\Stability, Load and weight estimation\Hull-Form-Main-Modeller´-mit-Cargo-Hold (Highest precision, 168 sections, Trimming off, Skin thickness not applied). Long. datum: AP; Vert. datum: Baseline. Analysis tolerance - ideal(worst case): Disp.%: 0.01000(0.100); Trim%(LCG-TCG): 0.01000(0.100); Heel%(LCG-TCG): 0.01000(0.100)

Loadcase - Extreme Loading LC07- Case 1
Damage Case - Intact
Free to Trim
Specific gravity = 1.025; (Density = 1.025 tonne/m^3)
Fluid analysis method: Simulate fluid movement



Name	Long. Pos. m	Mass t/m	Buoyancy t/m	Grounding t/m	Damage/NBV t/m	Net Load t/m	Shear x10^3 tonne	Moment x10^3 tonne.m
st 0	0.500	9.835	-29.548	0.000	0.000	-19.713	-0.010	-0.002
st 1	1.000	9.849	-29.557	0.000	0.000	-19.708	-0.020	-0.010
st 2	1.500	10.843	-29.566	0.000	0.000	-18.723	-0.029	-0.022
st 3	2.000	10.970	-29.575	0.000	0.000	-18.605	-0.039	-0.039
st 4	2.500	10.419	-29.584	0.000	0.000	-19.165	-0.048	-0.061
st 5	3.000	9.661	-29.593	0.000	0.000	-19.932	-0.058	-0.087
st 6	3.500	40.338	-29.602	0.000	0.000	10.737	-0.066	-0.119
st 7	4.000	40.907	-29.610	0.000	0.000	11.297	-0.059	-0.150
st 8	4.500	40.744	-29.619	0.000	0.000	11.125	-0.054	-0.178
st 9	5.000	40.796	-29.628	0.000	0.000	11.168	-0.048	-0.203
st 10	5.500	40.798	-29.637	0.000	0.000	11.161	-0.042	-0.226
st 11	6.000	40.799	-29.646	0.000	0.000	11.153	-0.037	-0.246
st 12	6.500	40.800	-29.655	0.000	0.000	11.145	-0.031	-0.263
st 13	7.000	40.800	-29.663	0.000	0.000	11.137	-0.026	-0.277
st 14	7.500	40.789	-29.672	0.000	0.000	11.117	-0.020	-0.289
st 15	8.000	40.777	-29.681	0.000	0.000	11.096	-0.015	-0.297
st 16	8.500	40.775	-29.690	0.000	0.000	11.085	-0.009	-0.303
st 17	9.000	40.772	-29.699	0.000	0.000	11.073	-0.004	-0.307
st 18	9.500	40.769	-29.708	0.000	0.000	11.061	0.002	-0.307
st 19	10.000	40.766	-29.717	0.000	0.000	11.050	0.007	-0.305
st 20	10.500	40.763	-29.725	0.000	0.000	11.038	0.013	-0.300
st 21	11.000	40.761	-29.734	0.000	0.000	11.026	0.019	-0.292
st 22	11.500	40.758	-29.743	0.000	0.000	11.015	0.024	-0.281
st 23	12.000	40.755	-29.752	0.000	0.000	11.003	0.030	-0.268
st 24	12.500	40.752	-29.761	0.000	0.000	10.991	0.035	-0.251
st 25	13.000	40.749	-29.770	0.000	0.000	10.980	0.041	-0.233
st 26	13.500	40.747	-29.778	0.000	0.000	10.968	0.046	-0.211
st 27	14.000	40.744	-29.787	0.000	0.000	10.956	0.052	-0.187
st 28	14.500	40.741	-29.796	0.000	0.000	10.945	0.057	-0.159

Name	Long. Pos. m	Mass t/m	Buoyancy t/m	Grounding t/m	Damage/NBV t/m	Net Load t/m	Shear x10^3 tonne	Moment x10^3 tonne.m
st 29	15.000	40.738	-29.805	0.000	0.000	10.933	0.062	-0.130
st 30	15.500	40.735	-29.814	0.000	0.000	10.921	0.068	-0.097
st 31	16.000	37.805	-29.823	0.000	0.000	7.983	0.073	-0.062
st 32	16.500	37.803	-29.832	0.000	0.000	7.971	0.077	-0.025
st 33	17.000	37.800	-29.840	0.000	0.000	7.959	0.081	0.015
st 34	17.500	37.797	-29.849	0.000	0.000	7.948	0.085	0.056
st 35	18.000	37.794	-29.858	0.000	0.000	7.936	0.089	0.099
st 36	18.500	37.791	-29.867	0.000	0.000	7.924	0.093	0.145
st 37	19.000	37.789	-29.876	0.000	0.000	7.913	0.097	0.192
st 38	19.500	37.786	-29.885	0.000	0.000	7.901	0.100	0.241
st 39	20.000	37.783	-29.893	0.000	0.000	7.890	0.104	0.292
st 40	20.500	37.780	-29.902	0.000	0.000	7.878	0.108	0.346
st 41	21.000	37.777	-29.911	0.000	0.000	7.866	0.112	0.401
st 42	21.500	37.775	-29.920	0.000	0.000	7.855	0.116	0.458
st 43	22.000	24.729	-29.929	0.000	0.000	-5.199	0.119	0.517
st 44	22.500	24.727	-29.938	0.000	0.000	-5.211	0.116	0.575
st 45	23.000	24.724	-29.947	0.000	0.000	-5.223	0.114	0.633
st 46	23.500	24.721	-29.955	0.000	0.000	-5.234	0.111	0.689
st 47	24.000	24.718	-29.964	0.000	0.000	-5.246	0.108	0.744
st 48	24.500	24.715	-29.973	0.000	0.000	-5.258	0.106	0.797
st 49	25.000	24.713	-29.982	0.000	0.000	-5.269	0.103	0.850
st 50	25.500	24.710	-29.991	0.000	0.000	-5.281	0.101	0.901
st 51	26.000	24.707	-30.000	0.000	0.000	-5.292	0.098	0.950
st 52	26.500	24.704	-30.008	0.000	0.000	-5.304	0.095	0.998
st 53	27.000	24.702	-30.017	0.000	0.000	-5.316	0.093	1.045
st 54	27.500	24.699	-30.026	0.000	0.000	-5.327	0.090	1.091
st 55	28.000	24.696	-30.035	0.000	0.000	-5.339	0.087	1.135
st 56	28.500	24.693	-30.044	0.000	0.000	-5.351	0.085	1.178
st 57	29.000	24.690	-30.053	0.000	0.000	-5.362	0.082	1.220
st 58	29.500	24.688	-30.062	0.000	0.000	-5.374	0.079	1.260

Name	Long. Pos. m	Mass t/m	Buoyancy t/m	Grounding t/m	Damage/NBV t/m	Net Load t/m	Shear x10^3 tonne	Moment x10^3 tonne.m
st 59	30.000	24.685	-30.070	0.000	0.000	-5.386	0.077	1.299
st 60	30.500	24.682	-30.079	0.000	0.000	-5.397	0.074	1.337
st 61	31.000	24.679	-30.088	0.000	0.000	-5.409	0.071	1.373
st 62	31.500	24.677	-30.097	0.000	0.000	-5.420	0.068	1.408
st 63	32.000	24.674	-30.106	0.000	0.000	-5.432	0.066	1.441
st 64	32.500	24.671	-30.115	0.000	0.000	-5.444	0.063	1.473
st 65	33.000	24.668	-30.123	0.000	0.000	-5.455	0.060	1.504
st 66	33.500	24.665	-30.132	0.000	0.000	-5.467	0.058	1.534
st 67	34.000	24.663	-30.141	0.000	0.000	-5.479	0.055	1.562
st 68	34.500	24.660	-30.150	0.000	0.000	-5.490	0.052	1.589
st 69	35.000	24.657	-30.159	0.000	0.000	-5.502	0.049	1.614
st 70	35.500	24.654	-30.168	0.000	0.000	-5.513	0.047	1.638
st 71	36.000	24.651	-30.177	0.000	0.000	-5.525	0.044	1.660
st 72	36.500	24.649	-30.185	0.000	0.000	-5.537	0.041	1.682
st 73	37.000	24.646	-30.194	0.000	0.000	-5.548	0.038	1.701
st 74	37.500	24.643	-30.203	0.000	0.000	-5.560	0.035	1.720
st 75	38.000	24.640	-30.212	0.000	0.000	-5.572	0.033	1.737
st 76	38.500	24.638	-30.221	0.000	0.000	-5.583	0.030	1.753
st 77	39.000	24.635	-30.230	0.000	0.000	-5.595	0.027	1.767
st 78	39.500	24.632	-30.238	0.000	0.000	-5.607	0.024	1.780
st 79	40.000	24.629	-30.247	0.000	0.000	-5.618	0.022	1.791
st 80	40.500	12.116	-30.256	0.000	0.000	-18.141	0.016	1.801
st 81	41.000	23.635	-30.265	0.000	0.000	-6.630	0.009	1.807
st 82	41.500	23.628	-30.274	0.000	0.000	-6.646	0.006	1.810
st 83	42.000	23.621	-30.283	0.000	0.000	-6.662	0.002	1.812
st 84	42.500	23.614	-30.292	0.000	0.000	-6.678	-0.001	1.813
st 85	43.000	23.607	-30.300	0.000	0.000	-6.693	-0.004	1.811
st 86	43.500	23.600	-30.309	0.000	0.000	-6.709	-0.008	1.808
st 87	44.000	23.593	-30.318	0.000	0.000	-6.725	-0.011	1.803
st 88	44.500	23.587	-30.327	0.000	0.000	-6.740	-0.015	1.797

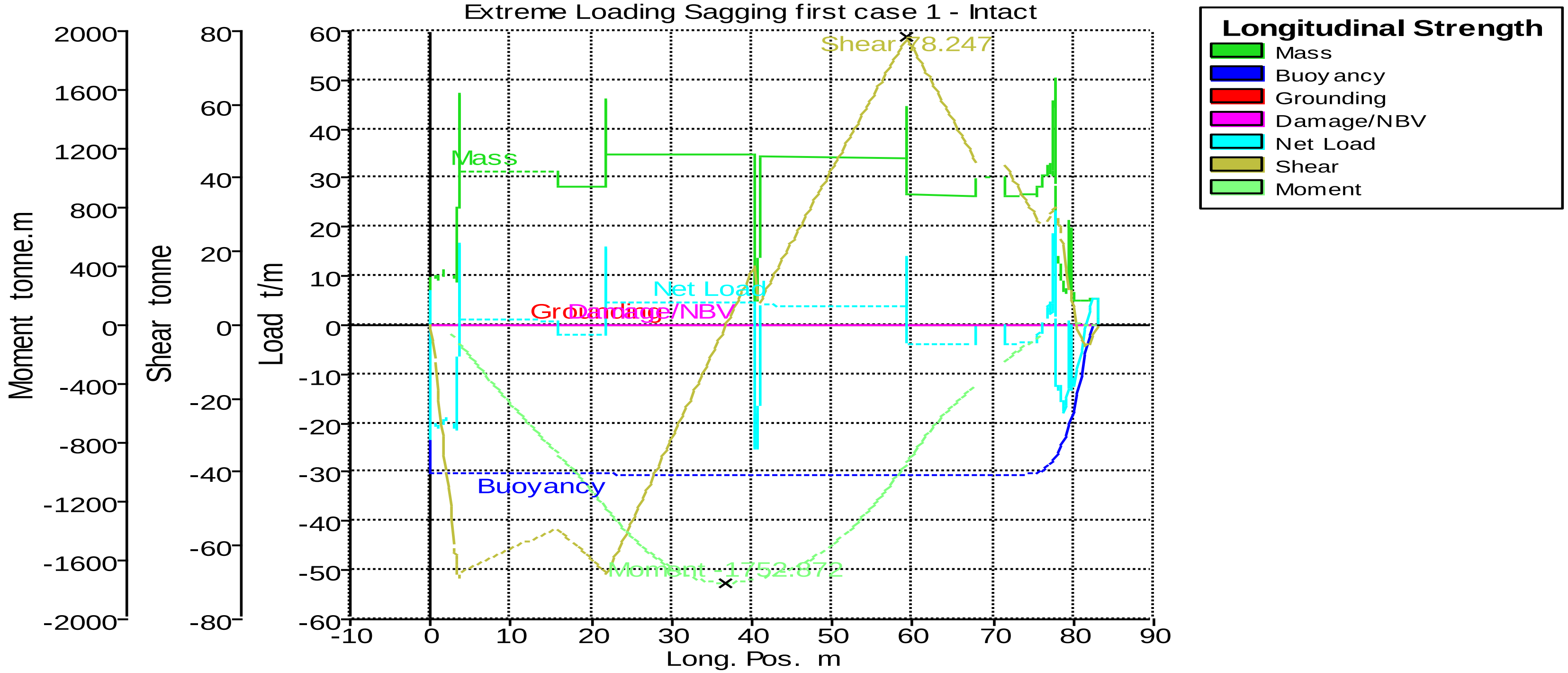
Name	Long. Pos. m	Mass t/m	Buoyancy t/m	Grounding t/m	Damage/NBV t/m	Net Load t/m	Shear x10^3 tonne	Moment x10^3 tonne.m
st 89	45.000	23.580	-30.336	0.000	0.000	-6.756	-0.018	1.789
st 90	45.500	23.573	-30.345	0.000	0.000	-6.772	-0.021	1.779
st 91	46.000	23.566	-30.353	0.000	0.000	-6.787	-0.025	1.767
st 92	46.500	23.559	-30.362	0.000	0.000	-6.803	-0.028	1.754
st 93	47.000	23.552	-30.371	0.000	0.000	-6.819	-0.032	1.739
st 94	47.500	23.545	-30.380	0.000	0.000	-6.835	-0.035	1.723
st 95	48.000	23.539	-30.389	0.000	0.000	-6.850	-0.038	1.704
st 96	48.500	23.532	-30.398	0.000	0.000	-6.866	-0.042	1.684
st 97	49.000	23.525	-30.407	0.000	0.000	-6.882	-0.045	1.663
st 98	49.500	23.518	-30.415	0.000	0.000	-6.897	-0.049	1.639
st 99	50.000	23.511	-30.424	0.000	0.000	-6.913	-0.052	1.614
st 100	50.500	23.504	-30.433	0.000	0.000	-6.929	-0.056	1.587
st 101	51.000	23.497	-30.442	0.000	0.000	-6.944	-0.059	1.558
st 102	51.500	23.491	-30.451	0.000	0.000	-6.960	-0.063	1.528
st 103	52.000	23.484	-30.460	0.000	0.000	-6.976	-0.066	1.496
st 104	52.500	23.477	-30.468	0.000	0.000	-6.992	-0.069	1.462
st 105	53.000	23.470	-30.477	0.000	0.000	-7.007	-0.073	1.426
st 106	53.500	23.463	-30.486	0.000	0.000	-7.023	-0.076	1.389
st 107	54.000	23.456	-30.495	0.000	0.000	-7.039	-0.080	1.350
st 108	54.500	23.449	-30.504	0.000	0.000	-7.054	-0.084	1.309
st 109	55.000	23.443	-30.513	0.000	0.000	-7.070	-0.087	1.266
st 110	55.500	23.436	-30.522	0.000	0.000	-7.086	-0.091	1.222
st 111	56.000	23.429	-30.530	0.000	0.000	-7.101	-0.094	1.176
st 112	56.500	23.422	-30.539	0.000	0.000	-7.117	-0.098	1.128
st 113	57.000	23.415	-30.548	0.000	0.000	-7.133	-0.101	1.078
st 114	57.500	23.408	-30.557	0.000	0.000	-7.149	-0.105	1.026
st 115	58.000	23.401	-30.566	0.000	0.000	-7.164	-0.108	0.973
st 116	58.500	23.395	-30.575	0.000	0.000	-7.180	-0.112	0.918
st 117	59.000	23.388	-30.583	0.000	0.000	-7.196	-0.116	0.861
st 118	59.500	37.562	-30.592	0.000	0.000	6.969	-0.115	0.803

Name	Long. Pos. m	Mass t/m	Buoyancy t/m	Grounding t/m	Damage/NBV t/m	Net Load t/m	Shear x10^3 tonne	Moment x10^3 tonne.m
st 119	60.000	37.559	-30.601	0.000	0.000	6.958	-0.112	0.746
st 120	60.500	37.556	-30.610	0.000	0.000	6.946	-0.108	0.691
st 121	61.000	37.553	-30.619	0.000	0.000	6.935	-0.105	0.638
st 122	61.500	37.551	-30.628	0.000	0.000	6.923	-0.101	0.587
st 123	62.000	37.548	-30.637	0.000	0.000	6.911	-0.098	0.537
st 124	62.500	37.545	-30.645	0.000	0.000	6.900	-0.094	0.489
st 125	63.000	37.542	-30.654	0.000	0.000	6.888	-0.091	0.442
st 126	63.500	37.539	-30.663	0.000	0.000	6.876	-0.087	0.398
st 127	64.000	37.537	-30.672	0.000	0.000	6.865	-0.084	0.355
st 128	64.500	37.534	-30.681	0.000	0.000	6.853	-0.081	0.314
st 129	65.000	37.531	-30.690	0.000	0.000	6.841	-0.077	0.274
st 130	65.500	37.528	-30.698	0.000	0.000	6.830	-0.074	0.236
st 131	66.000	37.525	-30.707	0.000	0.000	6.818	-0.070	0.200
st 132	66.500	37.523	-30.716	0.000	0.000	6.806	-0.067	0.166
st 133	67.000	37.520	-30.725	0.000	0.000	6.795	-0.064	0.133
st 134	67.500	37.517	-30.734	0.000	0.000	6.783	-0.060	0.102
st 135	68.000	41.370	-30.743	0.000	0.000	10.627	-0.056	0.073
st 136	68.500	41.372	-30.752	0.000	0.000	10.620	-0.051	0.046
st 137	69.000	41.374	-30.760	0.000	0.000	10.614	-0.046	0.022
st 138	69.500	41.376	-30.769	0.000	0.000	10.607	-0.040	0.001
st 139	70.000	41.378	-30.778	0.000	0.000	10.600	-0.035	-0.018
st 140	70.500	41.380	-30.787	0.000	0.000	10.594	-0.030	-0.035
st 141	71.000	41.383	-30.796	0.000	0.000	10.587	-0.025	-0.048
st 142	71.500	37.495	-30.805	0.000	0.000	6.690	-0.019	-0.059
st 143	72.000	37.492	-30.813	0.000	0.000	6.678	-0.016	-0.068
st 144	72.500	37.489	-30.822	0.000	0.000	6.667	-0.013	-0.075
st 145	73.000	37.486	-30.831	0.000	0.000	6.655	-0.009	-0.081
st 146	73.500	37.483	-30.840	0.000	0.000	6.644	-0.006	-0.085
st 147	74.000	37.881	-30.836	0.000	0.000	7.045	-0.003	-0.087
st 148	74.500	37.878	-30.793	0.000	0.000	7.085	0.001	-0.087

Name	Long. Pos. m	Mass t/m	Buoyancy t/m	Grounding t/m	Damage/NBV t/m	Net Load t/m	Shear x10^3 tonne	Moment x10^3 tonne.m
st 149	75.000	37.875	-30.675	0.000	0.000	7.200	0.005	-0.086
st 150	75.500	37.872	-30.451	0.000	0.000	7.422	0.008	-0.083
st 151	76.000	39.119	-30.067	0.000	0.000	9.052	0.013	-0.078
st 152	76.500	41.491	-29.512	0.000	0.000	11.978	0.018	-0.070
st 153	77.000	43.913	-28.791	0.000	0.000	15.122	0.025	-0.059
st 154	77.500	42.190	-27.825	0.000	0.000	14.365	0.032	-0.045
st 155	78.000	13.125	-26.590	0.000	0.000	-13.465	0.032	-0.028
st 156	78.500	10.555	-25.020	0.000	0.000	-14.465	0.025	-0.014
st 157	79.000	7.144	-23.078	0.000	0.000	-15.935	0.016	-0.004
st 158	79.500	20.437	-20.700	0.000	0.000	-0.264	0.010	0.003
st 159	80.000	5.672	-17.848	0.000	0.000	-12.177	0.006	0.007
st 160	80.500	4.892	-14.441	0.000	0.000	-9.549	0.000	0.008
st 161	81.000	4.992	-10.503	0.000	0.000	-5.511	-0.004	0.008
st 162	81.500	5.092	-6.290	0.000	0.000	-1.199	-0.005	0.005
st 163	82.000	5.437	-2.205	0.000	0.000	3.232	-0.005	0.003
st 164	82.500	5.547	-0.013	0.000	0.000	5.534	-0.003	0.001

Load case - Extreme Load Case – LC08-Case 2

Damage Case - Intact
Free to Trim
Specific gravity = 1.025; (Density = 1.025 tonne/m^3)
Fluid analysis method: Simulate fluid movement



Name	Long. Pos. m	Mass t/m	Buoyancy t/m	Grounding t/m	Damage/NBV t/m	Net Load t/m	Shear tonne	Moment tonne.m
st 0	0.500	9.835	-30.360	0.000	0.000	-20.525	-10.183	-2.552
st 1	1.000	9.849	-30.361	0.000	0.000	-20.511	-20.655	-10.264
st 2	1.500	10.843	-30.361	0.000	0.000	-19.518	-30.709	-23.106
st 3	2.000	10.970	-30.362	0.000	0.000	-19.392	-40.204	-40.834
st 4	2.500	10.419	-30.363	0.000	0.000	-19.944	-50.102	-63.432
st 5	3.000	9.662	-30.363	0.000	0.000	-20.701	-60.148	-90.972
st 6	3.500	35.637	-30.364	0.000	0.000	5.273	-68.885	-123.587
st 7	4.000	31.506	-30.364	0.000	0.000	1.141	-67.052	-157.333

Name	Long. Pos. m	Mass t/m	Buoyancy t/m	Grounding t/m	Damage/NBV t/m	Net Load t/m	Shear tonne	Moment tonne.m
st 8	4.500	31.343	-30.365	0.000	0.000	0.978	-66.562	-190.735
st 9	5.000	31.394	-30.365	0.000	0.000	1.029	-66.069	-223.903
st 10	5.500	31.397	-30.366	0.000	0.000	1.031	-65.554	-256.805
st 11	6.000	31.397	-30.367	0.000	0.000	1.031	-65.038	-289.457
st 12	6.500	31.398	-30.367	0.000	0.000	1.031	-64.523	-321.851
st 13	7.000	31.399	-30.368	0.000	0.000	1.031	-64.007	-353.987
st 14	7.500	31.388	-30.368	0.000	0.000	1.020	-63.492	-385.876
st 15	8.000	31.376	-30.369	0.000	0.000	1.007	-62.987	-417.489
st 16	8.500	31.373	-30.370	0.000	0.000	1.004	-62.485	-448.860
st 17	9.000	31.370	-30.370	0.000	0.000	1.000	-61.984	-479.981
st 18	9.500	31.368	-30.371	0.000	0.000	0.997	-61.485	-510.852
st 19	10.000	31.365	-30.371	0.000	0.000	0.993	-60.987	-541.474
st 20	10.500	31.362	-30.372	0.000	0.000	0.990	-60.491	-571.847
st 21	11.000	31.359	-30.373	0.000	0.000	0.987	-59.997	-601.973
st 22	11.500	31.356	-30.373	0.000	0.000	0.983	-59.505	-631.852
st 23	12.000	31.354	-30.374	0.000	0.000	0.980	-59.014	-661.486
st 24	12.500	31.351	-30.374	0.000	0.000	0.976	-58.525	-690.874
st 25	13.000	31.348	-30.375	0.000	0.000	0.973	-58.038	-720.018
st 26	13.500	31.345	-30.376	0.000	0.000	0.970	-57.552	-748.920
st 27	14.000	31.342	-30.376	0.000	0.000	0.966	-57.068	-777.578
st 28	14.500	31.340	-30.377	0.000	0.000	0.963	-56.586	-805.996
st 29	15.000	31.337	-30.377	0.000	0.000	0.959	-56.105	-834.172
st 30	15.500	31.334	-30.378	0.000	0.000	0.956	-55.627	-862.115
st 31	16.000	28.404	-30.379	0.000	0.000	-1.974	-55.828	-889.943
st 32	16.500	28.401	-30.379	0.000	0.000	-1.978	-56.817	-918.109
st 33	17.000	28.399	-30.380	0.000	0.000	-1.981	-57.806	-946.770
st 34	17.500	28.396	-30.380	0.000	0.000	-1.985	-58.798	-975.926
st 35	18.000	28.393	-30.381	0.000	0.000	-1.988	-59.791	-1005.578
st 36	18.500	28.390	-30.382	0.000	0.000	-1.991	-60.786	-1035.727
st 37	19.000	28.387	-30.382	0.000	0.000	-1.995	-61.783	-1066.375

Name	Long. Pos. m	Mass t/m	Buoyancy t/m	Grounding t/m	Damage/NBV t/m	Net Load t/m	Shear tonne	Moment tonne.m
st 38	19.500	28.385	-30.383	0.000	0.000	-1.998	-62.781	-1097.520
st 39	20.000	28.382	-30.383	0.000	0.000	-2.002	-63.781	-1129.166
st 40	20.500	28.379	-30.384	0.000	0.000	-2.005	-64.782	-1161.312
st 41	21.000	28.376	-30.385	0.000	0.000	-2.008	-65.786	-1193.959
st 42	21.500	28.373	-30.385	0.000	0.000	-2.012	-66.791	-1227.108
st 43	22.000	35.000	-30.386	0.000	0.000	4.614	-67.147	-1260.597
st 44	22.500	34.997	-30.386	0.000	0.000	4.611	-64.840	-1293.565
st 45	23.000	34.994	-30.387	0.000	0.000	4.608	-62.536	-1325.412
st 46	23.500	34.992	-30.387	0.000	0.000	4.604	-60.233	-1356.107
st 47	24.000	34.989	-30.388	0.000	0.000	4.601	-57.932	-1385.651
st 48	24.500	34.986	-30.389	0.000	0.000	4.597	-55.632	-1414.045
st 49	25.000	34.983	-30.389	0.000	0.000	4.594	-53.334	-1441.289
st 50	25.500	34.981	-30.390	0.000	0.000	4.591	-51.038	-1467.385
st 51	26.000	34.978	-30.390	0.000	0.000	4.587	-48.744	-1492.334
st 52	26.500	34.975	-30.391	0.000	0.000	4.584	-46.451	-1516.135
st 53	27.000	34.972	-30.392	0.000	0.000	4.581	-44.160	-1538.791
st 54	27.500	34.969	-30.392	0.000	0.000	4.577	-41.870	-1560.302
st 55	28.000	34.967	-30.393	0.000	0.000	4.574	-39.583	-1580.668
st 56	28.500	34.964	-30.393	0.000	0.000	4.571	-37.297	-1599.891
st 57	29.000	34.961	-30.394	0.000	0.000	4.567	-35.012	-1617.971
st 58	29.500	34.958	-30.395	0.000	0.000	4.564	-32.729	-1634.910
st 59	30.000	34.956	-30.395	0.000	0.000	4.560	-30.448	-1650.708
st 60	30.500	34.953	-30.396	0.000	0.000	4.557	-28.169	-1665.365
st 61	31.000	34.950	-30.396	0.000	0.000	4.554	-25.891	-1678.884
st 62	31.500	34.947	-30.397	0.000	0.000	4.550	-23.616	-1691.264
st 63	32.000	34.945	-30.398	0.000	0.000	4.547	-21.341	-1702.507
st 64	32.500	34.942	-30.398	0.000	0.000	4.544	-19.069	-1712.613
st 65	33.000	34.939	-30.399	0.000	0.000	4.540	-16.798	-1721.583
st 66	33.500	34.936	-30.399	0.000	0.000	4.537	-14.529	-1729.418
st 67	34.000	34.933	-30.400	0.000	0.000	4.533	-12.261	-1736.119

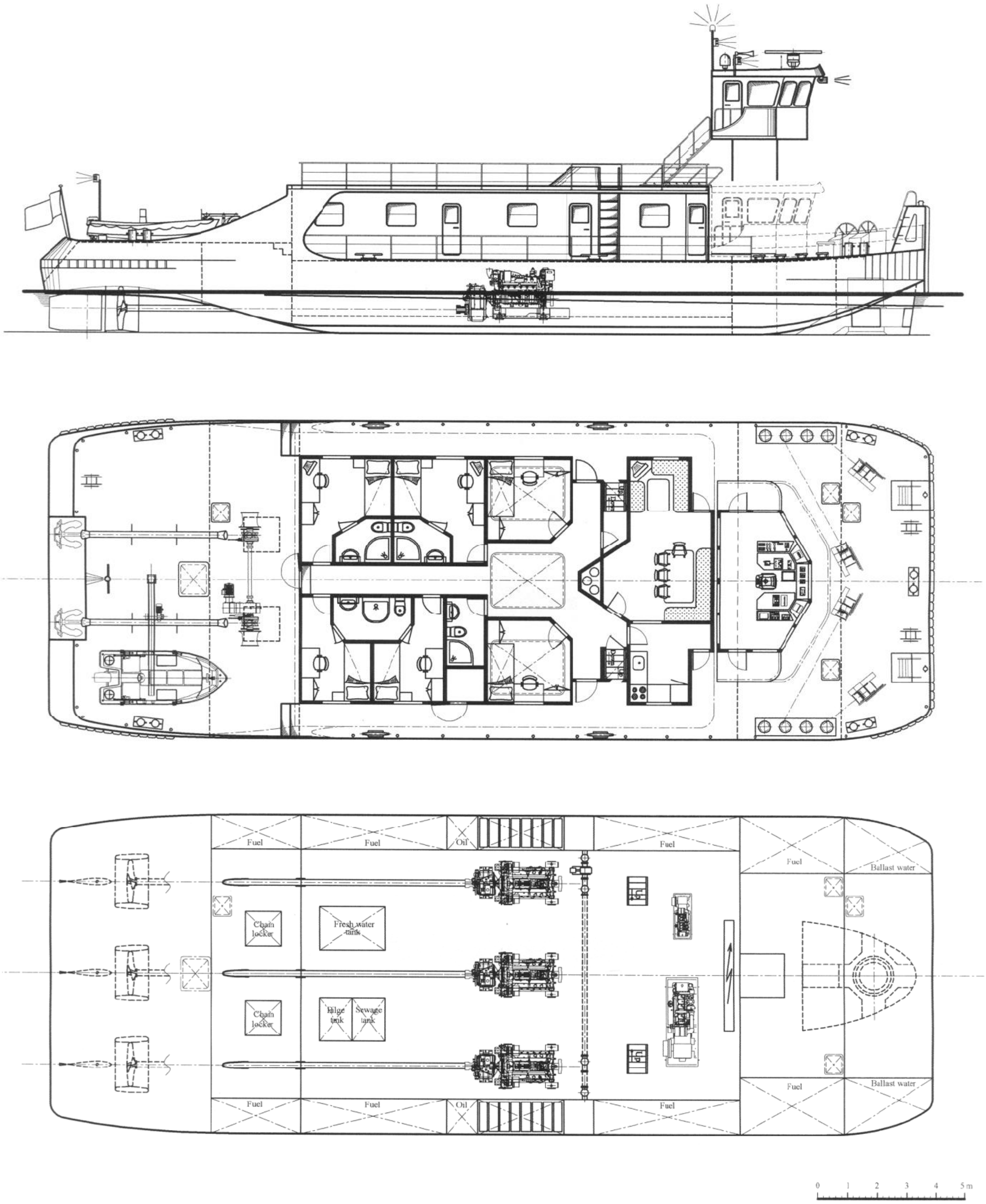
Name	Long. Pos. m	Mass t/m	Buoyancy t/m	Grounding t/m	Damage/NBV t/m	Net Load t/m	Shear tonne	Moment tonne.m
st 68	34.500	34.931	-30.401	0.000	0.000	4.530	-9.995	-1741.687
st 69	35.000	34.928	-30.401	0.000	0.000	4.527	-7.731	-1746.122
st 70	35.500	34.925	-30.402	0.000	0.000	4.523	-5.469	-1749.426
st 71	36.000	34.922	-30.402	0.000	0.000	4.520	-3.208	-1751.599
st 72	36.500	34.920	-30.403	0.000	0.000	4.517	-0.949	-1752.872
st 73	37.000	34.917	-30.404	0.000	0.000	4.513	1.309	-1752.555
st 74	37.500	34.914	-30.404	0.000	0.000	4.510	3.564	-1751.341
st 75	38.000	34.911	-30.405	0.000	0.000	4.507	5.819	-1748.999
st 76	38.500	34.908	-30.405	0.000	0.000	4.503	8.071	-1745.531
st 77	39.000	34.906	-30.406	0.000	0.000	4.500	10.322	-1740.937
st 78	39.500	34.903	-30.407	0.000	0.000	4.496	12.571	-1735.218
st 79	40.000	34.900	-30.407	0.000	0.000	4.493	14.818	-1728.375
st 80	40.500	12.116	-30.408	0.000	0.000	-18.292	12.587	-1721.439
st 81	41.000	34.514	-30.408	0.000	0.000	4.105	6.825	-1716.652
st 82	41.500	34.504	-30.409	0.000	0.000	4.095	8.875	-1712.680
st 83	42.000	34.495	-30.409	0.000	0.000	4.085	10.920	-1707.735
st 84	42.500	34.485	-30.410	0.000	0.000	4.075	12.960	-1701.770
st 85	43.000	34.476	-30.411	0.000	0.000	4.065	14.995	-1694.785
st 86	43.500	34.466	-30.411	0.000	0.000	4.055	17.025	-1686.784
st 87	44.000	34.457	-30.412	0.000	0.000	4.045	19.050	-1677.770
st 88	44.500	34.447	-30.412	0.000	0.000	4.034	21.069	-1667.745
st 89	45.000	34.437	-30.413	0.000	0.000	4.024	23.084	-1656.711
st 90	45.500	34.428	-30.414	0.000	0.000	4.014	25.094	-1644.671
st 91	46.000	34.418	-30.414	0.000	0.000	4.004	27.098	-1631.627
st 92	46.500	34.409	-30.415	0.000	0.000	3.994	29.098	-1617.583
st 93	47.000	34.399	-30.415	0.000	0.000	3.984	31.092	-1602.540
st 94	47.500	34.390	-30.416	0.000	0.000	3.974	33.082	-1586.501
st 95	48.000	34.380	-30.417	0.000	0.000	3.964	35.066	-1569.469
st 96	48.500	34.371	-30.417	0.000	0.000	3.953	37.045	-1551.446
st 97	49.000	34.361	-30.418	0.000	0.000	3.943	39.019	-1532.435

Name	Long. Pos. m	Mass t/m	Buoyancy t/m	Grounding t/m	Damage/NBV t/m	Net Load t/m	Shear tonne	Moment tonne.m
st 98	49.500	34.352	-30.418	0.000	0.000	3.933	40.988	-1512.438
st 99	50.000	34.342	-30.419	0.000	0.000	3.923	42.952	-1491.458
st 100	50.500	34.332	-30.420	0.000	0.000	3.913	44.911	-1469.497
st 101	51.000	34.323	-30.420	0.000	0.000	3.903	46.865	-1446.558
st 102	51.500	34.313	-30.421	0.000	0.000	3.893	48.814	-1422.643
st 103	52.000	34.304	-30.421	0.000	0.000	3.882	50.758	-1397.755
st 104	52.500	34.294	-30.422	0.000	0.000	3.872	52.696	-1371.896
st 105	53.000	34.285	-30.423	0.000	0.000	3.862	54.630	-1345.070
st 106	53.500	34.275	-30.423	0.000	0.000	3.852	56.558	-1317.278
st 107	54.000	34.266	-30.424	0.000	0.000	3.842	58.482	-1288.523
st 108	54.500	34.256	-30.424	0.000	0.000	3.832	60.400	-1258.808
st 109	55.000	34.247	-30.425	0.000	0.000	3.822	62.314	-1228.134
st 110	55.500	34.237	-30.426	0.000	0.000	3.812	64.222	-1196.506
st 111	56.000	34.228	-30.426	0.000	0.000	3.801	66.125	-1163.924
st 112	56.500	34.218	-30.427	0.000	0.000	3.791	68.023	-1130.392
st 113	57.000	34.208	-30.427	0.000	0.000	3.781	69.916	-1095.913
st 114	57.500	34.199	-30.428	0.000	0.000	3.771	71.804	-1060.488
st 115	58.000	34.189	-30.429	0.000	0.000	3.761	73.687	-1024.121
st 116	58.500	34.180	-30.429	0.000	0.000	3.751	75.565	-986.813
st 117	59.000	34.170	-30.430	0.000	0.000	3.741	77.438	-948.568
st 118	59.500	26.530	-30.430	0.000	0.000	-3.900	77.141	-909.862
st 119	60.000	26.527	-30.431	0.000	0.000	-3.903	75.190	-871.803
st 120	60.500	26.525	-30.431	0.000	0.000	-3.907	73.238	-834.698
st 121	61.000	26.522	-30.432	0.000	0.000	-3.910	71.283	-798.571
st 122	61.500	26.519	-30.433	0.000	0.000	-3.914	69.327	-763.421
st 123	62.000	26.516	-30.433	0.000	0.000	-3.917	67.370	-729.249
st 124	62.500	26.513	-30.434	0.000	0.000	-3.920	65.410	-696.057
st 125	63.000	26.511	-30.434	0.000	0.000	-3.924	63.449	-663.845
st 126	63.500	26.508	-30.435	0.000	0.000	-3.927	61.486	-632.613

Name	Long. Pos. m	Mass t/m	Buoyancy t/m	Grounding t/m	Damage/NBV t/m	Net Load t/m	Shear tonne	Moment tonne.m
st 127	64.000	26.505	-30.436	0.000	0.000	-3.931	59.522	-602.364
st 128	64.500	26.502	-30.436	0.000	0.000	-3.934	57.556	-573.097
st 129	65.000	26.499	-30.437	0.000	0.000	-3.937	55.588	-544.814
st 130	65.500	26.497	-30.437	0.000	0.000	-3.941	53.618	-517.515
st 131	66.000	26.494	-30.438	0.000	0.000	-3.944	51.647	-491.201
st 132	66.500	26.491	-30.439	0.000	0.000	-3.948	49.674	-465.873
st 133	67.000	26.488	-30.439	0.000	0.000	-3.951	47.699	-441.532
st 134	67.500	26.485	-30.440	0.000	0.000	-3.954	45.723	-418.179
st 135	68.000	30.354	-30.440	0.000	0.000	-0.087	44.109	-395.727
st 136	68.500	30.351	-30.441	0.000	0.000	-0.090	44.065	-373.687
st 137	69.000	30.349	-30.442	0.000	0.000	-0.093	44.019	-351.671
st 138	69.500	30.346	-30.442	0.000	0.000	-0.096	43.972	-329.678
st 139	70.000	30.344	-30.443	0.000	0.000	-0.099	43.923	-307.708
st 140	70.500	30.341	-30.443	0.000	0.000	-0.102	43.873	-285.763
st 141	71.000	30.339	-30.444	0.000	0.000	-0.105	43.821	-263.843
st 142	71.500	26.463	-30.445	0.000	0.000	-3.982	43.706	-241.952
st 143	72.000	26.460	-30.445	0.000	0.000	-3.985	41.714	-220.653
st 144	72.500	26.457	-30.446	0.000	0.000	-3.988	39.721	-200.297
st 145	73.000	26.455	-30.446	0.000	0.000	-3.992	37.726	-180.937
st 146	73.500	26.452	-30.446	0.000	0.000	-3.995	35.729	-162.573
st 147	74.000	26.849	-30.435	0.000	0.000	-3.586	33.914	-145.166
st 148	74.500	26.846	-30.385	0.000	0.000	-3.539	32.132	-128.657
st 149	75.000	26.843	-30.261	0.000	0.000	-3.418	30.393	-113.028
st 150	75.500	26.841	-30.031	0.000	0.000	-3.191	28.740	-98.246
st 151	76.000	28.088	-29.644	0.000	0.000	-1.556	27.727	-84.148
st 152	76.500	30.459	-29.086	0.000	0.000	1.373	28.049	-70.246
st 153	77.000	32.881	-28.360	0.000	0.000	4.521	29.843	-55.821
st 154	77.500	31.159	-27.392	0.000	0.000	3.766	31.354	-40.518
st 155	78.000	13.125	-26.154	0.000	0.000	-13.030	29.865	-24.508

Name	Long. Pos. m	Mass t/m	Buoyancy t/m	Grounding t/m	Damage/NBV t/m	Net Load t/m	Shear tonne	Moment tonne.m
st 156	78.500	10.554	-24.583	0.000	0.000	-14.029	23.362	-11.233
st 157	79.000	7.144	-22.638	0.000	0.000	-15.495	15.040	-1.605
st 158	79.500	20.437	-20.256	0.000	0.000	0.180	9.326	4.233
st 159	80.000	5.672	-17.400	0.000	0.000	-11.728	4.745	7.996
st 160	80.500	4.892	-13.988	0.000	0.000	-9.096	-0.637	8.977
st 161	81.000	4.992	-10.056	0.000	0.000	-5.065	-4.229	7.780
st 162	81.500	5.092	-5.892	0.000	0.000	-0.800	-5.653	5.294
st 163	82.000	5.437	-1.906	0.000	0.000	3.531	-5.074	2.606
st 164	82.500	5.547	-0.011	0.000	0.000	5.536	-2.655	0.668

Appendix 5. **General Arrangement plan of proposed push-boat concept**



Source: (Radojcic, 2009)