A model based approach to the automatic generation of block division plans

On the effective usefulness in ship production optimization algorithm

D.P. de Bruijn

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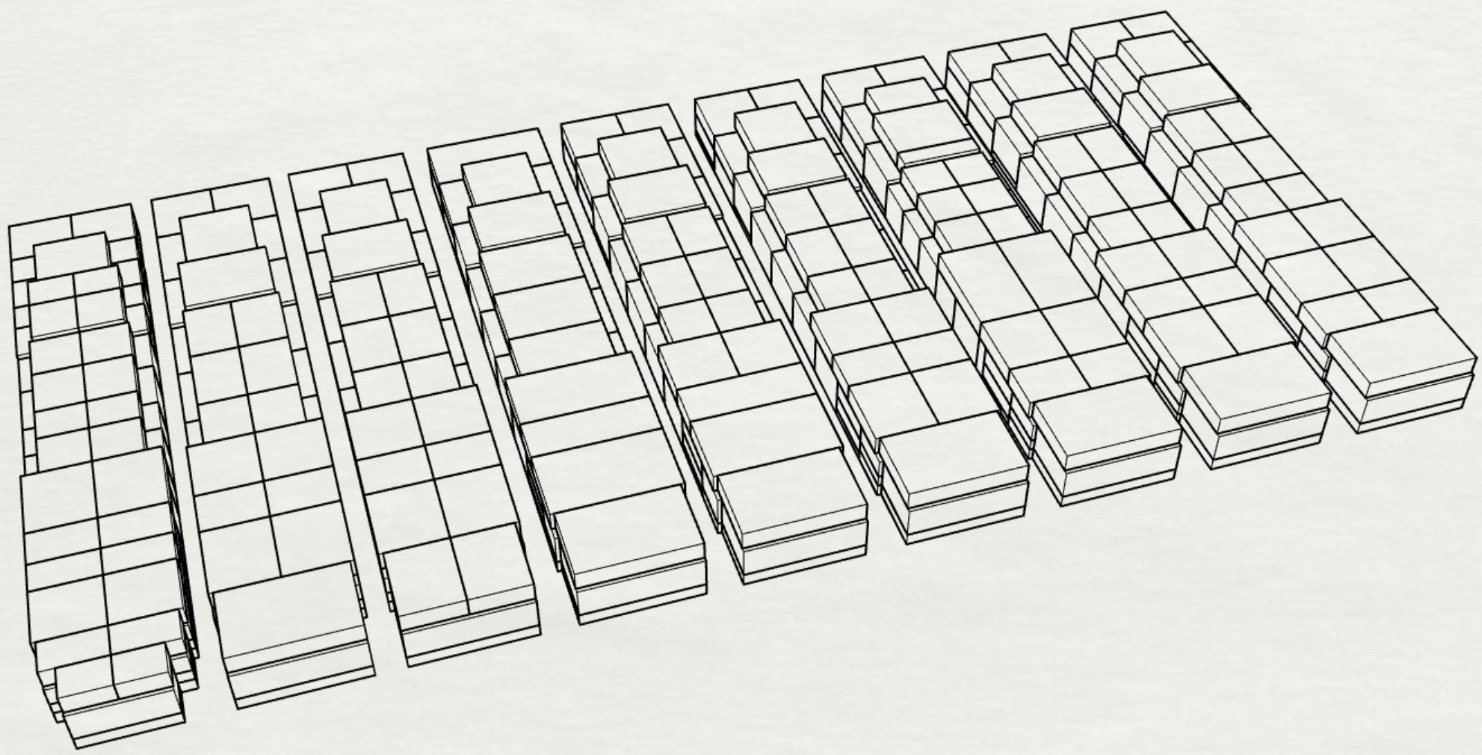

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On the effective usefulness in ship production optimization algorithm

by

D.P. de Bruijn

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Thesis committee:	Prof. ir. J.J. Hopman,	TU Delft, chairman
	Dr. ir. J.M.G. Coenen,	TU Delft, supervisor
	Dr. ir. H.P.M. Veeke,	TU Delft
	Ir. P. van der Poel,	Royal IHC

Preface

This report has been written in order to obtain the degree of Master of Science at the Delft University of Technology. This research project has been caries out from March 2017 to November 2017.

First of all I want to show my gratitude to Arie Runge who has provided me with all insights in the block division process, Peter van der Poel for more information about design and proposal of contracts and gather crucial information, Bram Scherf helping me in an attempt to develop an automated weight calculator based on steel plates and Kees Meijer for getting me up to speed and providing me with his developed model. Next to these gentleman from IHC I want to thank Arjen Poortvliet of DAMEN Schelde Naval Shipyard to receive me in Vlissingen and provide feedback on the created methodology.

Most of all concerning this project I want to Jenny Coenen for challenging me every step of the process, providing feedback and having faith in my independence. Without this flexible collaboration it would not have been possible for me to combine my graduation with other important aspects of my life.

Also all my friends at Swapfiets deserve to be mentioned in this preface for providing me with their trust, efforts to unburden me and stimulant to persevere and finish this graduation project. Neither without the support and faith of our investors would I have been in the position to be able combine those two worlds.

Primarily I want to say how much I am grateful for my girlfriend Jeanine who had to coop with me taking on too much responsibility and work. However, thanks to her understanding and unbroken support I was able to fully commit myself to the before mentioned challenges which deserves my great appreciation. I also want to thank my family for their support over the last years for me to be able to start and finish this chapter of my life.

D.P. de Bruijn
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Abstract

European shipyards are building increasing amounts of complex ships such as off-shore, dredging or naval ships that are engineered-to-order. Contracts are awarded through tender offers that consist of a ship's preliminary design and production milestones. Ships are build in blocks, combined sub-assemblies of steel structural parts and outfitting components that are combined and erected on the slipway. The block division dictates the decomposition of all working disciplines on the shipyard. The block division is made when only preliminary hull structural design, functional compartments and the location of major equipment are known.

Erection sequence schedule optimization algorithms have been developed to improve production schedules with respect to shipyard facilities, building time and costs. The existing production scheduling algorithms use a single manually created block division as a fixed input. Automatic generation of block division plans can potentially optimize the currently created production planning solutions for European shipyard building complex ships by examining different block division solutions in the ship production planning. Such an approach must be integrated with the available information, used production techniques, erection strategies and ship production optimization algorithms. This thesis develops an automatic block division generation methodology and assesses the potential effective usefulness in ship production optimization algorithm.

There are three sources of information available to create an optimal block division plan. The preliminary design information and general arrangement of the ship, implicit knowledge of engineers and detailed information from comparable reference ships. Interviews are conducted with Royal IHC and DAMEN Shelde Naval to establish the generally considered arguments for creating a block division plan. Because the only reason to create a block division plan is to build the ship effectively, the main objective of a block division engineer is to optimize towards an block division solution that supports the production process from the perspective of producibility of the ship. Producibility in this context means a block division that results in a redundant shipyard planning by allowing flexibility in erection sequences and being supportive to construction processes. The block division is also dictated by size of supplier materials, shipyard facilities and crane capacity. Therefore also weight calculations are performed as part of a block division plan.

This thesis describes the before mentioned block division methodology implemented in a model. The model uses the information available during the preliminary design stage. The model creates block division plans in three steps. The first step is to place transverse and longitudinal seams over the ship's hull structural design, after which the weight of the resulting blocks is calculated. The final step is to find feasible combinations of blocks by combining blocks that are aligned. The output was constructed in such a way to be able to use in an erection sequence schedule optimization algorithm. Feasibility constraints are implemented to make sure only feasible block division solutions are found. Design variables are implemented to be able to change the automated seam placing decision making process in order to find multiple different block division solutions. Two test case ships are analyzed and the manually created block division of the example problem test case ships is reproduced by the block division generator model. For one test case ship eight different block division solutions are created by choosing different sets of design variables. The different block division solutions are automatically scheduled by the erection sequence planning algorithm. Deviations in erection time, block building time, amount of erection constrains and required personnel are found. These optimization objectives are also used by block division engineers to come up with the manually created block division solution.

Only information is used that is available during the preliminary production planning stage to create the block division solutions. The block division model can reproduce manually created block division plans and can create different solutions that can be used in a ship production optimization algorithm. The different block division solutions result in deviations to relevant optimization objectives. It is concluded that it is possible to automatically generate block division plans that can be effectively used in ship production optimization algorithm. Due to simplifications in the block division generator and the erection sequence optimization algorithm, no quantitative optimization potential can be determined. Future research is recommended to focus on applicability of the methodology and improvement of the functionality of the developed model.

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1 Introduction

The number of increasingly complex vessels constructed in Europe has been growing over the last fifteen years, such as off-shore, dredging, naval and yachting ships [8]. A more detailed description of this development and the reasons of the increasing amount of simple vessels built in other parts of the world can be found in [2][11][20][27]. This industry development presented the aspect of outfitting in shipbuilding, that is only a minor part of the whole construction process for a simple ship such as container ships or bulk carriers, to become more significant in the design, engineering and production of a complex ship [27]. Outfitting is a non-steel related installation process of components that are part of systems on board of the ship. Tasks the outfitting process includes are the mounting of pipes, ducts, cable trays and equipment. Also painting and insulating are considered to be outfitting. These tasks need to be performed in every compartment of the ship. The amount or type of outfitting varies per area or compartment in the ship [6][27].

All work directly related to the construction of the ship on a shipyard is decomposed by the different chosen blocks. Blocks are large steel structures that are combined on the slipway (the erection process) to form the entire ship. This building strategy results a higher throughput of the slipway of a shipyard, which is leading in ship construction [27], because many production processes can take place simultaneously and construction work is moved away from the slipway [20]. For example, when building a ship from two blocks (a fore and aft block), these blocks can be built simultaneously and erected sequentially on the slipway. The only work that is done on the slipway is mounting the blocks together and as soon as this process is completed, the ship can be launched. This strategy reduces the time a project requires the slipway.

European shipyards have developed themselves conform their specialties in building complex ships. However, it still remains a huge challenge to deliver such a complex product within the set time schedule. Mostly because the time between an order and a delivery is very short at a European shipyard due to the competitive nature of the market [7] [17].

The market for complex ships stands out of common production industries, like the car and aircraft industry, by the fact that complex ships are most of the times completely built to customer specification orders, which results in one-of-a-kind orders or very short series [7]. To be able to build a one-of-a-kind ship, it has to be designed to comply with the owner's requirements including engineering and work instructions. Next to this, a custom building schedule has to be developed. Not only because of the unique decomposition of work, but also since the facilities of a shipyard are influenced by conditions such as overlapping projects and deliveries from third parties (including outsourcing) [16]. Because of this, most European shipyards have a relatively fixed planning process, based on available production plans from the past, (available) shipyard facilities and experience of planners with regard to comparability of designs already built [27].

1.1. Problems with Preliminary Planning

The processes and stages prior to production are driven by available information. A shipyard develops a tender offer (or contract offer) based on a Preliminary Design that is developed towards the requirements of the shipowner requesting a new ship. The tender offer includes several important dates such as preparation of costs, the time-to-build and moment of delivery [22]. The first indication of these milestones are based on rules-of-thumb and experience of a shipyard, examples of this are $tonnage/week$ production capacity [11]. In practise, it varies per shipowner, per shipyard and also the relation between these two, at what moment in time the contract is signed and also the exact content varies. In general, the Preliminary Design is completed together with the Preliminary Production Planning at contract signing.

Preliminary Design The information available at contract signing is the Preliminary Design and Preliminary Production Planning. The overview below shows the content of this Preliminary Design and is followed by the Preliminary Planning Planning of the design [22]:

- General Arrangement of the ship
- Capacities of variable weights
- Preliminary definition of major systems
- Preliminary Hull Structural Design

In the General Arrangement (GA) information such as dimension, stability, powering and machinery arrangement is defined. The capacities of variable weight define cargo capacity, handling equipment and habitability. Major systems are types of machinery including major routes of outfitting. The hull structural design provides the lines plan, mid ship section, placing of bulkheads and frame spacing.

Preliminary Production Planning The Preliminary Production Planning in a more developed version of the Master Planning, focused on production processes [11][16]. The Master Planning sets the major milestones of a shipbuilding project to which the payment schedule is linked [9]. Generally the following milestones are defined:

- Contract signing
- Start fabrication
- Start block building
- Keel laying
- Launching
- Start main engines
- Delivery

Based on the Preliminary Design a better milestone planning of the production process can be made by the shipyard, including lead times of major equipment to be purchased, required facilities and resources, material specifications and required outsourced capacity [11].

The Preliminary Production Planning uses the block division plan to make the Erection Planning and Section Building Planning [20]. This block division is made manually, based the 2D drawings which contain the GA, by an experienced engineer [28]. There are no defined weights per block available at this stage, these have to be estimated by crude-estimation techniques [20]. The complexity and size of a block determine the lead time. therefore, the decomposition of all the production tasks into simultaneously constructed and sequentially erected blocks by the block division plan, together with the erection sequence of the blocks, dictate all other activities on the shipyard [16].

The Erection Planning is made based upon experience with different erection strategies [16] and estimations on the block building time. Blocks go through a couple of phases. The initial phase is assembly, followed by pre-outfitting and eventually painting. After painting there is idle time for the blocks in a buffer, to optimize the supply of blocks to the slipway. The duration of assembly, pre-outfitting and the buffer are set using implicit knowledge and therefore estimations. These duration estimations and the erection sequence make up the Section Building Planning, at which only phase duration is estimated instead of specific activities which will be carried out [11].

Problems The current planning methods used in practise do not allow for complex interdependent optimization's, while cost savings for productions would be large if implemented in this early stage of production planning [20]. The limited availability of information requires shipyards to make estimates of crucial information for production planning and costs, and the shipyard is forced to determine most high-level schedules and costs in an early stage of product development in order to obtain a contract. Since block division and erection dominate the whole Preliminary Production Planning, the two main characteristics of a high-quality Section Building Planning, which are even workload and minimization of outsourced sections [20], are a good indication of the overall quality of the Preliminary Production Planning. The quality of the optimization to both characteristics is supported by the quality of the estimations and therefore a risk of apparent accuracy in the preliminary production planning is present. This will be improved when correct information is available at the moment of making the Preliminary Production Planning. This can be done in two ways, do not start the production until all required information is produced by the design and engineering department to make a high quality Detailed Production Planning to allow for global optimization, or rather good estimations techniques have to be developed to support a high quality Preliminary Production Planning in the early stage.
Due to the high amount of reliance on experienced engineers making estimations, and the number of such skilled engineers decreases [20][28], automated production planning tools are required to optimize this process of Preliminary Production Planning. Next to this, automated planning will increase the speed and flexibility of generating such plans and allow for iterations, which leads to higher quality planning [20], and therefore possibly better cost estimation and contract offers for a shipyard.

1.2. Automated Shipbuilding Optimization Software

Automated tools for design and planning can increase the amount of available information in the early design phase, with respect to design details and production planning details, by automatic generation of structural systems, outfitting or production sequences and schedules. Also, computerized methods can generate designs and schedules of higher quality compared to traditional iterative methods [20].

Design Designing a ship is an iterative process that repeatedly goes through several stages to further develops the design. This iterative process is often referred to as the Design Spiral [9]. In the course of the last decade, many research has been conducted to develop automated design tools, an exposition of these tools has been listed and elaborated upon by *Rose*[19]. An unexplored topic of research is automatic generation of block division plans. No further floor is sought in the subject of automatic ship design, because it is out of the scope of this research.

Planning and Scheduling Automatic planning software allows for multi-objective optimization, which global optimum can not yet be obtained using traditional planning methods due to the complex and interdependent nature of the shipbuilding process. Since there is a trade-off in objectives such as resource leveling, minimize outsourcing of blocks, and performing as much pre-outfitting on a block before erection, there is a more optimal (globally) erection sequence that can be found and still generate a schedule from keel laying to launch that is outperforming current schedules produced by the shipyard planners. The global optimum can only be researched when all distinguishing planning schedules are integrated and iterate upon their interdependent feedback, as showed successfully by different test cases[20].

Since outfitting is a major cost driver when planned insufficiently, extensive research has already been done to be able to get more insight in the Outfitting Planning so more realistic time-frames within which the work needs to be completed can be achieved. This results in a higher quality planning [20][27]. Existing research either assumes detailed information to be available to generate an automatic production planning, or use estimation techniques to determine the approximate weight of a block in the early design stage and use this as a basic variable to determine the amount of assembly-or outfitting work. Research has been done to be able to improve the accuracy of these estimations [6][11][26]. Also research has been conducted to asses quality of produced plannings, by running the shipbuilding in a virtual environment [24].

Many of the existing literature only seeks to optimize a single objective, most of the time to minimize the throughput time of a vessel on the slipway via erection schedule optimization while using fixed block divisions in the optimization algorithms. This is however, for European Shipyards building complex vessels, not the global optimum of optimization considering all other objectives[20]. *Cho et al.*(2001)[4] uses a spacial scheduling system for sequence and schedule optimization in painting halls. *Varghese et al.*(2005)[25] optimizes towards minimum required floor space using a dynamic spatial Genetic Algorithm for finished blocks using a fixed erection sequence. *Meijer* (2008)[16] uses fixed blocks to automatically generate an erection sequence using user interaction and estimated weights and assembly times, as does *Tokola et al.* (2013)[23] using general lifting and joining times. *Colthoff*(2009)[6] makes a Section Building Planning based on required man-hours per block based on weight estimates of each block, which *Vlaar*(2010)[26] has improved. *Rose*(2017)[20] has produced an integrated shipbuilding planning method that can visualizes and optimizes multiple objectives. *Iwankowicz*(2015)[12] generates assembly sequence schedules together with a budgeted costs of these schedules. Also *Kim et al.*(2001)[15] optimize the assembly process of blocks by optimizing a constrains satisfaction problem. All of the before mentioned researches use a fixed block division plan and therefore fixed blocks as input in optimization algorithms.

Block Division As stated above, conducted research focuses on other parts of the production stages of shipbuilding to optimize and use block division plans and blocks as fixed input. Currently, block division plans are generated by experienced engineers based on limited information such as the preliminary design, implicit knowledge. These block division plans are optimized to maximize the utilization of shipyard equipment, this means maximum size and weight, to minimize the amount of work on the slipway [16][18]. The number of such skilled engineers is decreasing [28]. The capacity of a crane is one of the constraints in determining the size of a block [6]. From a throughput optimizing objective of the slipway, it is important to consider this maximum capacity of the cranes and set an optimal number of blocks [18]. As mentioned earlier, this may not be the most important objective in European Shipyards. However, it is one of the objectives that can be analyzed or used to assess the quality of a certain production schedule. Research has shown that different mega-block configurations affect the quality of a schedule, because objectives are satisfied to another extend when using different mega-block configurations in the building process [20]. The efficiency of production activities over sub-assembly, block building and erection largely depends on the block division plan [14].

As generating block division plans is the link between Preliminary Design and Preliminary Production Planning, automated block division is the link in automatic design and automatic planning. However, such an automated Block Division Plan generation tool does not exist. Many other research focuses on closely related parts of block division, but most of these researches do not assess the European shipbuilding market building complex industrial ships, but rather large container ships or bulk carriers. *Ayoma et al.* (1990)[1] has developed a designer support tool that requires user input to allocate the seams between blocks, but helps to assess the resulting blocks for production equipment constraint such as weight and dimensions. In no way does the tool generate suggestions or automatically further develops the block division plan. *Roh et al.* (2007)[18] have developed different grouping strategies to determine which (whole or split by a block seam) structural parts are part of which block, using Very Large Crude Carrier (VLCC) detailed hull structure information as a test case. It is supposed this complete and detailed hull structure information is available for grouping structural parts, but at the time a block division plan is created this is not the case, as elaborated upon in Section 1.1. The seams of the block division plan are a given and the research only focuses on the grouping of structural parts, in no way automated seam locations or structural divisions are generated. *Wibisono et al.* (2007)[28] uses fixed steel parts to determine the composition of sub-assemblies that ultimately, as more parts and sub-assemblies are mounted together in a particular order, result in a complete ship. It also assumes detailed hull structure system information is available and uses different genetic algorithm strategies to determine the optimal combination sequence of parts to minimize welding time. It can be stated that the proposed schedule is an erection schedule for sub-assemblies. The research does not focus on early design stage with regard to availability of information and block division plans. *Karottu et al.* (2009)[14] is a successive research on the sub-assembly erection schedule proposed by *Wibisono et al.*[28]. The deepening of this research goes into achieving the same quality assembly sequence with significantly reduced processing power. *Zhong et* *al.* (2013)[29] focuses on the automatic generation of unit-blocks, or sub-assemblies, taking into account detailed hull structure information. The perspective of global production optimization with regard to other objectives than welding length based on hull structure information is not included in this research. No other research regarding the automated generation of block division plans was found.

1.3. Problem Definition

Block division is in current planning algorithms merely a fixed input, just as the design of a ship itself. The difference however, is that a block division is secondary to the design. The division of the ship into blocks is only made to be able to produce the ship efficiently, where the ship design is the end result. Altering the design of a ship for improved producibility may not be in the interest of a shipowner, but if altering the block division for the same reason results in higher quality production processes, it needs to be taken into account. Defining a ship's constituent blocks is an important prerequisite for generation of the production planning of a ship. Furthermore it dictates the decomposition of engineering work, manufacturing of panels and assembly of blocks to a large extent. The rationale for where to put the boundaries between blocks is often dictated by a shipyard's maximum hoisting capacity, the independent strength and stiffness of the resulting block and experience of the responsible engineer, based on preliminary design information. But other criteria might be of relevance such as choosing a block division that is most effective in terms of overall cost, or outfitting cost, or more robust in terms of disruption of the critical path, in levelling resources such as required floor space and outsourcing.

Research has shown that different mega-block configurations affects the quality of a schedule. This result suggest that choosing different block division plans can have the same result, either this may directly affect erection time on the slipway, resource levelling, or indirectly via other mega-block configuration possibilities that will affect these objectives. Maximization of the weight and dimension of blocks towards shipyard facilities may only be a local optimum for a European shipyard building complex ships.

Optimization towards an ideal block division plan requires iterating through possible alternatives and that in turn requires for automatic generation of such plans. therefore, the research question of this report assesses the feasibility of such an automatized effort.

Research Question: Is it possible to automatically generate block division plans in the preliminary production planning stage that can be effectively used in ship production optimization algorithm?

This research question is further defined by the following three sub-questions.

Research Sub-question #1: What is the available preliminary design information input and what is the required information output to incorporate an automated block division plan into ship production optimization algorithms?

Research Sub-question #2: What are the constraints and design variables that determine possible block division plans at a shipyard, and how can these be captured by a model or algorithm?

Research Sub-question #3: How can the quality of automatic generated block division plans be assessed to determine their potential effectiveness in ship production optimization algorithms?

The first sub-question addresses the information availability either generated by automated design software, or available design drawings that may need to be processed. To be able to demonstrate the feasibility of the automated generation block division plans, the available information from the preliminary design and implicit knowledge of the responsible engineer need to be set forth.

The second sub-question examines the required functionality of an automated block division tool. This functionality, together with the available information, will determine what suitable software or programs can be to used to develop such an Automated Block Division Plan Generator. Because the initial objective of this thesis is to assess the feasibility of a Automated Block Division Plan Generator, no further research is done or requirements are added to determine the most suitable software for this aspect of production optimization.

Any suitable software can achieve results that determine the feasibility of a automated block division generator, which is not dependent on the to be achieved efficiency of for example processing power. Although, reasonable time to generate a block division plan is required for the effective implementation of a working Automated Block Division Plan Generator in optimization algorithms.

The third sub-question quantifies this effectiveness of a developed Automated Block Division Plan Generator to be able to assess the effectiveness. A developed Automated Block Division Plan Generator can only be used effectively in optimization algorithms if it is able to generate a spectrum of possible solutions that can be aligned with certain objectives.

This thesis merely focuses on the development of an Automated Block Division Generator. therefore, the information used as input of this generator is sometimes simplified and for that reason may not always reflect reality. Also, since many detailed information is not available in the preliminary design drawings, but implicitly present at experienced engineers, the decision was made to quantify this information in such a way that it can be used as fixed input in the model. No effort was made to automate the generation or implementation of such information in the Automated block Division Generator. Neither is the goal of this research to be able to determine in detail to what extend an automatic generated block division can impact a global single or multi-objective function for ship production optimization at a specific shipyard or in general. The model solely is set up in such a way to be applicable in multiple situations so it can be used in further research to assess and quantify such possible results and improvements.

1.4. Research Structure

This thesis is divided into six. The first Chapter, the introduction, gives an overview of the reason for this research, including problem definition and approach. The second Chapter provides background information about the subject of ship production. The third Chapter Elaborates on the general approach to the block division problem, where Chapter 4 discusses the requirements of the developed model. Chapter 5 explains the overall architecture of the model, including all implemented mechanisms. Chapter 6 discusses the verification block division results and the resulting alternative block division solutions. Chapter 7 discusses the conclusion and recommendations.

1.5. Research Conditions

This research is done as part of the graduation program at the TU Delft, limited time and resources have been available. This research is the first research solely focusing on the Block division design process for complex ships build at European shipyards, and is the first attempt to automatize this process. therefore, an effort is made to quantify a single erection strategy and Block division approach as a starting point for this research area. This is done by reproducing an actual used Block division and its Block division approach to map the degrees of freedom in which this block division process takes shape. These results will be used to find feasible other Block divisions.

This research was executed as part of the internal research group "Ship Design, Production and Operations - Ship Production" and no partner company can be defined as problem owner. Royal IHC and DAMEN Schelde Naval Shipbuilding were found willing to provide time, effort and information to be able to execute this research. Since DAMEN Schelde Naval Shipbuilding was contacted at a later stage during this research, and also only builds ships based on classified information. IHC was asked to provide information about a ship build at one of their shipyards in the Netherlands that could serve as an example for the test case in this research. The Block division generator was build using the information of this example ship to be able to verify the results. The verification of the model is explained extensively in Section 6.1.

2
Background

In this chapter background information is given on the shipbuilding process. Comprehensive attention is payed to the Preliminary Design stage including the different supporting systems or methods that result in the available information in this stage. The subject of the preliminary design is followed up by the current way most European shipyards plan their production processes while building complex ships, while using the Preliminary Design as input for planning tools and methods. Finally, this chapter will discuss optimization algorithms in general that support the choices and mechanisms used in the Automated Block Division Plan Generator.

2.1. Shipbuilding Process

This Section describes the general processes taking place at a European shipyard building complex ships. Using various literature and definitions, it is attempted to provide a clear and complete overview of all existing terminology frequently used in this Thesis.

2.1.1. Design

In this thesis the design stage definitions in shipbuilding of *Storch et al.*(1995)[22] are used as a reference point. Figure 2.1 gives an overview of the main stages of ship design, prior to the start of construction. The

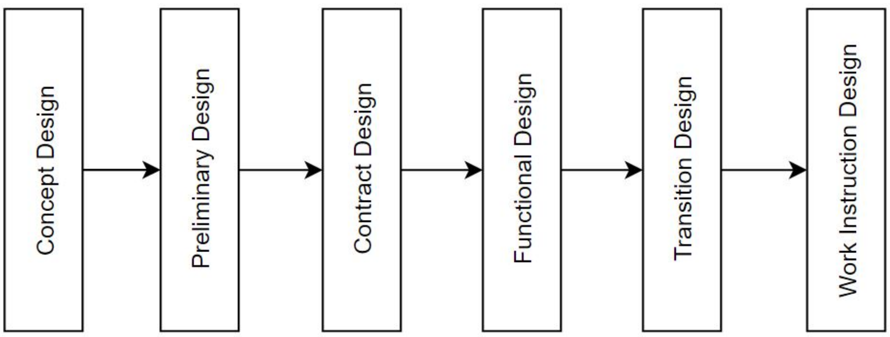


Figure 2.1: Different stages of ship design

first stage is the Concept Design, which is the stage in which the owner's requirements are translated into a conceptual design to give an impression of how these requirements can be fulfilled. This can either be by the owner itself, a Design Company or being part of a Shipyard's internal processes. Sometimes this stage is referred to as the initial design [18]. The Concept Design stage takes roughly three weeks in which the main objectives are to get a clear understanding of the requirements, area of application, capacities and specifications. This is done by creating a preliminary GA, dimensions, hull shape and propulsion configuration to make an assessment on weight and efficiency [19][22].

The Concept Design is followed up by the Preliminary Design stage, once a final concept is agreed upon. The Preliminary Design stage is also referred to as Basic Design stage. The chosen final concept will be further developed, including a GA, load and variable weight capacities, stability calculations, definition and placing of major systems, placing of minor systems, and a major and partially minor structural system.

The focus of the Contract Design is mainly on developing the design to be able to make a better determination of the production process. This includes definition of equipment to be able to plan with the lead times associated with a particular piece of equipment. Also, materials are chosen and required resources are estimated. In this stage, the first version of the block division plan is made, to be able to estimate throughput time, costs and delivery date. This results in the Preliminary Production Planning, which together with the Preliminary Design and total time line of the shipbuilding process at a particular shipyard is referred to as the Master Planning [11]. A more detailed description of all planning stages and how these are generally applied in practise is described in Section 2.2.

After the contract offer is awarded by the tendering shipyard, the Preliminary Design will be worked out into more detail, called the Detail Design stage. This stage can be divided into three sub-stages, respectively Functional Design, Transition Design and Work Instruction Design. During the Functional Design stage, also referred to as systems engineering, the engineering departments receives the design described in requirements documentation [5]. The information is translated into system diagrams of all the major equipment, and as many of the minor equipment already available. All required outfitting links are drawn out on these system diagrams to get a full understanding of how all the systems on the vessel should be connected.

There is an intermediate stage called Transition Design where the system diagrams and schematic drawings of the outfitting are translated to placing of all the equipment on board of the ship and all the major outfitting routing. It is important to be able to see the visual representation of equipment on particular locations to be able to get into detail of the outfitting such as pipe spools and accessibility of high density outfitting areas.

The final stage of the Detail Design is the Work Instruction Design stage, also referred to as detailed engineering [5]. In this stage, all detailed drawings of structural parts, pipe spools, detailed routing of outfitting, insulation and work instructions including mounting sequences are made to be able to built the vessel, this is done by the engineering department. The main goal of this stage is to provide the workers with detailed work instructions and an overview of the detailed structural design and outfitting routing to be able to built the ship efficiently. Of all design stages, Detail Design requires the largest workforce due to the high amount of work and takes up around 5-10 months. High costs are associated with changes of the ship design when initiated at this stage of the design process [19].

2.1.2. Block Division

A complex ship constructed at a European shipyard is built according to the block assembly method. Rather than erecting every steel part directly on to the ship, partial blocks are built next to the slipway or by an outsource partner at their facilities. These blocks are than assembled on the slipway to form the ship. To reduce the number of erection actions on the slipway, blocks are generally constructed as large and heavy as possible, limited by shipyard and supply facilities [6][16].

In the early stage of the design of a new ship, just after the Preliminary Design is completed, the block division process is started by an experienced production engineer and planner. Ship design data is extracted from the 2D GA to decide upon the placing of seams that divide the individual blocks. Since no detailed hull structure information is available at this stage of the design of a complex ship built at a European shipyard, it can and is not included in the decision making process of seam placing, as can be found in Appendix G. The block division is required at this early stage to be able to determine the milestones of the individual blocks, which results in the Detailed Production Planning. Chapter 3 explains upon the considerations made by the experienced engineer when dividing the ship into blocks.

2.1.3. Production

In this thesis the production stages as defined in *Colthoff* (2009)[6], *Eyres et al.* (2012)[9], *Gregory* (2012)[11], *Kaarsemaker et al.* (2006)[13], *Rose* (2017)[20], *Storch et al.* (1995)[22] and *Vlaar* (2010) [26] are summarized and used as a reference point. Ship production can be divided into two main areas, the block building area and the erection of the ship on the slipway. Figure 2.2 gives an overview of the main stages of ship production, once the Detail Design is completed for a specific sub-assembly.

Block Building The production of a ship start with steel pre-fabrication. This is the stage where all the steel components that are needed to to built panels and blocks are cut from steel plates, this includes bending of shell plates and the cutting and bending of profiles [13]. Detailed Design must be completed before the first cuts are made, since all holes that are required to transit profiles or outfitting are preferably cut in this stage. The reason for this is that during steel pre-fabrication the extra time required to cut such holes in the steel plates using advanced computer controlled equipment is much less compared to doing the same job by hand at a later production stage. Generally, a shipyard has steel at stock in a stockyard for between one and three months [9]. The second production stage is panel construction. An average European shipyard uses a

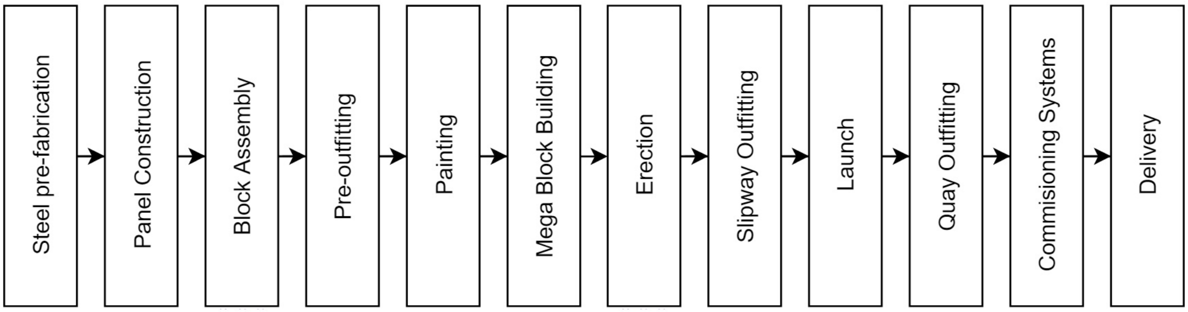


Figure 2.2: Different stages of ship production

so-called panel lane to produce such sub-assemblies. A typical panel is composed of several steel plates butt-welded together, profiles are used to stiffen the panel next to brackets and girders [20]. The panel production station can be partly automated using a panel lane, that automatically welds stiffeners on steel plates while the plate travels through the machine [13].

Next comes the block assembly where the sub-assemblies are mounted together to form a block. A typical complex ship consists of up to around 50-200 blocks depending on its size [20]. Block assembly and pre-outfitting is generally referred to as the block building process, since these two production stages are performed while the block is at the block building floor. The amount of pre-outfitting is maximized at this stage because it is less costly to do at this stage, when every area is generally more accessible than after erection [21]. Typical outfitting tasks include the mounting of pipes, ducts, cable trays and equipment. Other outfitting tasks are adding small iron works, foundations for equipment and staircases. After completion of these stages, the block is transported to the painting or conservation hall. Painting is also considered to be an outfitting task.

After being painted, the block can either be used to built a mega block or be erected on the slipway directly. A mega block is composed of multiple blocks and erected on the slipway as a whole. The building strategy and composition of mega blocks can influence the overall efficiency of the shipbuilding process, as is shown by *Rose*[20]. The goal of this step is to maximize the amount of work done next to the slipway, decreasing the total throughput time of a ship on the slipway.

Either the block or the mega block is subsequently erected on the slipway, either by crane or by a specially designed platform trailer [26]. The erection process can be divided into three steps. The first step is to place the block at the right location. Thereafter, it is fixed or mounted by steel workers using tag-welds and special equipment. Finally, the seams are fully welded and the block will be an inherent part of the ship[20]. The reasons to erect blocks in a certain sequence is elaborated upon in Section 2.2.

Once a block is erected on the slipway, other outfitting parts can be installed that could not have been installed earlier, such as pipe spools that cross block seams. Also at the slipway outfitting stage, are the main engines and major machinery installed. The large machinery can only be installed using an overhead crane. This required the ceiling of the room, where the item needs to be placed, to not yet be installed previously[2].

Once all the major equipment is installed and all the blocks have been erected, the ship is ready to be launched and make room on the slipway for the next project. The ship is completed on the quay, where outfitting will be in stalled that required more time than was available during slipway outfitting. A major part of this stage also is painting and insulation, since all hot work (welding and grinding for example) needs to be completed before a room can be fully painted and subsequently be insulated [11].

After completion of the whole construction, painting and installation of the ship, all components are commissioned. The next step is to test the performance of all systems and the behaviour of the ship, which is done during sea trials. After required adjustments are made due to make sure all requirements are met, the ship is delivered and transferred to the ship owner.

2.1.4. Erection

The erection of a ship can follow several erection strategies. An erection strategy is the approach to erecting the ship. For example the first block that will be erected depends on this strategy, where it can be decided to start with a block from the aft, mid or fore part or the ship.

Mega Blocks Also the individual blocks can be combined to form Mega Blocks before erection on the slipway. After mounting and welding these smaller blocks that form the Mega Block together, the whole Mega Block is erected by one erection action. Figure 2.3 shows an example of the erection of a Mega Block. Mega Blocks can also be combined using different strategies.

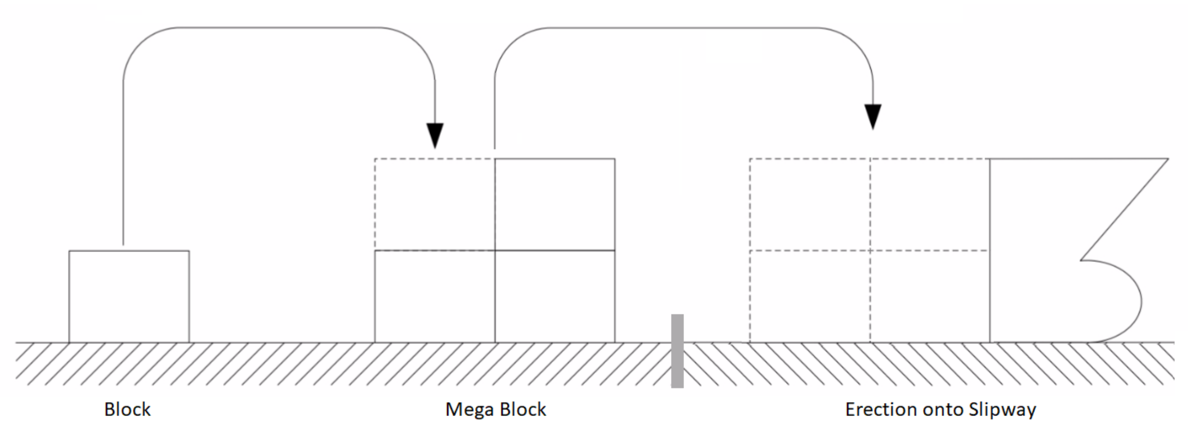


Figure 2.3: Example of how single blocks are combined to form a Mega Block which is erected onto the slipway

Erection Sequence Next to the erection strategy there are erection constraints that influence the optimal erection sequence in which the blocks must be mounted together to build the ship as fast as possible. Figure 2.4 shows the erection sequence constraints as defined by *Rose*(2017)[20]. All defined erection sequence constraints are listed below.

- **Vertical Feasibility Constraint** - All blocks that are geometrically beneath the next block must be erected before this next block can be erected. In Figure 2.4(a) block *G* must be erected before block *D*
- **Inside Out Constraint** - Figure 2.4(b) shows how must be started with a center block and worked towards the outside, so that block *L* will always be erected only after the erection of block *J* and *K*
- **No Placing Between Constraint** - It is not possible to erect a block in between two blocks, always built in a consecutive order to elongate or rise the ship. This shows in Figure 2.4(c) where block *N* can not be placed after block *P*, *M* and *O*

- **Sister Block Constraint** - When two blocks must be erected directly after each other, when the alignment of the two blocks depends on each other. Figure 2.4(d) shows an example of this constraint
- **Closing deck Constraint** - This constraint is similar to the Vertical Feasibility Constraint and exception to the No Placing Between constraint. A closing deck can only be erected when the two outer blocks already have been erected. Figure 2.4(e) shows an example of this where block T is the closing block and must be erected only after block S and U. More information about closing decks can be found in Sub Section 3.3.2
- **Structurally Supportive Constraint** - In case a block can not support itself, the supporting blocks must be erected beforehand, similar to the vertical feasibility constraint. Figure 2.4(f) shows how blocks V and X can only be erected after the erection of block W

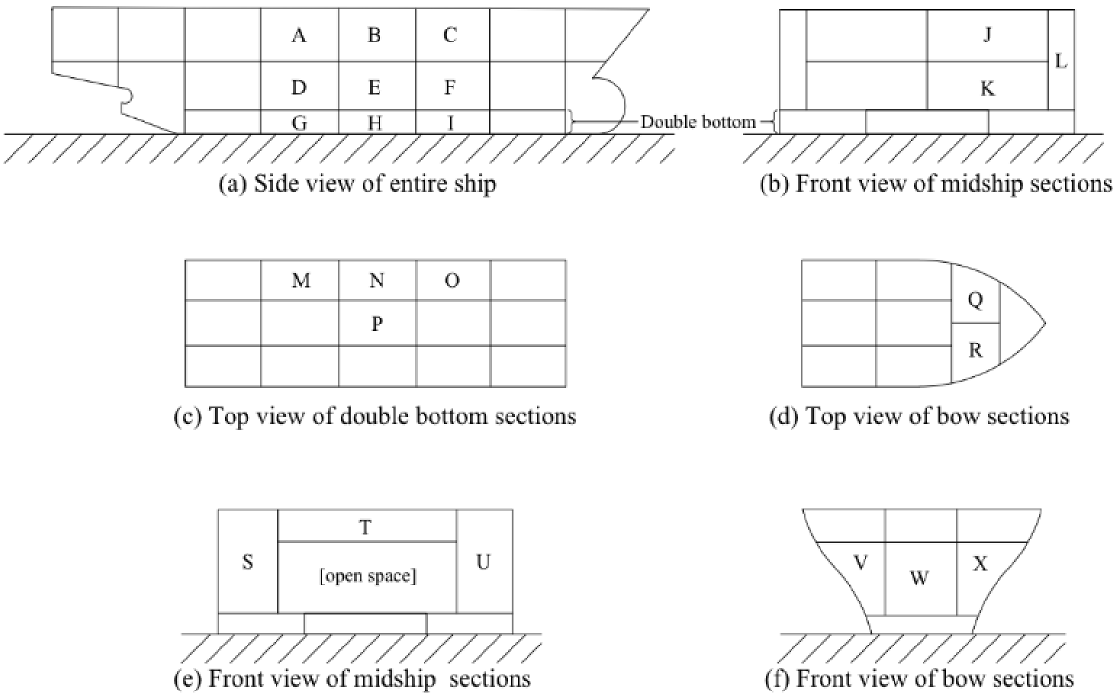


Figure 2.4: Example block arrangements to illustrate erection sequence constraints [20]

2.2. Shipyard Planning in Practise

During the tender proposal process, the ship design is still in the preliminary stage and production milestones already need to be determined to be able to make a tender offer, which has to include the delivery date. The production planning of a to be constructed ship goes through several stages of development, as is the design of the ship itself. The first stage is the Master Planning which is required to complete the contract design and state the several production milestones. After a contract is assigned to a shipyard, the preliminary production planning will be created to determine in which sequence the different parts of the vessel are required to be ordered or be completed with respect to the detailed engineering. The final planning stage is the detailed production plan, consisting of work instructions and mounting sequences of steel fabrications and sub assemblies. The detailed production plan comes in the form of detailed drawings and prioritized lists of tasks.

2.2.1. Master Planning

Ship production planners at different shipyards have different approaches when it comes to making the initial Master planning, based on each shipyard's experience of building similar ships. At Royal IHC the first estimation is based on the expected weight of the new design, as mentioned in Appendix G.2. This estimation is corrected for the existing orders and workload of the shipyard[20]. Based on global $tonnes/month$ reference metrics, the time it takes to build the on the slipway is estimated. Depending on the complexity of the vessel, a certain amounts of months is reserved up front of the slipway building phase to complete the ship design and engineer the first work instructions. Depending on the overall size of the ship, superstructure and amount of to be installed systems, a certain amount of quay outfitting time and commissioning time frame is added to the back of the planning. Together these three stages (design and engineering, erection and quay outfitting and commissioning) define the throughput time of a ship at the shipyard and result in the to be stated milestones for the particular concept design in the contract design stage. Generally the milestones shown in Figure 2.5 are defined by the Master Planning, which is added to the contract for a tender offer. Note that the representation in Figure 2.5 is only showed to give insight in the sequence of following stages and milestones, and by no means is meant as an accurate gantt sheet representation.

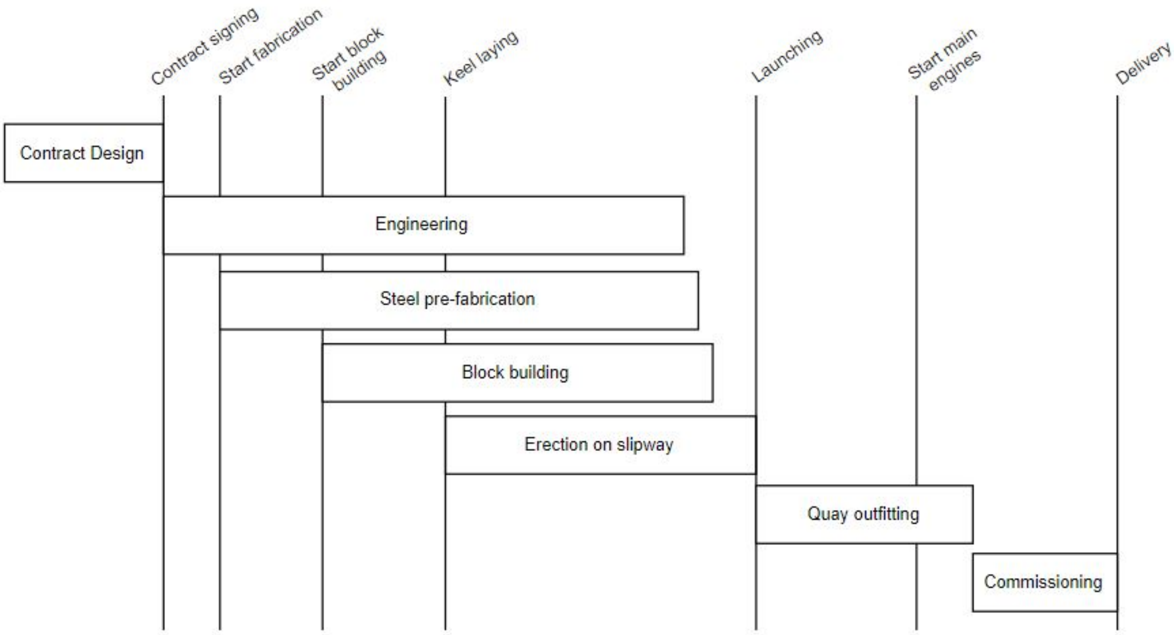


Figure 2.5: Master planning milestones for contract offering

2.2.2. Preliminary Production Planning

When the contract is awarded, the Master Planning milestones are used as reference points in the development of the Preliminary Planning. The start of the block building and launching dates dictate the time frames available for block assembly, pre-outfitting, painting, possible mega-block building, erection and slipway outfitting. In comparison, the outfitting plan starts with time slots based on estimated required man-hours and available personnel. When more detailed outfitting information is generated by the engineering department, the sequence of different outfitting parts to be mounted by different teams is optimized and this reflects on the block building schedule due to its high dependency in the shape of earlier starting dates and maybe an increase of subcontractors due to a high required amount of outfitters for a specific task over a short period of time[20]. This is only applicable for shipyards that build most of the blocks at their own facilities.

Figure 2.6 shows how the set milestones from the Master Planning result the development of the more detailed planning. The keel laying milestone results in backward planning with respect to the engineering, block fabrication and erection. In the time frame defined by the keel laying and the delivery of the ship, the slipway and quay outfitting and commissioning will be planned in more detail using forward planning. When more detailed information is produced the planning can be revised, these different plannings will be categorized as for example "revision A" and "Revision B"[6].

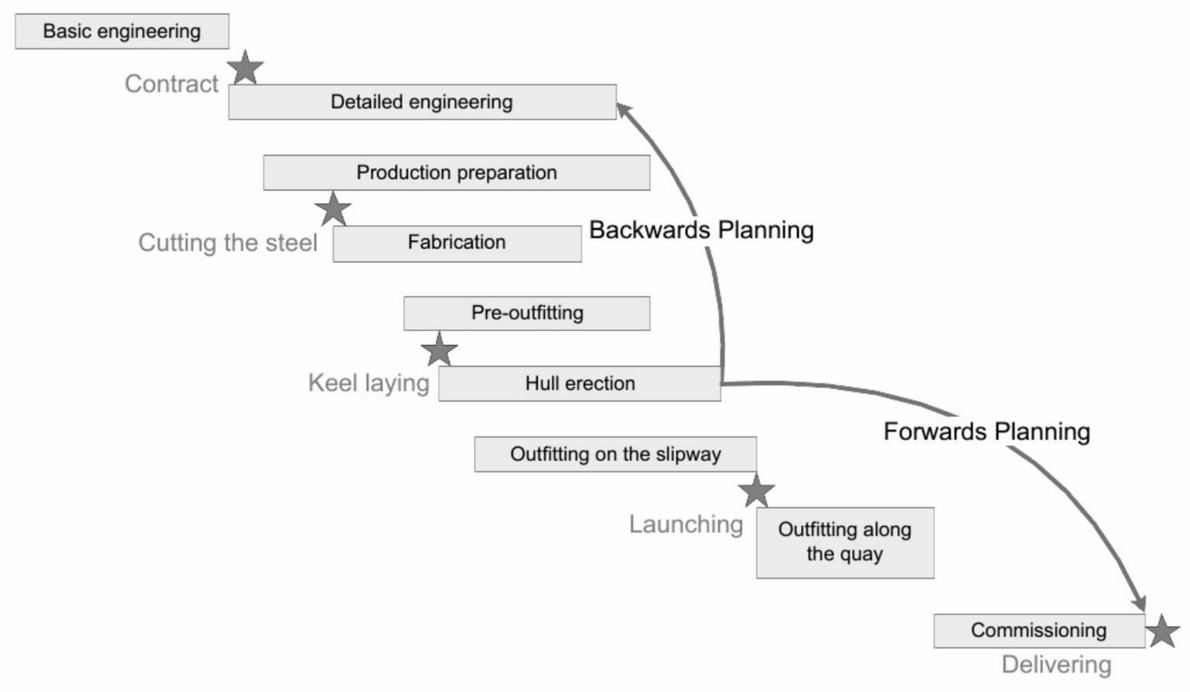


Figure 2.6: Forward and backward planning in the production planning[27]

Erection Planning Erection is the parent planning of block building planning[6]. Figure 2.8 shows an example of a part of the erection plan. Each Block requires three steps to be completely erected. The first step is to place it onto the already partially erected ship, next it is fixated using spot welds and the final step is to completely weld the block to the partially erected ship. After the block is placed the next block can be started to be placed. Different erection strategies can be used to build the ship as efficient as possible, such as starting in the middle to be more redundant in block building time lines since there are two sides of the ship that allow erection. Another strategy is to erect the full length of the ship as soon as possible, this creates more work area and work space for workers. The sequence can also be dictated by shop floor and slipway configuration, where either side of the ship is less accessible than the other with the present equipment[16].

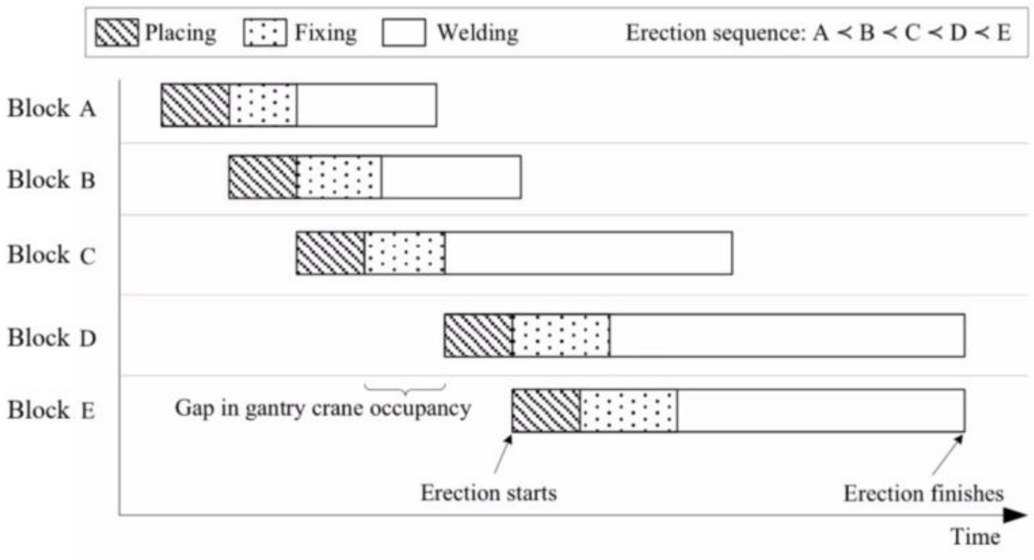


Figure 2.7: Example Erection plan[20]

Next to the erection of blocks, also large equipment is scheduled in the erection planning. These pieces of equipment often have long lead times and must be placed and installed by specialized workers often supplied by the equipment manufacturer. As a result, the date the equipment will be placed and installed is determined when the equipment is purchased and the erection schedule of the blocks will be created in such a way that all erection sequence constraints of the equipment are satisfied[20]. Next to placing of equipment, the erection schedule will have to comply with other supply constraints of the blocks such as available floor area to build the blocks, or capacity of production partners where blocks may be outsourced.

The erection planning is not changed when small delays in for example outfitting progress occur. When a single block will be rescheduled, this imposes all neighbouring blocks to be rescheduled also. Eventually such rescheduling will result in the delay of the launching of the ship[27], which will be avoided at all time.

Block building planning The erection planning results in milestones for the blocks to be erected onto the slipway and thus be completely fabricated. The block building process consists of assembly and pre-outfitting processes. Doing more outfitting work in a section prior to erection (pre-outfitting) results in lower costs due to the better accessibility of the area where components need to be installed [21]. The previous is not only the case for the installation of outfitting components such as pipes and cable trays, but also for painting and conservation. It is more cost effective to be able to install more outfitting components to be able to paint or conserve more area of block before erection. Also, when the block is erected the systems inside this block can be completed earlier in the production planning resulting in more time for testing and commissioning.

Figure 2.8 shown an example of the block building process. The pre-outfitting can already start before the assembly of the block is completed. For example in case of pipes within the double bottom, this is required to be able to install all larger outfitting components. After pre-outfitting there is a default buffer time in the block building schedule to make sure all required blocks for erection are available to erect. Traditionally, IHC has built the blocks in house. Nowadays, most if not all blocks are outsourced as part of the new competitive strategy in the current high pressure market situation. The required man-hours and the size of a block, which determines the amount of workers that can safely work on a block simultaneously, determine the minimum required time to built a block, which together with the Erection Planning results in the Section Building Planning [20].

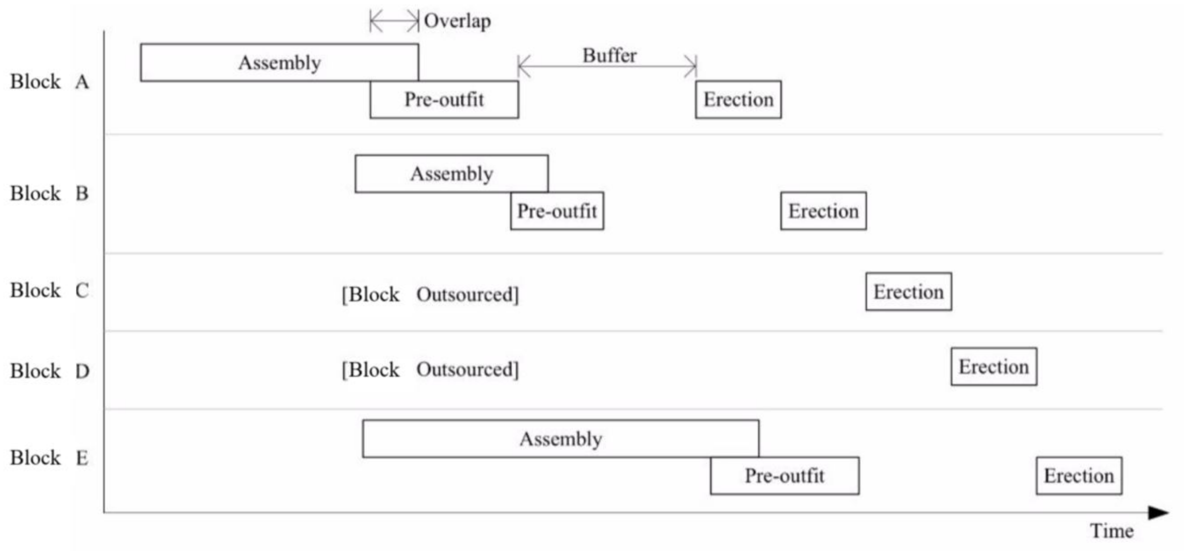


Figure 2.8: Example Block plan[20]

Outfitting Planning Since the outfitting planning is a deduction of the Master Planning and Block building planning, it is more a planning of resulting time frames and required amount of work to be done than the other way around. This results in a planning driven by flexible work forces to get the job done. Because the time required to do an outfitting job is increased significantly when it is not done in the pre-outfitting stage but for example on the quay, as much outfitting as possible is planned to do in the pre-outfitting stage. The constraints of the amount of outfitting to be able to be carried out is either in seam overlapping outfitting that can only be completed post erection, or because there are only a limited amount of people able to work safely in a block to install all the outfitting that result in not being able to put enough hours of work in within the dedicated time frame at this stage. In those cases, the outfitting will have to be postponed when a block is already erected on the slipway or when it is docked at the quay in the final stage of ship assembly. For this reason the outfitting planning is considered more flexible than the erection planning[27].

2.2.3. Detailed production planning

After the preliminary production planning defines the individual milestones for each individual block, the detailed production plan is developed. The detailed production planning defines the sequence of fabricating and assembling steel parts and sub assemblies to fabricate the blocks. Also the outfitting components are listed and a installation sequence is developed. Next to assembly sequences also detailed construction drawings are created. On these drawings workers can see which welds must be performed in order to assemble the sub assemblies and the block. The required amount of workers results of the defined of work that needs to be done in a particular time frame as set by the preliminary production plan. When necessary and depending per discipline, 'sub contractors can be hired to be able to complete the required amount of work. Because the detailed production planning is a result of the erection planning, the erection sequence dictates all work on the shipyard. Therefore it is not only required to have all the detailed engineering information available on time, but the whole production process must work in total harmony with the design and engineering department[16].

2.3. Optimization Algorithms

Extensive research has been done into the subject of decision support tools and automatic generation of shipyard planning and optimal ship production schedules. The main focus of these researches has been the erection planning [6][16][20][26] and block building planning [20][25][26].

2.3.1. Erection planning

Erection planning optimization algorithms create erection sequences for the entered block division. Below several developed optimization algorithms are discussed from earlier research.

Meijer(2008)[16] has created an erection sequence schedule support tool that can be used by shipyard planners to assess what impact and check variances in the erection schedule result from changing the erection sequence. The model requires the user to enter the size of the blocks, weight, location and type. The model automatically generates a set of erection constraints, which are discussed earlier in this Chapter. The output of the model is an erection sequence, lead times of Blocks and of the different production processes such as Block building and erection. The model gives feedback on the fitness of the production schedule by showing required resource levels for floor spacing, required production personnel and crane use.

Vlaar(2010)[26] has improved several simplifications incorporated by *Meijer*(2008)[16]. The goal of his research was to improve the accuracy of the erection schedule by adding accurate lead time calculations for specific block types. For example to correct for identical blocks with different plate thicknesses and thus different weights but no different required man-hours for placing and mounting of the block due to similar size of these blocks. A complexity characteristic is added that can be determined per block manually for a more accurate required building man hours estimation. In the end the initially developed model by *Meijer*(2008)[16] is improved in the already developed functionality rather than expanding the models application.

Rose(2017)[20] has developed an erection sequence schedule algorithm that incorporates all different disciplines of skilled workers required for building and erecting the blocks. The thread through his research is the optimization towards outfitting maximization in the perspective of cost reduction, because installing components during the pre-outfitting stage is more cost effective than later in the ship production process, as mentioned earlier. The goal of the developed algorithm by *Rose*(2017)[20] is to improve throughput time a ship by optimizing shipyard planning while increasing accuracy of required resource utilization.

2.3.2. Block building Planning

The block building schedule has to be supportive to the erection schedule as blocks are required to be ready for erection as soon as they are scheduled for erection. The previously mentioned models create a block building schedule, erection sequence and erection schedule due to to interdependence relation between these different planning schedules. The block building planning results in an individual start and end date of every block. Per block the assembly and pre-outfitting periods are scheduled. The block building planning directly has more impact on the required resources of different disciplines, but the erection planning directly results in the block building planning.

3
Block Division

This chapter elaborates on the Block division conditions taken into consideration as such is generally carried out by experienced engineers at the two interviewed shipyards building complex ships in Europe. Both shipyards do have their own building strategy and specific ways of cooping with problems they encounter on a regular basis as a result of the type of complex ships they build more often. The primary information used to support the information stated in this Chapter can be found in Appendix G. The general approach to creating a block division plan is elaborated upon in this Chapter.

3.1. Definitions

In found literature some definitions are used with different meaning. For clarity, the definitions around Block division used in this research are briefly summarized in this Section.

- **Blocks** - Combined sub-assemblies of steel structural parts and outfitting of the ship that are used to partition the building of the ship in work packages with individual milestone planning schedules and reference numbers, that can be individually be handled by shipyard equipment and together be combined to form the ship
- **Mega-Blocks** - A combined set of Blocks that is not yet erected on the slipway, but will be as a one single piece. Mega-Blocks come in different shapes and sizes, no standard combination of Blocks is part of this definition
- **Module** - A particular part of the total ship, that consists of multiple Blocks or Mega-Blocks. For example the whole fore ship in front of a hopper will be referred to as a fore ship Module
- **Compartments** - Different functional compartments such as rooms and tanks, are in this research referred to as Compartments. Compartments can contain multiple different types and components of outfitting such as piping, cable trays and paint

3.2. Design Information

The Block division has to be made in the early stage of ship design, as this is required to make the erection sequence schedule as shown in Figure 2.6. This sequence planning prioritizes the engineering and steel prefabrication in the form of milestones for the individual Blocks, to be make sure drawings are finished in time and steel is cut to the right size when the assembly of the first Block starts. Different sources of direct and indirect information are used to be able to have a maximum understanding of the ship to be built. Next to the information shown on the drawings, the engineers have a lot of implicit information at hand to base their decision upon when dividing the ship into Blocks.

3.2.1. General Arrangement

The information available at the Preliminary Design stage is a General Arrangement (GA), overall size (including mid ship section), overall weight, load and variable weight capacities, stability calculations, definition and placing of major equipment, placing of minor equipment, and a major and partially minor structural system [22]. The GA is direct information as it directly represents the ship to be build. An example of a GA is added in Appendix H.1 and shows the preliminary structural design, such as:

- Decks and transits
- Frames and bulkheads
- Longitudinal Girders
- Various stiffeners

The structural design can still change, but just as at shipyards building complex ships, decisions have to be made in the early stage on the available information. Some decisions can be changed in a later stage but some of these decisions also limit design freedom that may turn out unfavourable. Experienced engineers use the GA to draw the Block division seams and separate the steel hull structure into Blocks. The GA also shows the height of decks over the length of the ship, as well as the breadth. Foundations can be deducted from the areas where major equipment is placed. A lot of expected detailed structural design and types or amounts of outfitting components can be estimated using comparable reference ships that have been build in the past. The main information used from the GA is shown below:

- Preliminary structural design
- Compartments and major systems
- Major long lead time equipment

3.2.2. Calculation Data

This Sub Section is partially based on Appendix G.2. When a Design Proposal department starts with the stability calculations and engineering for a design of a complex ship at a European Shipyard, the first step is to analyze comparable reference ships, preferably built at the same yard they plan to built the to be built ship. The reference ships are chosen based on similar main dimensions and frame spacing. The reference ship must be of a comparable function, such as dredging for example. Also, the systems installed on board of the ship are preferably similar to fulfill the required function, since these systems can dictate structural design of Blocks anywhere at the ship to a large extend. A reel-lay pipe laying vessel encounters a very different loading profile compared to a ship that is equipped with a moon pool and a J-lay tower for example. The structural system of each vessel is engineered according to this loading profile, and thus also the steel plate thicknesses, structural design and weight of similar sized ships can deviate a lot between similar Blocks but different systems to full fill a similar function. The ship's total weight, weight distribution (longitudinal, latitudinal and height), centre of gravity and stability are estimated with the information gathered from these comparable reference ships. This information needs to be corrected for dissimilarities between the new ship design and the reference ships. Next to this also regulations and software are useful sources of information to obtain general information about the expected details of the ship's structural design. The constructed data about the centre of gravity and stability are assessed using a hydro static model by testing several load cases.

Next to the available data of a reference ship, there is also experience in building this ship with the chosen Block division of that particular reference ship. This experience can either result in reproducing similar seams that worked out well in production, or result in an attempt to rearrange the Block seams to improve the producibility of the Block division plan and therefore the ship.

3.2.3. Hull Structural Design

There are different systems on board of a ship that are designed to a certain amount of detail in the preliminary design stage. The general location of significant parts of these Systems are drawn on the GA, such as primary equipment and main outfitting routes. In the early phase only the preliminary structural design is present.

Detailed Structural Design Depending on the type of order of a ship or ships to be built, the detailed hull structural design is developed to a certain extend. In case the order consists of a ship already built by the shipyard or the order is for a series of similar ships, the detailed structural design is already available. When a series of ships will be built the detailed hull structural design will be developed to a larger extend compared to an engineered-to-order contract at the time the Block division has to be made. In the final engineered-to-order case, the Block division has to be made in an earlier stage due to the fact that every part of the ship has to be newly developed. When waiting to fully develop the detailed structural design until creating the Block division this process would take too long to be competitive. For this reason, as mentioned in Sub Section 3.2.1, the Block division is made based on only the GA. Because of the early development of the Block division, and in favor of the producibility of the Blocks, the detailed structural design will depend on the Block division

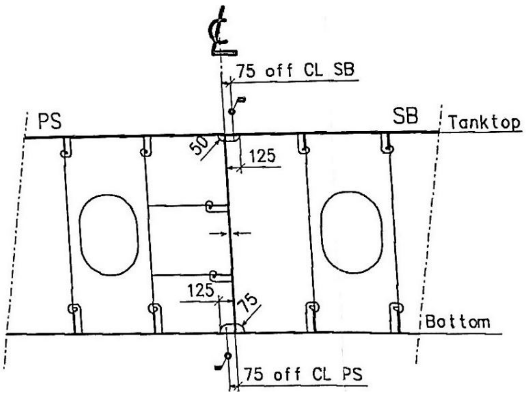


Figure 3.1: Example of detailed structural design following a block division seam at CL

plan and will support the seams in the plates by means of assembly order of minor parts, weld direction and accessibility. Figure 3.1 shows an example how the detailed structural design that depend on a Block division seam at the Center line of a double bottom Block to support the erection and thus the seam position between those Blocks. It can be seen that the center line girder is part of the port side Block. When the starboard Block will be erected first, 75 mm of the bottom shell will cross the seam and therefore provide a mounting platform for the center line girder which can be rested upon this bottom shell.

Stiffened Panels Whenever stiffeners on panels are shown or known in the preliminary design stage, seams are placed accordingly. Meaning, a seam will never be placed on the side of a panel on which stiffeners are present, as shown in Figure 3.2. The reason for this is that it is very inconvenient to first erect the plate as part of a Block and at a later stage the stiffeners. Stiffeners are ideally welded upon plates in the panel street, when they are easy accessible and can be welded under hands. Whenever the stiffeners are unknown or are switched from on side to another, the seam can be switched accordingly. When there is no valid reason to do so, for example structural integrity or available space, the optimal seam placing can dictate the side of the plate on which the stiffeners are welded.

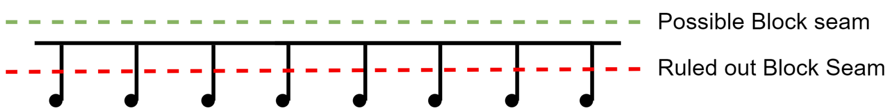


Figure 3.2: Example intersection of a stiffened panel where seams are placed on side without stiffeners

Curved or Bulbous Panels Another aspect of the structural design that influences the Block division is the amount and integration of curved or bulbous shell at parts of the ship. Preferably, all seams run over flat surfaces which results in easier mounting and aligning of the different Blocks. However, in strongly curved areas of the shell this is not always possible. The starting point will always be to include as much of the curved shell in a single Block. The same goes for foundations of large equipment, preferably this is kept within a single Block. When weight or material constraints do not allow for this, the constraint can and will be overruled.

Structural integrity The final ship is designed to withstand all kind of loads. When dividing this interdependent structural system into Blocks, this capacity of withstanding these loads is impaired. Depending on the seam placing, Blocks can consist of panels in the x, y or z plane direction. Any Block can have any combination and number of panels in these directions. Some Blocks might be stiff enough to be able to hoist while others are stand alone too flexible to even built properly without any supporting temporarily construction. Based on the interviews with the two shipyards, it was concluded that structural integrity of a Block is not a seam placing argument. Most of the Blocks do not have any problems when hoisted regarding stiffness or structural integrity because they will always include frames/bulkheads and decks. For the Blocks that do have problems, production solutions are found in temporarily stiffeners for hoisting or mounting the Blocks on the slipway, these will be removed afterwords or integrated in the structural design.

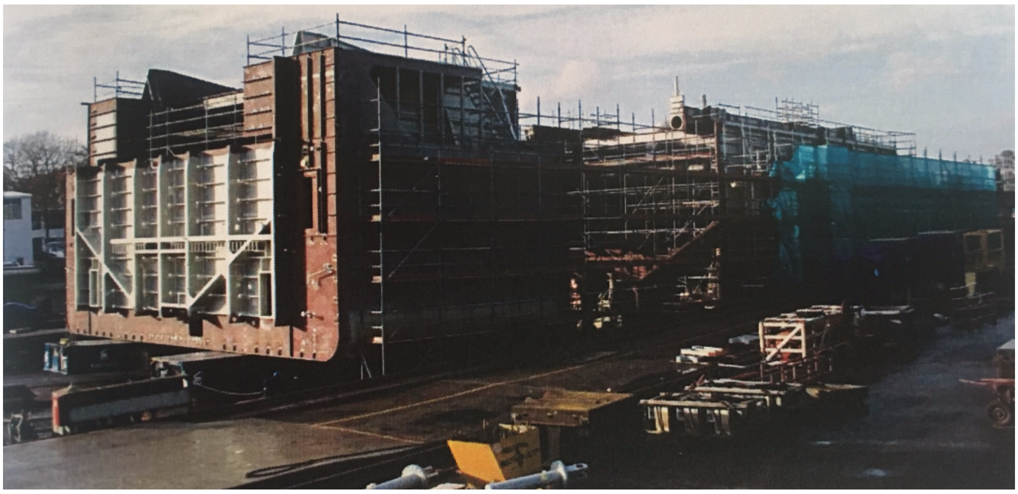


Figure 3.3: Example of a Ring-Mega-Block being erected on the slipway [26]

3.2.4. Erection Strategy

The general presumption about minimizing throughput time of ship is to minimize the amount of erection actions on the slipway [16][20]. This is implemented by aiming to erect Blocks that are as large and heavy as the shipyard facilities can possibly handle. The most import facilities at a shipyard that limit the size and weight of Blocks are cranes and possibly other transportation equipment. The maximum size is generally limited by the height of doors and production halls like the hall over the slipway and conservation hall.

Depending on the shipyard facilities, different erection strategies are possible to built a ship. Generally, one building strategy suits a specific shipyard the most and will therefore always be the starting point when developing the Block division and production planning. There are generally two distinguishing building strategies that also have a lot in common. The first building strategy is to maximize the size and weight of individual Blocks that are erected onto the slipway one by one. The second building strategy is to first combine Blocks to form Mega-Blocks, as elaborated upon in Sub Section 2.1.3. Any combination of Blocks can be chosen to create a Mega-Block, as long as this Mega-Block complies with the shipyard facility constraints. Figure 3.3 shows an example of a common Mega-Block configuration where the Blocks are combined over the entire breadth and height of the hull of the ship. This type of Mega-Block building is referred to as Ring-Mega-Block Building. Due to the size of the Ring-Mega-Blocks and the space required to assemble these, not every shipyard can follow this building strategy. The different erection strategies result in different approaches when it comes to creating the Block division plan, but the methodology does not differ fundamentally. The single Block building strategy and the Mega-Block building strategy will both strive towards the objective of maximizing weight and size of individual erected structures onto the slipway, where in the first mentioned approach this structure is a single Block and in the second mentioned this structure is a Mega-Block. The order of relevance of seam placing arguments may differ but the seam placing arguments taking into consideration are based on the same principles and available information.

3.3. Design for Production

The Block division plan is essentially a design process, which is created for the sole purpose of being able to produce the ship in the shortest amount of time possible. The owner of the ship has no interest in a specific Block division plan other than it being supportive to a low price or faster production time, but in no way it results in a better or worse to operate ship. For this reason, the main objective of a Block division engineer is to optimize the Block division plan towards an optimal production process from the perspective of producibility of the ship. This is achieved by means of an iterative process.

Producibility in this context means a Block division that results in a redundant shipyard planning by being supportive to other shipyard departments such as procurement, by allowing flexibility in erection sequences in for example placing of long lead time items.

3.3.1. Erection

Next to the assembly of the Blocks, including outfitting and finishing, they must be erected onto the slipway. Seam placing directly results in the applicable erection constraints explained in Sub Section 2.1.4. Because the production process knows many variables that can influence the ability to meet the deadline for the erection planning, the Block division is therefore required to be flexible by creating Blocks with the least amount of erection constraints as possible per Block. In case of the delayed completion of a Block, this can be overcome because many other Blocks are being able to be erected rather than only one Block where the rest of the erection schedule will be waiting for due to insurmountable erection constraints. One unavoidable condition will always be the Vertical Feasibility Constraint that ensures all Blocks below the next to be erected Block are in place, because a ship must always be built from the ground up. When by no means certain erection constraints can be avoided, depending on the situation, exceptions can be made in the Block division. A smaller amount of Blocks can be chosen resulting in larger Blocks that maybe can not be managed by the available shipyard facilities, other resources in such case will be put forward.

This approach to Block division for production optimization with respect to the erection process and minimizing the erection sequence constraints also results in multiple building strategies where Mega-Blocks can be used. This is another example of how the Block division can support flexibility in the assembly of the ship, by ensuring multiple possibilities to continue to erect the ship and increase the likelihood of meeting all production milestones.

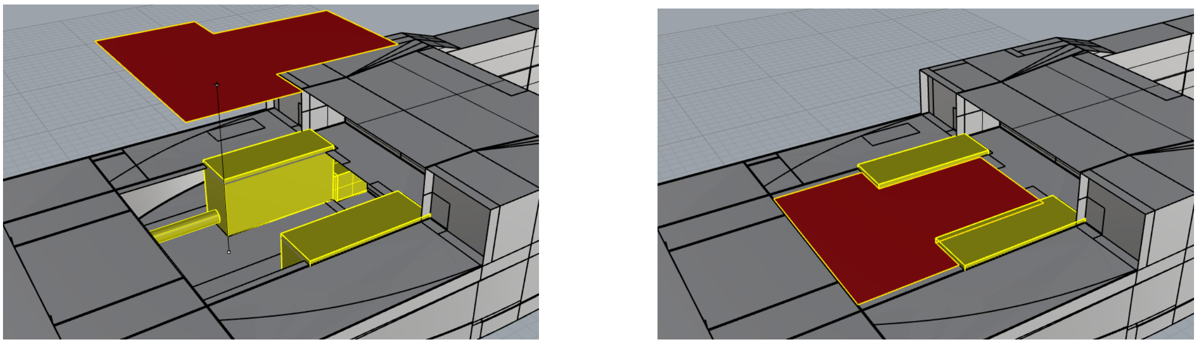
The resulting erection constraints can be satisfied by multiple erection sequences. The optimal sequence, the sequence that results in the shortest building time, for a shipyard will also differ depending on the resource conditions at a shipyard. When a shipyard has a high workload, the erection sequence might use another starting Block because of utilization of the slipway by another ship being built. However, generally these shipyard conditions do not influence the Block division plan. The only way shipyard conditions reflect in the building strategy of a ship is by an altered erection sequence to be able to coop with the given shipyard conditions. As elaborated upon in Sub Section 2.3 many research has been done to mathematically solve this optimization problem.

3.3.2. Closing Blocks

Closing Blocks are used to increase the redundancy of the of shipyard planning and to remove long lead time equipment as much as possible from the critical path of the building schedule. When a piece of equipment is penetrating or below a deck at a certain area, as shown in Figure 3.4a, the overhanging structure will be isolated as a closing Block. In this case, the large piece of equipment is required to be erected on the slipway before the closing Block. The Block division is chosen in such a way that the piece of equipment is surrounded by individual Blocks, as shown in Figure 3.4b. As elaborated in Sub Section 2.1.4, the Blocks and the piece of equipment are erected on the slipway, with respect to the "Inside Out Constraint". Finally, the remaining Block consisting of only a deck or multiple steel structural parts will be erected and will complete the deck, locking the equipment in place as shown in red in Figures 3.4a and 3.4b. When a closing Block consists of only a deck it is also referred to as closing deck. The "Closing Deck Constraint" makes sure the Blocks are erected in the right order to be able to erect a closing deck. In this way the surrounding Blocks can be erected and less dependency of the delivery time of the piece of equipment is translated into the schedule. Also, this building strategy results in higher accessibility of the piece of equipment and higher efficiency in installing pre-outfitting components and thus total erection speed. Not only decks are used in this matter to increase the redundancy of the planning and reach a higher level of accessibility of the equipment. Also the side Blocks on starboard and port side can be considered closing Blocks, next to the blocks on the main deck. All these Blocks close the center of the ship and seal the ways of bringing in equipment and parts for the slipway outfitting process. This is also one of the supporting arguments for the "Inside Out Constraint", since this building strategy increases supply of materials, equipment and facilities to be able to build the ship as fast as possible.

3.3.3. Transit

In many locations where large equipment is installed on board of a ship, the equipment is higher than the available deck height, as the example in Figure 3.4a also shows. To be able to install the equipment, transit holes need to be created through the deck above. When a possible seam position is nearby a transit, it can be chosen to split through the transit. An example of a seam splitting through a seam is shown Figure 3.5.



(a) Open closing deck (b) Closed closing deck

Figure 3.4: Closing deck to close the deck over the engine room before and after erection

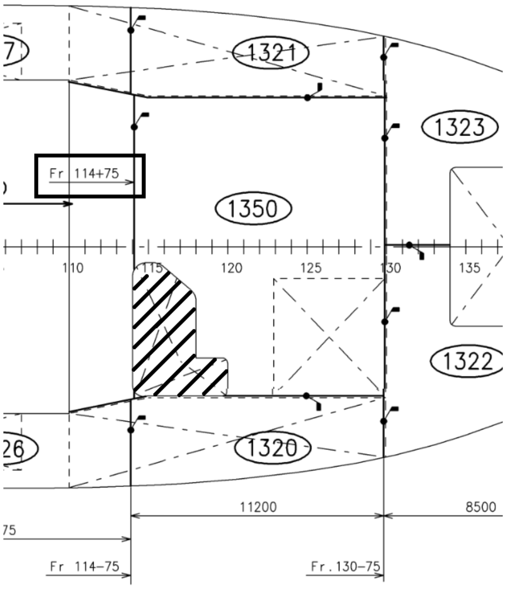


Figure 3.5: Example of a seam splitting through the edge of a transit

The diagonally hatched area is a transit for the bow pumps of a hopper dredger. The seam, indicated with the reference "Fr 114+75" is chosen just within the transit. This chosen seam results in two advantages over the "Fr 113" seam position. The first advantage is more simple erecting of Block 1350 around the installed bow pump. The open transit allows erection of the bow pump after the erection of Block 1350 resulting in a more flexible erection plan. The second advantage is not ending up with small strips of plate material next to transits and on the edge of chosen Blocks, which are vulnerable to damages and more difficult to weld and mount. In general, when considering transits, the transit is maximized within the chosen closing Block to increase the accessibility when erecting all equipment within the surrounding Blocks. Only transits that include a lot of outfitting components or long lead time equipment are taken into consideration in the Block division process.

3.3.4. Assembly

The assembly of the steel system is one of the main focus points when aiming to increase the producibility of the ship. As mentioned in Sub Section 3.2.3, the detailed structural design to a certain extend supports the Block division and is optimized for the production process. For assembly this means that as much welding as possible can be executed under hands. This increases the speed and quality of the welds performed by welders, because it is much more convenient to perform an underhand weld than performing vertical welds or welds that are above shoulder height. Blocks will for that reason also be turned several times when necessary to be able to perform the majority of the welds under hands, demonstrating the influence of the shipyard facilities to be able to do this. Blocks are generally chosen per deck above the deck plates as an example of this assembly optimization. In combination with the stiffeners on the downside of the decks, such seams and Blocks result in accessible under hands welds that increase producibility. Another example of this is that Block seams are never exactly on frame but always between two frames. This allows the frame to be assembled as part of the Block and is not required to be fitted after erection, over the mounting weld of the Block.

Also the material influences in what is convenient in the assembly of Blocks and what Block design results in extra or reduced amounts of work. therefore the general objective for placing these seams is the minimization of steel residual material and welding meters. To reduce residual material that goes to waste, the size of steel plates is one of the reference values for the size of a Block, in combination with the size of building beds and door sizes. Welding meters are reduces by minimizing the amount of welds by placing the seams on the position where material would otherwise also be welded together for creating larger assemblies than the available materials size allow. Extra material can be left over at the end of a plate for being able to cut a Block to the exact length during mounting or make up for shrinkage of materials as a result of welding.

Another aspects of assembly is the handling of Blocks. Enormous Blocks that the shipyard's crane can barely lift are not easy to handle due to the limited buffer in capacity and therefore safety requirements, so instead Blocks are generally well below the maximum lift capacity of a crane and can rather easily fit through doors. Smaller Blocks are also easier to mount and align with already erected Blocks. On the other hand, smaller Blocks require more erection actions on the slipway before the whole ship is completed.

3.3.5. Maximize Pre-Outfitting

Next to assembly of the steel structure, installation of outfitting components can be a cost driver when not organized properly. For this reason, it is pursued to install as much outfitting components during the Block building stage [20][27] as possible. The chosen Blocks in a Block division plan can support this building strategy, when the right arguments are taken into consideration. For example main routes for outfitting like ducts for ventilation or exhaust pipes can be gathered in a particular Block. These routes are formed by ducts through the deck. When such a duct is split by a Block seam, the amount of outfitting within those routes that can be placed before erection is reduced because of accessibility when the two Blocks are erected around that seam. Less splitting of outfitting results in less connections to be made, which reduces the risk of misalignment's and mistakes. Hence, less outfitting overlaps with the chosen seams which enables workers to install more outfitting in an earlier production phase.

Another way of maximizing the amount of outfitting that can be installed during Block division and on the slipway, is to route it around Block seams. The least amount of outfitting components as possible are present on a closing Block, to be able to install all the outfitting during the pre-outfitting stage and erection. Once the equipment is installed, everything is connected and when the closing Block is mounted no more outfitting needs to be installed and the building process can proceed to erecting the next Block.

3.3.6. Separability of Compartments

Next to keeping Compartments intact from an outfitting maximization point of view, there are other arguments to split Compartments at the position where they interface with other Compartments rather than split these Compartments arbitrarily. The general approach to this is aiming to place seams where different Compartments meet. For example walls, frames or decks that separate different Compartments. Different Compartments count different amounts of outfitting components and therefore are more suitable or less preferable to split for creating the Block division compared to other Compartments. Because also bulkheads are likely to be a separator between Compartments, these are common locations to place seams. Mounting Blocks at the position of bulkheads is more convenient because this is already a location where the longitudinal structural system is interrupted with a crosswise structural part.

By minimizing the amount of Compartments that will be split by the Block division, a higher level of finishing of these Compartments can be obtained. Examples of this are increased adjacent area to be painted and increased progress on completing installation of integrated equipment such as the bow thruster, foundations and outfitting components. Creating these conditions helps to decrease the total production time of a ship, as also mentioned in Sub Section 2.2.2.

The final argument that is taken into account by the perspective of separability of Compartments are multiple pieces of equipment that must be aligned through multiple Compartments, for example the drive train. Complex aligning connections are preferably not split and constructed as a whole, such as the bow thruster, engine room and axle's of propulsion or steering gear. When such equipment stretches a long area which has to be split into multiple Blocks, it will always be chosen to have the least amount of crossing seams over these aligning equipment.

3.3.7. Outsourcing

Depending on building capacity at outsource partners who can build a selection of the Blocks required to erect a ship, certain Blocks can or can not be chosen in certain situations when no capacity in the planning of an outsource partner is available. Some outsource partners are limited in building all Block types due to facility constraints such as doors, cranes and size of Block building beds. Also, lack of required skilled personnel to build for example complex bulb shaped Blocks with many curved shell plates can prevent certain outsource partners to produce these Blocks. When the production plan is developed, contact with outsource partners is sought for and there is determined which party will build which Block. As with procurement of equipment it is important to verify that the delivery can take place in time to meet shipyard scheduling demands. This is done during the process of creating the Block division plan.

3.4. Weight Estimations

The weight of a Block is of high important to building the ship. If the shipyard facilities can not lift the Block, other equipment must be arranged or the Block must be split additionally, both resulting in high extra costs.

3.4.1. Cubic Weight

The first possible estimation method to calculate the weight and weight distribution of a new ship is to use reference ships, as mentioned in Sub Section 3.2.2. With the known longitudinal, latitudinal and height distribution of the weight of a previously built vessel, the cubic weight of a volume at a specific location of the ship can be calculated. This calculation is referred to as the Cubic Weight Method. When the new ship design deviates from a previously built ship, the weight and weight distribution are corrected. Because relations like breadth vs weight are not linear, this analysis must be made by an experienced engineer which can correct for this. For example, widening the ship with a factor two does not result in weight being doubled.

The Cubic Weight Method can be used in a very early stage to make a rough estimate of the expected weight of a preliminary Block in case a Block building planning is required to assess the shipyard's planning at high work loads. This method is particularly suitable to apply in the early stage since it requires only weight distributions of a reference ship and can be executed rather quickly. The downside of this method is that is only based on volumes. The steel structure is the main driver of the weight of a Block, not the enclosed volume. Using the Cubic Weight method, the weight of a chosen Block will only minimally change in case of a change of a seam position. This may result in big inaccuracies as this small change of seam position can result in including an extra bulkhead in the Block, resulting in a more significant steel weight contribution than the cubic weight representation is accounting for. This inaccuracies can result in problems during production, such as the crane beign unable to lift the Block because the final weight is higher than initially calculated.

3.4.2. Panel Method

Another estimation method to calculate the weight of Blocks in the Preliminary Design stage is the Panel Method. Just as reference data of already built ships is used to start with for example the stability calculations, already built Blocks are also used to support the weight estimation process. Reference Blocks have to be chosen from the same reference ships as used for the preliminary calculations. Of the reference Blocks the actual weight, centre of gravity, costs, building duration and detailed design drawings are known. There are several aspects of reference Blocks important in particular to determine the applicability of the Block data as input for the new estimations. These aspects are listed below.

- Main dimensions
- Location
- Function
- Type

The frame spacing is already comparable because the reference Block is derived from a comparable reference ship. The location of the reference Block also provides information about the loading profile the structural system at that location will encounter, in combination with the function of the ship and with that a particular Block. The function of the reference Block is therefore required to be similar to the preliminary Block. The Block type is to a large extend a result of the function and location of a Block. More information about Block types can be found in Sub Section 3.4.3.

By the amount of square meters and thickness of plates and stiffeners it is possible to calculate the weight of each structural part. Combinations of steel plates and stiffeners are referred to as panels. The detailed structural information is used of a comparable Block, as these elements are expected on the to be built Block. A combination of panels and their weight result in a total weight of a Block. The thickness of deck plates will differ over the length of the ship due to expected loads. The coaming deck at mid ship will be significantly thicker than at the fore and aft of the ship, due to the longitudinal bending moment. Such information can be found in the reference ships or Blocks to be able to accurately estimate the weight of panels and Blocks. When the detailed structural design is finished, the information is available and developed using computer software. All major and minor steel structural parts are known including steel thickness. When a Block division plan is also available in the software, it is also able to calculate the weight of the individual Blocks based on the total square meters of the present steel plates within the Block and thicknesses of these plates. This weight calculation method is fairly accurate as it is in detail almost identical as the physical end result. The weight estimation using CAD software is based on the same principles as the Panel Method. However, the result is more accurate since more detailed structural parts are taken into consideration.

3.4.3. Block Types

In previous research a list of Block types is defined. In general these Block types are more of a result of the Block division than an objective to work towards. It can be seen as a categorization of the resulting Blocks after Block division with similar characteristics such as function or complexity. The list below shows the Block types as defined by *Meijer*(2008) [16].

- Straight bottom Block
- Curved bottom Block
- Double bottom Block Engine Room
- Side Tanks
- Curved Side Tanks
- Curved Shell
- Supertructure Block
- Large and heavy 3D / intricate Block
- Decks
- Dredging special

4
Requirements

This chapter discusses the implementation and requirements of the developed Block division generator (BDG). The available information from literature and interviewed shipyards to some extend have determined the scope of this research. The specific way-of-works and constraints of the spoken shipyards are generalized as much as possible to come up with a single Block division method to use as the starting point for the automated Block division generator, which is discussed further in Chapter 5. The combination of the research goal and the available gathered information result in the requirements of the model, including the chosen shipyard planning and scheduling optimization algorithm used to assess the quality of different results and the required information output structure.

4.1. Implementation

The main objective of the model is to be able to create $n+1$ different Block division solutions to a Block division problem. With these Block division solutions it is assessed whether these results will impact the overall shipyard planning by using them as input in shipyard planning optimization algorithms. As mentioned in Chapter 1 and 3, this requires the model to process the preliminary design information. Figure 4.1 shows an overview of the Block division generator's implementation in the overall structure of the Block division process. The focus of this research is indicated in this Figure. The general information of Chapter 3 and this Chapter have to be implemented in the Block division generator. Several conditions have to be taken into account in order to answer the research question.

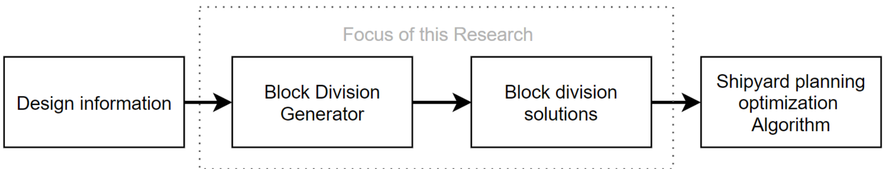


Figure 4.1: Overview model requirements

4.1.1. Block Division Approach

Different erection strategies can be applicable to build a ship depending on the shipyard, as elaborated upon in Sub Section 3.2.4. Different erection strategies result in different requirements for the Blocks to be erected. For example, the previous mentioned example of Ring-Mega-Blocks requires a specific Block division approach. All transverse seams are required to be aligned over all decks, to create the rings as shown in Figure 3.3. However, the arguments taken into account to determine the positions of this transverse seam is the same as for other Block division approaches supporting other erection strategies, as can be found in Appendix G. Different ship hull structures are constructed similarly and must comply with the same set of class regulations. Therefore also the production steps of these hull structures are similar. These similarities result in similar experiences in efficiency of production with particular seams and Blocks. Therefore, together with the conveyed interviews, it can be stated that different shipyards take the same arguments into consideration.

Depending on the erection strategy and therefore Block division approach the importance of different arguments may vary. Since the different seam placing considerations in the Block division approaches for certain erection strategies are comparable methodologies, it can be assumed that answering the main research question for one Block division approach. Therefore, one erection strategy will be applicable to all Block division approaches. When it can be concluded that a Block division generator for a specific erection strategy can come up with $n+1$ solutions that result in a difference in meeting the set optimization objectives, other Block division generations that follow other approaches that do not differ fundamentally can also be assumed to be used effectively in shipyard planning optimization algorithms. The initially chosen Block division approach to model is based on the available information.

4.1.2. Available Information

To be able to demonstrate the ability of the to be developed model a test ship must be chosen to verify the resulting Block division and to be able to validate the potential effectiveness of the different resulting Block divisions in shipyard planning and scheduling optimization algorithms.

Ship Data The data received from Royal IHC is from a trailing suction hopper dredger built at the company's shipyard in Kinderdijk a couple of years ago. In Appendix H.1 an overview of the GA can be found. Table 4.1 shows an overview of the principle dimensions of the ship. Because dredgers come in all sizes and shapes, most of them are custom engineered to order. This makes this type of vessel, build in the Netherlands, an appropriate test case for the scope of this research. Figure 4.2 shows the schematic drawing of the side view of the chosen ship.

Table 4.1: Overview principle dimensions of example ship data

Length over all (hull)	approx. 114.00	[m]
Length between p.p.	106.40	[m]
Breadth	21.30	[m]
Depth	7.50	[m]
Draught at international free board	5.90	[m]
Draught at dredging mark	approx. 6.50	[m]
Dredging depth	25.00	[m]
Suction pipe diameter	700	[mm]
Hopper capacity	5,500	[m^3]
Complement	35	[pers.]
Frame spacing	700	[m]

Figure 4.2: Schematic 2D drawing of test case ship 1 - trailing suction hopper dredger

Shipyard The shipyard where the above mentioned ship was built is Royal IHC in Kinderdijk. This shipyard is fairly compact and versatile because a range of different ships is build at this site. Next to all kinds of dredging vessels, also offshore vessels are build. Hence it is fundamentally different from DAMEN Schelde Naval and for example the Meyer Werff in Germany that is market leader in building large cruise ships. At the Meyer Werff the range of vessels built are more comparable. The shipyard of Royal IHC in Kinderdijk is more compact in terms of size. Also, the whole shipyard organization is organized and optimized around building engineerd-to-order ships that are newly developed. This shipyard configuration shows in the erection strategy and thus in the chosen Block division approach of Royal IHC Kinderdijk.

As mentioned in Sub Section 3.2.4, the general presumption to Block division is to maximize the to be erected Blocks or Mega-Blocks onto the slipway, in terms of weight and size. The applicable erection strategy at Royal IHC Kinderdijk is to build individual Blocks are as large and heavy as possible. These Blocks are erected directly on the slipway. The maximum crane capacity of the gantry cranes over the slipway at Kinderdijk is 140 tons. Due to high amount of custom engineered-to-order projects at Royal IHC, building in any Mega-Block configuration would reduce flexibility and buffers in the planning. As mentioned in 2.1.2, each Block has its individual milestones. When Mega-Blocks are built, the lead time increases significantly as this whole structure has to be completed by design, engineering, steel pre-fabrication and eventually Block building. The next step is to combine the different Blocks to form the Mega-Block. It is more redundant for all departments if the planning is based on smaller work packages, that allows for a higher amount of options when something is delayed which results in a higher likelihood of realizing the original planning.

Royal IHC used to build Blocks at their own shipyards. The surface area assigned to the Block building activities was approximately 50% of the total shipyard [6]. Currently, all Block building is outsourced. Since the Block division plan has to made in an early phase of ship design, many uncertainties about details of the production process are not yet taken into consideration. Again, choices are based on experienced scenarios or will be solved at a later stage when there is more certainty about the situation. The Block division is in reality still somewhat flexible[20]. Corrections in the Block division plan will only be made by creating extra seams within a Block rather than to the Block division plan as a whole, since this Block and therefore work package is already a fundamental part of the overall detailed production and milestone planning.

4.1.3. Sequential Steps to Block Division Solutions

As mentioned in Sub Section 4.1.1, showing a single Block division approach can create $n+1$ Block division solutions will be able to provide an answer to the research question of this thesis. Also is mentioned that the Block division approach where the BDG is based on, depends on the available information that can be used to develop the BDG. As mentioned above, information about the shipyard, test case ships and the used Block division approach at Kinderdijk is available. Therefore the BDG will be developed to automatically create Blocks division solutions that are comparable or equal to the created Block division plans by the engineers at Royal IHC in Kinderdijk. This Section elaborated upon how Royal IHC creates the Block division plan.

Creating Modules At Royal IHC, the engineer uses a systematic approach to create the Block division of the ship. The ship is divided into four major Modules, as a start to making a block division plan of a single hull complex ship. Figure 4.3 shows an example of the before mentioned Modules.

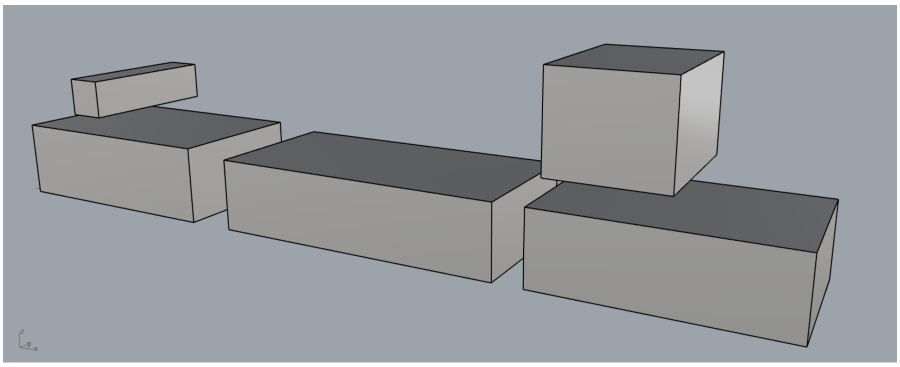


Figure 4.3: Ship divided in fore, mid, aft and superstructure Module

The first isolated Module of the ship is the superstructure and funnels, or anything that rises above the coaming deck of a ship is split from the rest. Next, depending on the ships' function, the core functionality of a ship is isolated. For example, in case of a passenger ship this would be the length from the start of the first hut up until the end of the final hut and in case of a hopper dredger the hold will be isolated to make sure this area of the ship will meet up with the requirements set by the ship owner. Generally, the mid ship Module of a ship that will be isolated is the part where the mid ship section does not change. Finally, the fore and aft ship Module are a result of the splitting of the total ship in smaller parts and include all major curved shell areas.

Transverse seam placing From a top view, seams will be placed in the transverse direction. Crossing the ship from starboard to port side and across one or multiple decks, as shown in Figure 4.4(3). As mentioned in Sub Section 3.3.4 the maximum size of a Block is based on the sizes of the building materials and frame spacing. At Royal IHC the size of the delivered steel plates is equal to 12 meters and the frame spacing can differ per ship. Therefore the general approach is to create Blocks that are 12 meters long. Sometimes a Block can be increased in size which results in some extra Block building work, for example when an area of 25 meters must be split crosswise in two Blocks, one of the Blocks will be larger than 12 meters. Based on experience, an engineer decides whether to create a Block that is larger than 12 meters and increase welding length and residual material, or to create three smaller Blocks which results in more erection movements on the slipway.

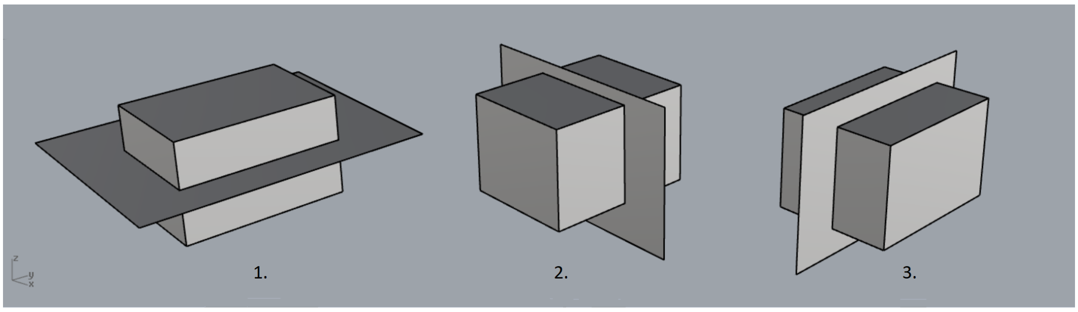


Figure 4.4: Seam placing directions: (1) Dept seam (2) Longitudinal Seam (3) Transverse Seam

Next to the approach to create resulting Blocks of around 12 meters, several other arguments are taken into consideration to determine where to place a seam. As mentioned earlier, aspects that influence the seam placing decision making are the hull structural design, placing of major equipment and Compartments. How these different aspects are generally taken into consideration is elaborated upon in more detail in Section 3.3.

Seams preferably run over flat surfaces for easier welding. Curved plane areas are enclosed by a single Block as much as possible. Therefore the starting point for measuring the length can be different for each Module of the ship. To minimize the amount of curved planes to mount, the starting point of measuring the maximum Block size is from the most curved side of the ship. In case of the aft this is starting at the stern and measuring forwards. In case of the fore ship, this is starting at the bulb and measuring back words. The mid ship has no curved panels and therefore will be analyzed as a whole.

The superstructure is a rather homogeneous part of the vessel, since no fundamentally different rooms are present. All rooms are areas where people need to live or work. For this reason, the general approach to dividing the superstructure into Blocks is driven by material size and crane capacity, rather than separability of systems. From the perspective of outfitting maximization this also holds, because many different workers are required to outfit and finish a superstructure with recreational and navigational area's. When separating these building activities from the steel building, less interaction and crowded building site are created resulting in a safer and more efficient work environment.

As elaborated upon in Sub Section 3.3.1 the transverse seam placing is only different for the combined lower decks and main deck to increase aligning, mounting and fixing speed during slipway erection. Because of this, all seam placing conditions such as the major structural system, transits and separability of system are analyses throughout all the lower decks and combined. If at any deck a transit is present that is preferred to remain open during erection, the crosswise seam will be placed through the transit and be at the same position for all lower decks. In a side view of the ship this results in vertical seams until the main deck, where the Blocks will close the hull and the seams will not be influenced by the seam placing on the lower decks.

Depth seam placing The seam placing over the depth of the hull is generally based on the decks, as shown in Figure 4.4(1). Depth seams over decks are always placed above the desk for two reasons. The first reason is that deck stiffeners are always on the downside of the deck plates, resulting in preferably placing the seam on above the decks. Next to the stiffeners, placing the seam above the deck also results in extra work area during erection which increases the mounting and welding process of erecting blocks.

Because a ship is erected from the ground up, the Block division is also focused on creating a solid basis of Blocks up on where other Blocks can be placed. The start of this basis is often found in the double bottom, which results in a standard seam over the length of the ship. Also because the double bottom Blocks are fairly heavy due to the high amount steel incorporated in this area, these Blocks are isolated and can be erected

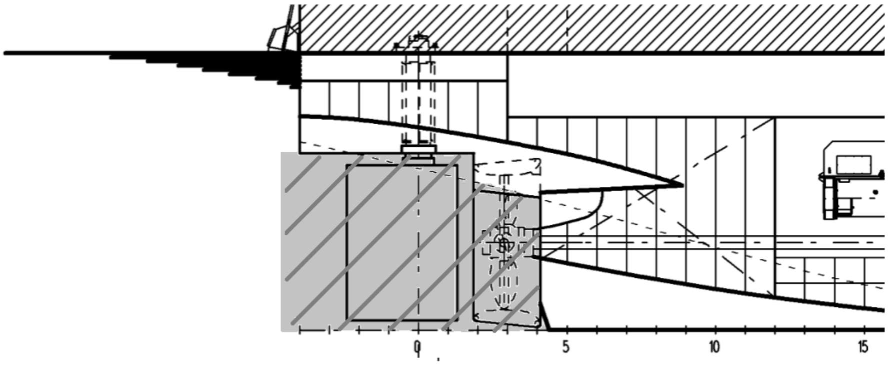


Figure 4.5: Example of unsupported aft of ship

with great accuracy due to the limited size, creating the solid basis on the slipway for the rest of the Blocks.

In the case of a hopper at mid ship or closing deck at the location of large equipment, side Blocks will be chosen. In Figure 2.4 Block *S* and *U* are side Blocks. Side Blocks can either stretch a the height over a single deck, or multiple decks. The side decks are also a form of a closing Block, since it seals the ships hull from either side when a side Block is erected. This also supports the erection flexibility and accessibility of the centre of the ship during construction. The Blocks at the highest hull deck, or coaming deck, also act as closing Blocks for the entire hull from a vertical accessibility perspective.

The aft ship is an exception to this general approach of depth seam placing, since the shell commonly rises up until the waterline at the aft of the ship to provide space for the propellers and steering installation. Due to complex 3D curved shell and lack of structural basis underneath the aft, this area is tried to be kept together and split as least as possible. Highlighted in grey, Figure 4.5 shows the lack of supporting structure at the aft where the number of number of depth seams are preferred to be reduce as much as possible, to increase the structural integrity and reduce the effort of erection such aft Block.

Longitudinal seam placing To split Blocks that are too wide longitudinal seams will be chosen, as shown in Figure 4.4(2). Only one seam in longitudinal direction is chosen if otherwise a resulting Block would exceed dimensions considered manageable and therefore easy to erect on the slipway. These maximum dimension can be overruled when otherwise a system would have to be split that is preferably not divided over two or more Blocks. In all other cases, the seams will be placed just next to the center line of the ship. The slipway at Royal IHC Kinderdijk does not allow wider ships that require multiple longitudinal seams to coop with the wideness of Blocks.

As explained earlier, in the case of the erection of large equipment a closing Block will be created. The engineer at Royal IHC chooses to place two longitudinal seams to be able to create two side Blocks and a center Block. These center Blocks can more specifically be referred to as closing decks if the they consist of only one panel. Because of the type of ships build by Royal IHC, the average used plate thickness is much higher than for example at DAMEN Schelde Naval. Thicker plates require more welding, thus more heat to be added to the structure to be able to build the ship. More heat results in higher shrinkage of the steel. For example when only symmetrical closing Blocks are chosen, due to delays of equipment the "No Placing Between Constraint" can be overruled ,as mentioned in Sub Section 2.1.4. By overruling this constraint the an opening in the ship for erecting this equipment is maintained. However, as the ship will be further erected in longitudinal direction, the shrinkage due to welding can be of such significance that the Block that needs to be erected between the two already erected Blocks does not fit anymore and can not be erected. Therefore Royal IHC prefers to erect the side Blocks around long lead time equipment first. The side Block will coop with the stresses by shrinkage but can withstand those. The closing deck will always be able to be placed due to no significant deformations and the planning is much more redundant due to the late erection possibilities of the equipment and the shrinkage by welding is much less likely to result in major construction issues.

4.1.4. Initial Conditions

The to be developed model is not required to incorporate an exact reality of changing shipyard conditions because initially only the effectiveness of different Block division solutions is to be researched. Therefore several initial conditions are taken into account. Implementing these conditions would not result in a stronger argumentation regarding the research question. The initial conditions are listed below.

- The preliminary design is considered as input and will not change over time. Neither will this design be changed by results of the Block division generator to improve the production schedule
- Only the lead time of major equipment is taken into account as a characteristic of this equipment that can result in different Block dividing decisions due to erection constraints. Procurement is assumed to not influence the production or Block division plan by any means
- As also stated by the experienced Block division engineer at Royal IHC, the Block division does not depend on the shipyard conditions. This can be the case however in high work load situations. For example the erection of a new ship can start while another ship is yet to be launched. This different building strategy can result in different erection starting Block. However, this is exceptional situation and is not considered standard. Therefore shipyard conditions or the relation between the first erected Block and the Block division plan are not taken into account
- To be created Blocks will have to be enclosed by rectangular Blocks and thus will only have straight seams, for simplicity reasons
- Block types will not be taken into account due to the somewhat subjective nature of determining which type of Block a particular Block would be. Also, Previous research has shown that for around 40% of the defined Block types in Sub Section 3.4.3 no linear relation can be found for several characteristics[6]
- Outsource partners are not considered to be constraint in building any Block and therefore influencing the erection schedule or Block division plan
- Special Blocks such as the castings of the suction tube inlet manifold are also not taken into account. Since the suction tube inlet manifold will always be isolated in the block division plan due to required installation as a whole casted system. The manifold will never be split or otherwise be integrated in another Block due to the long and uncertain lead time. In combination with the aim to remove long lead time items from the critical planning path, there will be never be chosen to change the Block division in this area. For this reason, removing this exception from the scope of the Block division generator will not result in a lower amount of unique feasible solutions to the Block division problem
- Only the hull is taken into account for creating the Block division plan. As mentioned in Section 4.1.3, all structure above coaming deck is by default separated from the hull by a Block seam due to many different finishes present in the superstructure. Due to the homogeneous area in the superstructure no variation in possible results of different possible seams will be found. In the case of a larger ship with an extraordinary large superstructure, the assembly will have to take place along the quay due to height constraints of the hall over the slipway. This again will therefore not influence the throughput time on the slipway or other ship production optimization objectives

4.2. Required Output

The output of the BDG is required to describe individual Blocks. The most important characteristics of a Block is the size, to be placed location and weight. Next to this, the required output of the automated Block division generator is defined by the required input of the chosen optimization algorithm. The main driver for the required information structure of the output of the BDG is the way in which the effectiveness of the model will be assessed, next to the absolute minimum requirements of what is to be defined as being a feasible Block division.

4.2.1. Effectiveness in Optimization Algorithms

The suggested automated Block division generator is not an optimization algorithm, it is a design (support) tool. To answer the third sub-question and to be able conclude if different feasible Block divisions result in different quality shipyard planning or ship production schedules, an optimization algorithm has to be chosen to do this analysis. As mentioned in Sub Section 4.2.2, the Block division can only indirectly account for certain assumptions that in the end result in further improving the chosen optimization objective. The first step in assessing the effectiveness and quality of an automated Block division plan to be used in optimization algorithms is to be able to generate at least $n+1$ solutions to the Block division problem. If only one Block division solution is found, no comparison can be made between building schedules to assess the supremacy of one Block division over the other, because the following optimization algorithm can only vary the parameters within the scope of this algorithm rather than varying the used input.

The quality of the solutions can only be determined from the perspective of the global optimization objective regarding the overall planning and throughput of the to be built ship. A stand alone Block division can not be assessed on any quality within optimization of ship building schedules other than building feasibility. When all Block division constraints are satisfied no distinction can be made between Block division plans without analyzing the resulting production plannings and thus the impact of the differences in chosen Blocks. therefore, it was chosen to assess the effectiveness and quality of the output of the to be developed model by means of an shipyard planning and scheduling optimization algorithm.

To be able to let the Block division generator come up with $n+1$ results, the constraints can not be fixed. In that case there would always be only one feasible solution. Therefore design variables must be isolated that are valid in a range of values to be able to have $n+1$ resulting feasible Block division plans. At the time when fully integrating the Block division generator in a genetic algorithm for optimization of the whole shipbuilding process, these design variables could be part of the parameter set that is altered towards finding the most optimal solution. Potentially, these parameters can be directly linked to the found results to be able to increasing the probability of finding the most optimal solution after only a few parameter alterations.

4.2.2. Meet Optimization Objectives

The choice between several options to place a seam and to meet shipyard's global production optimization objectives as much as possible, can not be overseen by a Block division engineer due to the high amount of complex interdependent parameters influencing these objectives. Default choices of seam placing by an engineer are mainly based on the experience of how these have influenced building processes in the past, when observations of the influence of certain choices can be made on the producibility of the ship with these chosen Blocks. Any form of translation of certain characteristics to following preferred seam position are in this sense a quantification of this experience. As mentioned earlier, the main objective a Block division engineer is optimizing by means of an iterative process towards an optimal production process from the perspective of producibility of the ship. In order to create a Block division that can be produced using a redundant building schedule it must to able to be build with high flexibility. Flexibility is a way to coop with all the uncertainties and last minute changes that can not yet be foreseen but unavoidably will present themselves at all different design and production stages. By having the most flexible building schedule possible, the likelihood of meeting all production milestones will be much higher than when a single optimized schedule is the only way to complete the ship on time.

4.2.3. Erection Sequence Scheduler

To be able to assess the flexibility and building time of a ship, an erection sequence schedule or erection planning must be created of a particular Block division. As shown in Sub Section 2.3 there are various optimization algorithms developed over the past years that may suffice in creating an erection sequence schedule which are able to show to what extend certain optimization objectives are satisfied. The main difference between the available optimization algorithms is the amount of detail or amount of parameters included in the scope of the model when it comes to the generation of erection sequence schedules and a fitness function.

To be able to conclude if the different generated Block division plans result in a different planning a simple model can be used. Only the erection sequence schedule and an quantitative fitness function must be generated to compare the results. The erection sequence scheduler must be able to follow at least comparable erection strategy principles as are used by the Royal IHC shipyard in Kinderdijk to be able to verify the resulting schedules.

Since the goal of this research is not to be able to quantify the maximum impact of different Block division solutions on the erection schedule, but to prove an impact can be achieved on relevant optimization objectives by developing $n+1$ feasible Block divisions, it will not be a problem that some reality is simplified or not taken into account in the chosen erection sequence scheduler as validation software for the generated Block division plans towards a final or multi-objective optimization objective or fitness function. Using a model that requires a lot of parameters to be able to come up with an erection sequence schedule therefore does not fit better or worse to illustrate the impact on these optimization objectives. The high amount of parameters that are only relevant for the shipyard conditions and not for the Block division generation can therefore be left out of scope of the required erection sequence scheduler.

The model of *Meijer*(2008) [16] is chosen to use to generate the erection sequence schedules automatically. This model is developed using data also from Royal IHC and reproduces erection schedules using the same erection strategy principles as has been used for the ship data received to use to verify the BDG.The BDG is not required to generate the erection constraints of each individual Block that are needed to create an erection sequence schedule. The model of *Meijer*(2008) [16] automatically applies a simplified set of the erection constraints as described in Section 2.1.4 to create the individual erection constraints per Block, , or table of neighbours as it is referred to by *Meijer*(2008) [16].

4.2.4. Information Structure

The output of Block division generator must either be able to be directly used in the erection sequence generator, or at least contain enough data points to be able to convert without any shortcomings, to be able to generate a feasible erection sequence. Figure 4.6 shows a graphical representation of how *Meijer*(2008) [16] defines Blocks, that is the input of the erection sequence schedule model. The total input data set required for

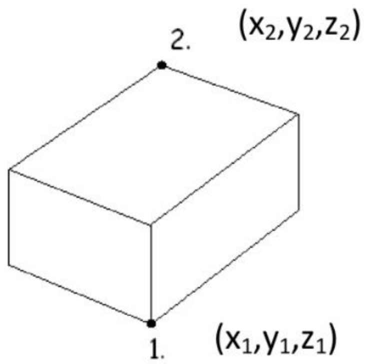


Figure 4.6: Used coordinate structure by model of *Meijer*(2008) [16]

Meijer(2008) [16] is shown in Table 4.2. All Blocks have a unique number or name, six coordinates, a weight, are of a certain Block type and have an indication whether it is a closing deck. The x-coordinates are expressed as factor of frames, the y-coordinates as a ratio of the breadth of the ship and the z-coordinates are showed as actual z positions. The weight is used together with the Block Type to calculate the lead time, representing the Block building process. The indication of whether a Block is a closing deck is used to check if the "Closing Deck Constraint" is applicable. In the model of *Meijer*(2008) [16], the Block Type is merely an extra dimension

Table 4.2: Required information structure input erection sequence model *Meijer*(2008) [16]

Block name	[number]
Coordinate 1, x	[mm/frame spacing]
Coordinate 1, y	[mm/0.5*breadth]
Coordinate 1, z	[# deck]
Coordinate 2, x	[mm/frames]
Coordinate 2, y	[mm/0.5*breadth]
Coordinate 2, z	[# deck]
Mass	[ton]
Block Type	[type]
Closing deck	[x/-]

to vary lead time parameters. As mentioned in Sub Section 4.1.4, earlier research has attempted to find linear relations or other predictive characteristics for Block types. By changing the size or weight of the Block, an estimation could be made of the Block's characteristics such as costs and required man hours to assemble the Block. First *Meijer*(2008) [16] added the dimension of Block types to his developed erection schedule support tool to add differentiation of the characteristics of man hours per ton (mh/ton) per Block type. The following research of *Colthoff* (2009) [6] and *Vlaar*(2010) [26] have deepened this research area. However, mixed results were found about predicting characteristics of certain types of Blocks. Table 4.3 gives an overview of these results. It can be seen that for around 40% of the previously defined Block types no linear relation between mass and lead time of the Block was found. Therefore the BDG will not be required to categorize resulting Blocks by certain Block types.

Table 4.3: Overview of usability of Block types [6]

Type	Type of Block	Relation [Mass - Lead Time]
1	Straight bottom block	Linear
2	Curved bottom block	Non Linear
3	Double bottom block engineroom	Linear
4	Side tanks	Linear
5	Curved side tanks	Linear
6	Curved shell	Non Linear
7	Superstructure block	Non Linear
8	Large and heavy 3D / intricate block	Linear
9	Bulbous shaped block / specials	Non Linear
10	Decks	Linear
11	Dredging special	Linear

4.3. Feasibility of Solutions

To be able to determine the effectiveness of the Block division generator in optimization algorithms, it is required to create $n+1$ feasible solutions to the Block division design problem. Not every solutions can be considered feasible due shipyard supply and facility constraints, which need to be incorporated in the BDG accordingly. Feasibility of Block division solutions is different from viability of these solutions. Feasibility measures the ability of a shipyard to build the ship using the Block division solution. Viability or fitness is a measure of how suitable the Block division solution is to result in the most optimum shipyard planning schedule regarding one or more optimization objectives.

4.3.1. Supply and Facility Constraints

As mentioned earlier, the Blocks need to be processed and erected onto the slipway by cranes or other supply and shipyard facilities. Creating the largest and heaviest Blocks as possible is limited by these supply and facility constraints.

Supply Constraints By Supply Constraints are understood, the constraints dictated by suppliers. This can either be outsource partners building Blocks, lead time of to be installed equipment or the size of materials. As mentioned in Sub Section 4.1.4, production partners where Blocks are outsourced or suppliers of long lead time equipment will not be implemented in the BDG as constraints. The size of supplied materials is used by Royal IHC as reference value for the creation of Blocks. Theoretically, building Blocks with the same size as the supplied steel results in less welding. However, this is not a fixed constraint. For production reasons, some Block may be larger than the size of the supplied steel. Such exceptions are subjective to the person making the decision and therefore also the steel size is not an can effectuated as a fixed constraint in the BDG.

Facility Constraints Next to external suppliers, the shipyard has to supply the Blocks through all the production processes and onto the slipway. Because Royal IHC outsources the production of all the Blocks, the Blocks only require conservation before being erected. These last two production steps come with two types of facility constraints.

The first facility constraint is the height and width of the doors of the conservation hall and the erection hall. If the size of a Block surpasses the maximum size in at least two dimensions, it will not fit through the doors. If the size of a Block only surpasses the maximum size in one dimension, the Block can be turned to make it fit through the doors. The door size constraint is hard, a Block can never be bigger than the maximum size of the doors because there is no way to work around this and still be able to erect the Block on the slipway.

The second facility constrains is the maximum weight lifting capacity of the cranes that need to erect the Block on the slipway. If a Block is exceeding this maximum weight it either has to split into two smaller Blocks or other handling equipment has to be arranged to be able to erect the Block. The latter is done only with high exception due to the additional incurred costs. In this research the weight capacity of the shipyard facilities are regarded as a fixed constraint. The gantry crane that must erect the Blocks on the slipway at Royal IHC Kinderdijk has a capacity of 140 tonnes.

As mentioned in Sub Section 4.1.4, the BDG will not take into account shipyard conditions. Therefore, the BDG will not create Block division solutions that do not comply with the before mentioned fixed feasibility constraints. Eventually, any Block division solution that results in Blocks that fit through the doors and can be lifted by the cranes are considered feasible. Not all off these Block division solutions are considered viable by the Block division engineers and planning department because of their experience. However, the BDG can not make this assessment. The optimization algorithm as described in Sub Section 4.2.3 should be able to determine which of the feasible Block division solutions is the most optimal considering certain optimization objectives.

4.3.2. Weight Calculation

The weight of the resulting Blocks by the BDG must be calculated for two main reasons. The first reason is that the erection sequence scheduler calculated the lead time, or Block building time, by using a general man hours per tonnes parameter in combination with the Blocks' weight. This lead time is then used to be able to calculate the erection duration in combination with the created erection and shipyard production constraints. The second reason that requires the weight of the Blocks to be available is to check for the feasibility of the Block division solution regarding the supply and facility constraints of the shipyard. Especially to know if the cranes are able to lift the Block, the weight of the Block must be known and be lower than the maximum to be lifted weight by the crane.

4.3.3. Design Variables

To be able to generate a Block division, all arguments discussed in Chapter 3 must be taken into account to finally result in a single solutions. To be able to generate $n+1$ Block division solutions these arguments or the order of taking these arguments into account must must be able to vary. This requires the automated Block division generator to contain sets of variables that can be altered for each run to come up with different, these variables are referred to as Design Variables. Every unique set of design variables can result in a different Block division solution. All Design Variables have applicable ranges within they will result in feasible Block division solutions, as elaborated upon in Sub Section 6.1.6.

5 Model

This Chapter elaborates upon how the general Block division, as described in Chapter 3 and more specifically the Block division approach as described in Sub Section 4.1.3, is translated into a model while taking into the account all the requirements as stated in Chapter 4. Initially the overall architecture of the build model is discussed, after which the developed data representation and logic mechanisms.

5.1. Overall Architecture

The overall approach of the model in order to generate a Block division plan is elaborated upon in this Section. Including the major functionality that provides the basis for creating seam placing logic and to create design variables for altering the Block division solutions are explained. Any exceptions for specific seam placing decisions have been neglected, generalized or simplified. A series of aspects defined in Chapter 3 and 4 are taken into account when deciding upon the placing of a seam, in such a way that the model in most of the cases should come up with the general Block division solution.

5.1.1. Model Overview

Figure 5.1 shows the overall flow of the general logic to create feasible Block division solutions. The input of the model is already discussed in Chapter 4, including the chosen Erection Strategy and Block division Approach as set by the shipyard facilities. Initially Placeholder Blocks are created, this methodology is elaborated upon in Sub Section 5.1.2. The basic methodology for choosing the seam position to be able to apply the logic is shown in Sub Section 5.1.3 and to determine where to split these Placeholder Blocks is discussed in Sub Section 5.1.4. The incorporation of the seam placing arguments, including weight calculations and Grouping mechanism, are discussed in Section 5.3. After all required splits are made the output of the model are only feasible Block division plans, considering the requirements from Section 4.3. Finally these results are used to generate Erection sequence schedules generated by the chosen optimization algorithm discussed in Sub Section 4.2.3. The feedback on the effect of the design variables on the erection sequences is shown by a dashed line because this is a representation of the hypothesis and reason to do this research and is elaborated upon in Chapter 1. The results of this research determine whether this relation can be found and validated and will be discussed in Chapter 6 and 7.

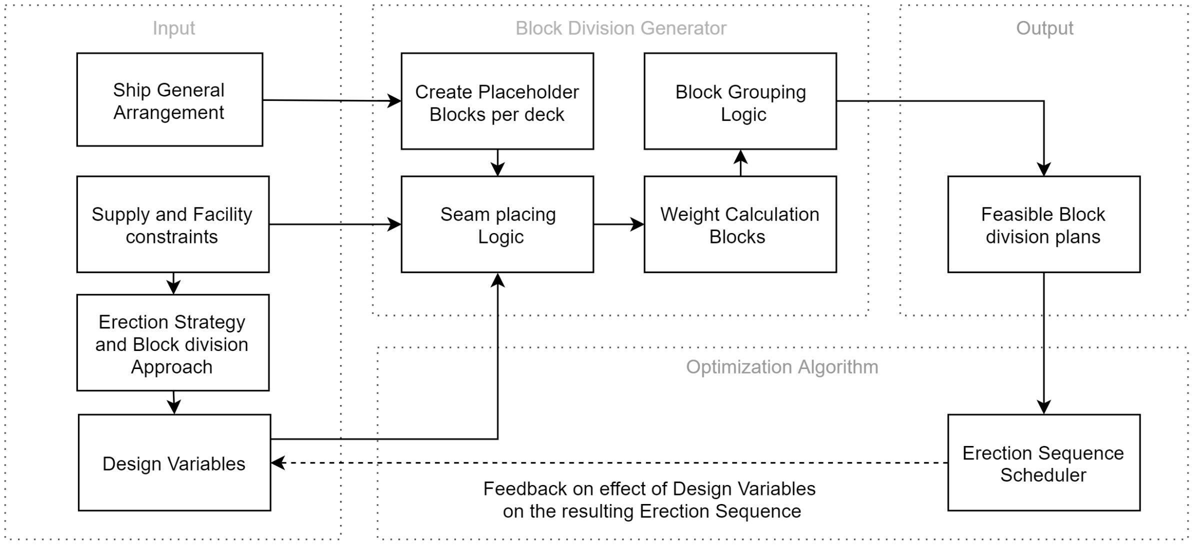


Figure 5.1: Overall view of the architecture of the Block Division Generator

5.1.2. Placeholder Blocks

To make sure the created Blocks enclose all structural parts of the ship, Placeholder Blocks are introduced. By creating Placeholder Blocks it is made sure that no part of the ship will be excluded from being part of the created Block division. Placeholder Blocks are Blocks that are not yet considered feasible Blocks by the BDG, but do contribute to the requirement of the whole ship being divided into feasible Blocks. Placeholder Blocks are chosen per ship Module per deck, as shown in Figure 5.2. Blocks are often chosen per deck for producibility reasons, as elaborated upon in Sub Section 3.3.4 and 4.1.3. It can be seen that a transverse split is already made due to a change in deck height over the length of the ship in this example. Because the double bottom must be erected first, the bottom deck is analyzed first. The Placeholder Blocks should follow the the change in deck height. This is only possible by splitting the Placeholder Block due to the simplification of rectangular blocks. These Placeholder Blocks are split until all resulting Blocks are feasible from the supply and facility constraints point of view, as elaborated upon in Sub Section 4.3.1. The position of the splitting seams are determined by the Seam Placing Logic, consisting of the Transverse and Longitudinal Seam Placing Logic. The Seam Placing Logic will be discussed in this Section and the underlying mechanisms will be discussed in Section 5.3. Splitting the Placeholder Blocks will not always result in the largest and most heavy Blocks possible due to the initial approach per deck. Therefore Grouping logic is used to find resulting Blocks that can be combined to create less and heavier feasible Blocks. More information about the Grouping Logic can be found in Sub Section 5.3.8.

Figure 5.2: All Placeholder Blocks per ship Module before any splitting

5.1.3. Optional Seam Position

As mentioned in Chapter 3 and Section 4.1.3 there are many different arguments to be taken into consideration to find a feasible Block division plan that must simultaneously be compared for relevance depending on the Block division approach, as mentioned in Sub Section 4.3.1.

The starting point for seam placing in general is to create as large and heavy (Mega-)Blocks as possible. The size of the supplied steel, the building beds and the frame spacing (L_{Fr}) are used as reference sizes to start finding a seam position that is most supportive to the producibility of the ship. At Royal IHC these steel and building bed sizes are 12 meters, as mentioned in 4.1.3. This Maximum Block Length constraint is the initial Design Variable ($L_{B_{max}}$) and dictates the initial starting point for the length of a Block. Blocks that are only equal to this Maximum Block Length constraint are not expected to result in seams that always make the most optimal split. To evaluate the conditions around this starting point a string of Optional Seam Positions is created. The initial starting point to start evaluating other Optional Seam Positions will be referred to as p_0.

Table 5.1: Overview of Optional Seam Position calculations

Optional Seam Position	x-coordinate Position	unit
1	p_0 - 5*$L_{Fr} - 75$	[m]
2	p_0 - 5*$L_{Fr} + 75$	[m]
3	p_0 - 4*$L_{Fr} - 75$	[m]
4	p_0 - 4*$L_{Fr} + 75$	[m]
5	p_0 - 3*$L_{Fr} - 75$	[m]
6	p_0 - 3*$L_{Fr} + 75$	[m]
7	p_0 - 2*$L_{Fr} - 75$	[m]
8	p_0 - 2*$L_{Fr} + 75$	[m]
9	p_0 - 1*$L_{Fr} - 75$	[m]
10	p_0 - 1*$L_{Fr} + 75$	[m]
11	p_0 - 0*$L_{Fr} - 75$	[m]
12	p_0 - 0*$L_{Fr} + 75$	[m]
13	p_0 + 1*$L_{Fr} - 75$	[m]
14	p_0 + 1*$L_{Fr} + 75$	[m]

As mentioned in Sub Section 3.2.3 seams are always placed at least 75 [mm] next to frames, so for every frame position there are two Optional Seam Positions, one 75 [mm] in front of the frame and the other 75 [mm] over the frame. Based on material and building bed constraint only one frame position beyond this maximum value is considered to still be an Optional Seam Position, otherwise this constraint is no longer considered satisfied. A Block can be up to five frame positions shorter than the initial p_0 if there is a more optimal seam position found. The decision to take p_0 minus five frames into consideration is based on the test case ship. When evaluating the chosen Block division created by Royal IHC it can be found that no Block is smaller than the minimum resulting Block using this methodology. Table 5.1 shows all considered Optional Seam Positions surrounding p_0. To start creating blocks of a specific length, the model checks the conditions per frame position. In case this length is met, measured from a certain analyzing direction, the Optional Seam Position string will be created.

5.1.4. Seam Placing Logic

Below the flow of the Seam Placing Logic is discussed, for both the transverse and longitudinal seam placing. The first step is to place the transverse seams because these will go over the whole breadth of the ship, to increase erection possibilities as mentioned in Sub Section 3.3.1. Also, because resulting Blocks are simplified to be rectangular, a longitudinal seam can not deviate between two transverse seams. This Section provides an overview of the incorporated mechanisms, where Section 5.3 will discuss functionality of these mechanisms extensively.

Transverse Seam Placing Logic Figure 5.3 shows the flow of the transverse seam placing part of the Seam Placing Logic. It starts by checking if the Placeholder Block is longer than the Maximum Block Length Design Variable. In this the case the transverse seam placing will start with the creation of the Optional Seam Placing string. This string is filled with the found arguments at these positions, these arguments will be further discussed in Section 5.3. The final seam position will be chosen from the Optional Seam Position string where the lowest weight characteristic is found. At this seam position, the Placeholder Block will be split. After a split the model will start assessing the next Placeholder Block.

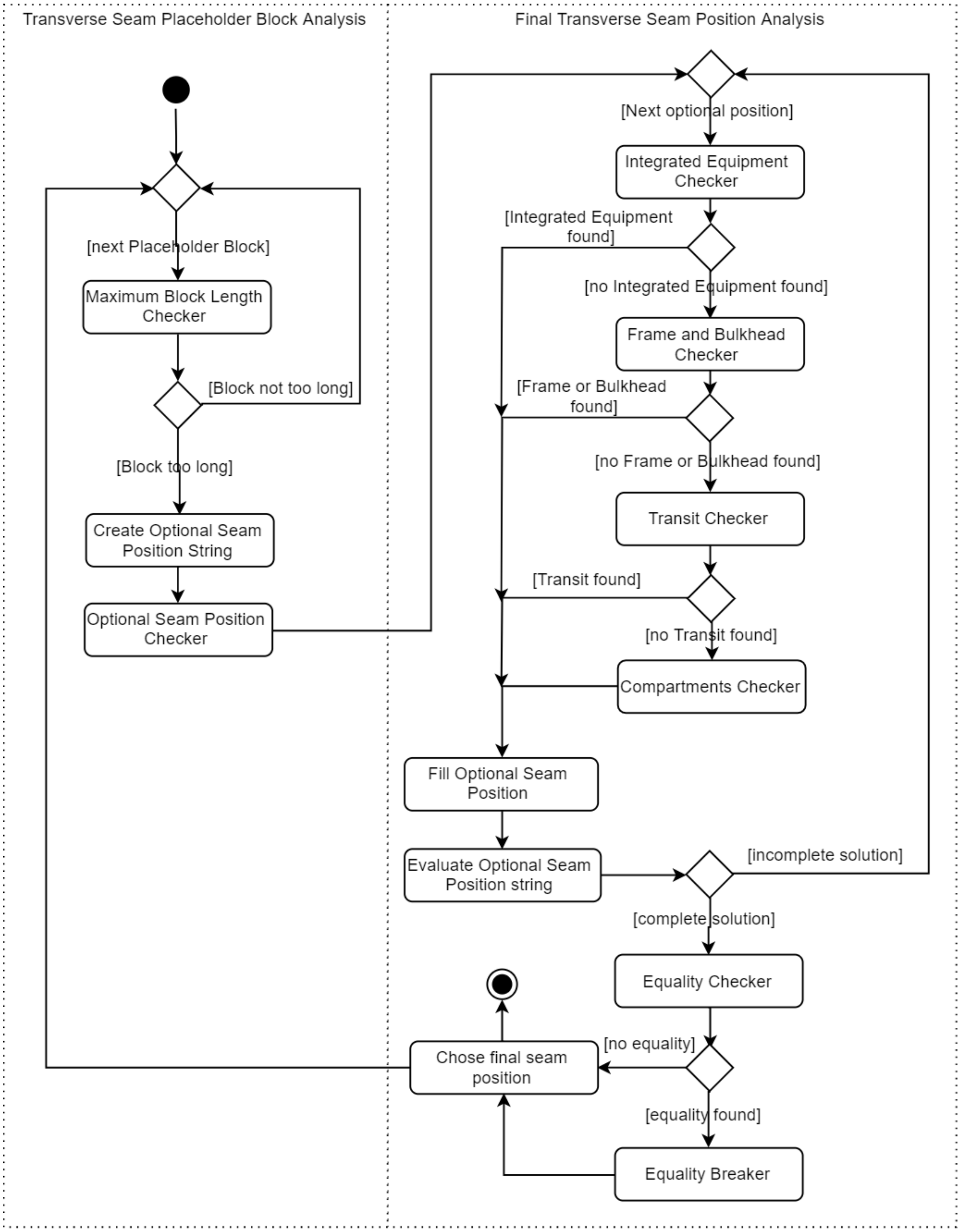


Figure 5.3: Flow of the transverse seam placing logic

Transverse Seam Placing Logic Figure 5.4 shows the flow of the longitudinal seam placing part of the Seam Placing Logic. It starts by checking if the inside the considered Placeholder Block long lead time items are present. If this is the case, this can either be integrated equipment or not. When integrated equipment is found within a Placeholder Block, no longitudinal seam will be placed. When long lead time equipment is found within a Placeholder Block that does not classify as integrated equipment, the Placeholder Block will be split into three Blocks. The resulting Blocks can be referred to as Side Blocks and a Closing Block. If no equipment is found in the Placeholder Block and it is not wider than the maximum indicated breadth by the supply and facility constraints, it will be split just off the center resulting in two almost symmetrical Blocks.

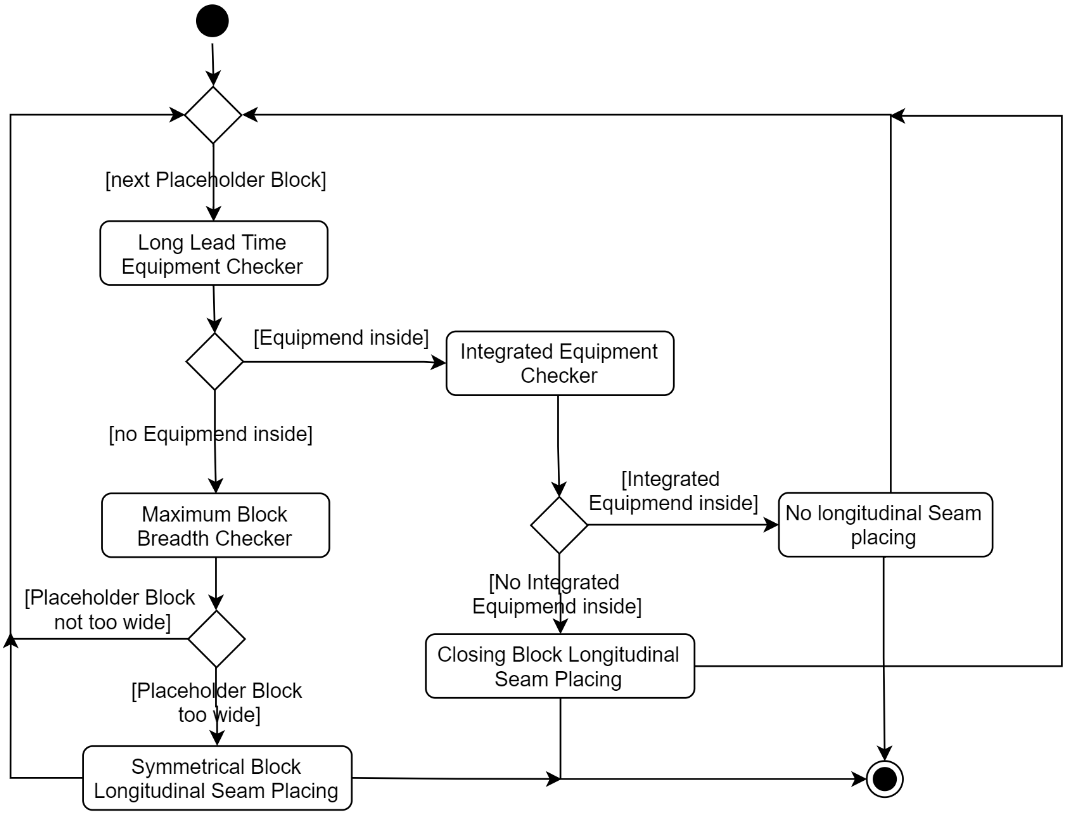


Figure 5.4: Flow of the longitudinal seam placing logic

Weight Calculations and Grouping Logic Because the initial Placeholder Block approach is an analysis per deck, the resulting Blocks have to be grouped to create Blocks across multiple decks. Before resulting Blocks can be potentially grouped, the weight must be calculated to be able to check if the combination of Blocks into a single Block will not exceed the facility constraints. Sub Section 5.3.7 and 5.3.8 elaborate more on these mechanisms.

5.2. Data Representation

The database system used will be a relational database for flexibility and convenient altering Design Variables. The stored data must be stored in multiple tables. Generally there are two categories of data. First is the input data, based on the 2D GA as elaborated upon in Sub Section 3.2.1. Second is the output data of which the structure is already explained in Sub Section 4.2.4. All data sets are constructed by only including the data points which are used during seam placing and for creating the input data set to be able to generate the erection planning.

5.2.1. Simplifications

The data is sometimes simplified in order to reduce the complexity of the data and therefor model. Only simplifications are made that do not influence the results in scope of this research or that will not significantly change the representation of the original ship, but will result in significantly smaller of less complex data sets.

General The required information to be able to create a Block Division is elaborated upon in Section 3.2. Because the 3D CAD visualization software Rhinoceros is used to be able to verify the results of the BDG, the data from the 2D design information of the GA can also be visualized in 3D using also available deck height information. Figure 5.5 shows the results of constructing this 3D data set using only the available preliminary of the test case ship, as stated in Sub Section 4.1.2.

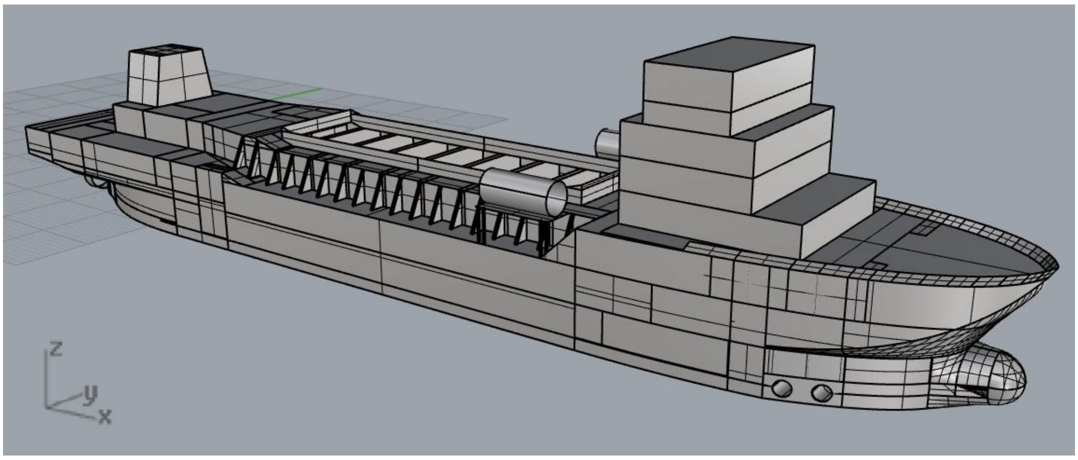


Figure 5.5: 3D representation of the GA found in Appendix H.1

As dictated by the erection sequence generator, discussed in Sub Section 4.2.4 the output requirements of the BDG are rectangular Blocks. Therefore the boundary conditions allow the ship data also to be represented simplified by rectangular blocks or planes. The rectangular blocks completely include Compartments and therefore the coordinates of these rectangular blocks are based on the maximum values of these Compartments, a good example of this can be found at the bow of Figure 5.6, which shows the simplified ship as a result of the original ship shown in Figure 5.5.Other simplifications that are a direct result of the representation of data in particular tables is described in the following Sub Sections 5.2.2 and . Other model simplifications are described in Section 5.1 and 5.3.

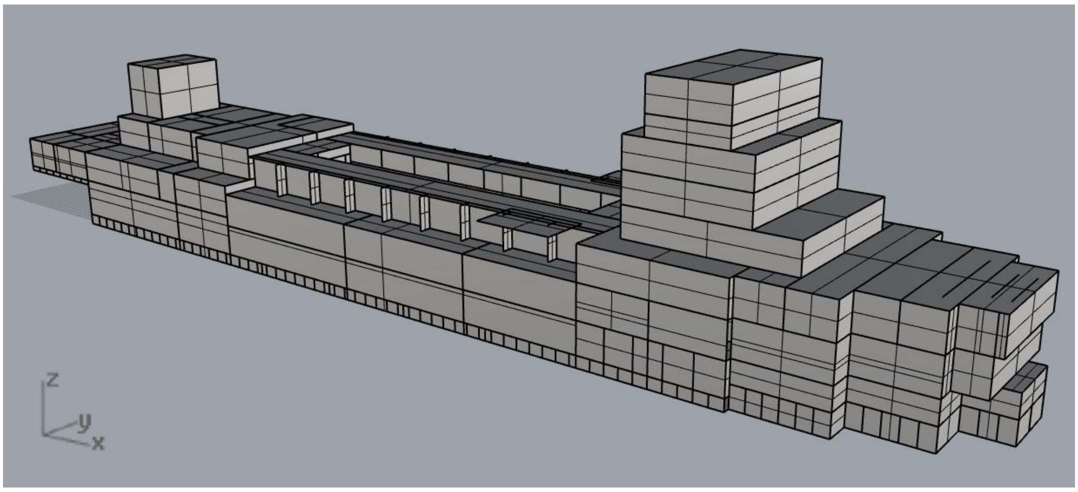


Figure 5.6: Simplified 3D representation of the GA found in Appendix H.1

5.2.2. Structural Parts

Figure 5.6 shows the 3D representation of the structural parts information. In this research, every piece of steel that is welded together with other steel pieces to from the ship are considered structural parts. Below the variety in found relevant structural parts and the different characteristics are described.

Structure type As mentioned above, steel structural parts can be referred to differently by their function and therefore characteristics. This distinction between steel structural parts is made by creating Structure

Types. To be able to create one table with all steel structural parts but still be able to easily change the general characteristics of Structure Types, a separate table is made that can be related to from other tables in the relational database. The chosen Structural Type characteristic is the thickness of the steel structural part, as this varies throughout the ship and is an important variable in the ship's steel weight. Table 5.2 shows the columns present in the Structure Types Table. The indication "PK" refers to Primary Key, which is a constraint that in this case the Structural Type ID has to be unique in all rows of the table. The constructed Structure Type Table of the test case ship can be found in Appendix J.1.

Table 5.2: Structural Types table columns

Column name	Data Type	Unit	Constraints
Structural Type ID	Character	-	PK
Structural Type Name	Character	-	FK
Steel Thickness	Real	[mm]	-

Structural Parts Table Due to the simplification of structural parts into rectangular panels, the Structural parts can be categorized in three directions. The first direction is panels parallel to the x and y plane, also referred to as decks. The second direction are panels parallel to the x and z plane, also referred to as frames or bulkheads (depending on the piece of steel structure). And finally the panels parallel to the y and z plane, also referred to as girders. The before mentioned referring names are generally applicable but are not necessarily the only pieces of steel structure than will be found in the specified directions, such as Compartment walls or the shell of the ship. Table 5.3 shows the present columns in the Structural Parts table. The indication "FK" is a constraint for the data in this column for always being equal to the specified Structure Types present in the Structural Types Table. Appendix I shows the relations between all following table structures. As mentioned in Sub Section 3.2.3, during the preliminary design stage already some detailed information is available on the hull structural design, regarding stiffeners. Because also stiffeners are taken into account when placing seams during the developing of the Block division, as mentioned in Section 3.3, this information has to be stored. The "Stiffeners" columns provide information about the presence of stiffeners on a particular side a structural part, indicated by "1" when stiffeners are present is in the positive $x/y/z$ direction, "0" indicates when no stiffeners are known or are present and "-1" is found when stiffeners are expected in the negative $x/y/z$ direction relative to the structural part's plane. The constructed Structural Parts Table of the test case ship can be found in Appendix J.2.

Table 5.3: Structural Parts table columns

Column name	Data Type	Unit	Constraints
Structural Part ID	Character	-	PK
Structural Part Name	Character	-	-
Coordinate 1x	Real	[mm]	-
Coordinate 1y	Real	[mm]	-
Coordinate 1z	Real	[mm]	-
Coordinate 2x	Real	[mm]	-
Coordinate 2y	Real	[mm]	-
Coordinate 2z	Real	[mm]	-
Structural Type	Character	-	FK
Stiffeners on x side	Integer	-	-
Stiffeners on y side	Integer	-	-
Stiffeners on z side	Integer	-	-

Transit Table Because transits are considered in the Block division process, as mentioned in Sub Section 3.3.3, these also need to be taken into account in the database. A separate table for transits is chosen to maintain the overview and since no stiffener attributes have to be given for transits. To minimize complexity transfers are constructed as a form of structural parts with a negative thickness indicated by the structural type. This is done so the steel panels can be defined as large areas rather than multiple smaller panels surrounding a transit. Next to this convenience, it is more reliable to search for transits through a defined list rather than finding transits by searching for certain conditions around the edges of multiple steel panels. Table 5.4 shows the relevant data columns for transits in the BDG. The constructed Transit Table of the test case ship can be found in Appendix J.3. The Structural Type of a transit will have a negative value to do a weight correction for the access in deck area.

Table 5.4: Transit table columns

Column name	Data Type	Unit	Constraints
Transit ID	Character	-	PK
Transit Name	Character	-	-
Coordinate 1x	Real	[mm]	-
Coordinate 1y	Real	[mm]	-
Coordinate 1z	Real	[mm]	-
Coordinate 2x	Real	[mm]	-
Coordinate 2y	Real	[mm]	-
Coordinate 2z	Real	[mm]	-
Structural Type	Character	-	FK

5.2.3. Decks and Longitudinal Reference Lines

Decks consist of steel plates and transits. Not always over the whole length or width of the ship is a steel deck present, but for modelling purposes it is convenient to always be able to have a reference deck value to be found. For that reason, a decks reference lines table has to be constructed.

Deck Height Decks can change in depth position over the length of the ship, Figure 5.7 shows the original varying deck heights and bulkheads from a side view of the mentioned ship in Sub Section 4.1.2. Figure 5.8 shows in white the made simplifications of diagonal decks and changing deck heights between bulkheads. Because the Placeholder Blocks are created to include the entire deck and therefore split when the deck height varies because of the rectangular representation, it was chosen to let deck height only vary at the position of a bulkhead. A bulkhead is a preferred seam placing location as mentioned in Sub Section 3.2.3.

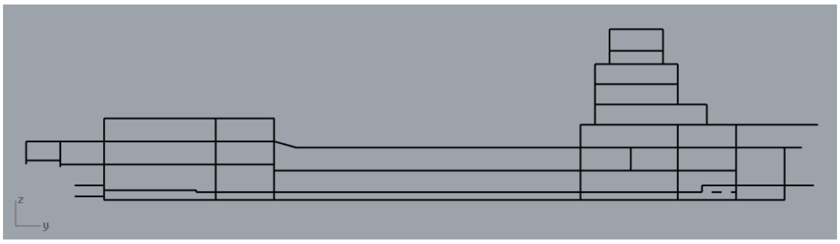


Figure 5.7: Original decks representation of the GA found in Appendix H.1

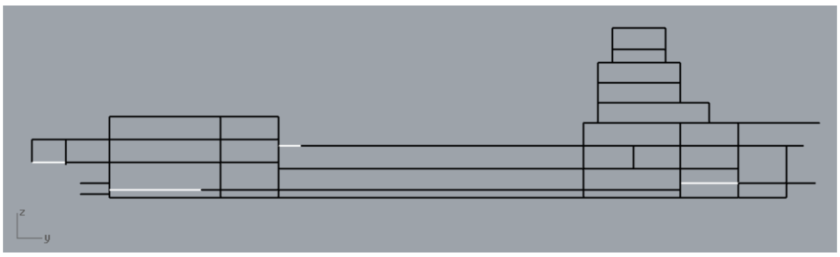


Figure 5.8: Simplified decks representation of the GA found in Appendix H.1

Longitudinal Reference Lines To be able to place longitudinal splits and to create symmetrical Blocks and Closing Blocks, longitudinal reference lines must be known. Because the ship's width changes over the length there must a varying reference line. Also not all Compartments are on the same reference y value over the length, or even per deck. Figure 5.9 shows the chosen reference lines that are chosen to be able to search for references at any given point on any deck in the ship. The red line shows the varying port side reference line, as is the green one showing the starboard reference line. The only constant reference line along the ship is the center line, shown in purple. Finally, the varying port side and starboard center reference lines are shown in blue, as can be seen in Figure 5.9. When there is no other Compartment or structure to place to reference line upon, the reference line position is copied from one frame behind.

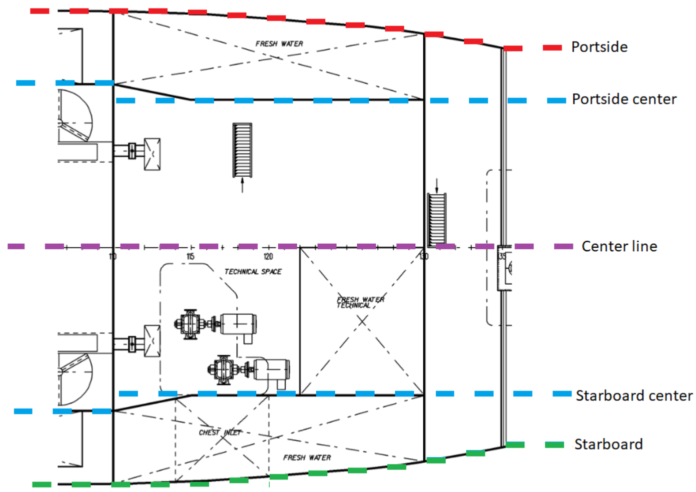


Figure 5.9: Five reference lines along a deck, in this example Below Tween Deck

Curved Shell and Structure Next to varying breadth of the ship over its length, also the amount of curved panels varies over the length and height of the ship. As mentioned in Sub Section 3.2.3 curved panels are isolated as much as possible in a single Block and seams are rather placed over flat plates rather than curved shell and other structural parts. For this reason an indicator is defined that provides information about the amount of curved plates present at a certain frame position and deck height, which can be used to derive for every Module from which direction counting p_0 must be chosen. Table 5.5 shows the different values that represent different levels of curves present.

Table 5.5: Curved plates indicators

Indicator value	Explanation
0	No structure present
1	Straight structure
2	Slight curved structure
3	Medium curved structure
4	Heavily curved structure
5	Bulbous structure

Decks Table A separate table is constructed for every deck, that per frame indicates the height of the deck above that frame, the y position of the before mentioned reference lines and an indication of how curved the shell and structure is at that frame position. Table 5.6 shows the relevant data columns for the decks in the BDG. The constructed Decks Tables of the test case ship can be found in Appendix J.4. From the Curved Indicator it can be found that for the aft and mid ship Module a the Blocks are maximized in a positive x direction. For the fore ship Module it can be found to maximize the Blocks in a negative x direction. As mentioned Sub Section 4.1.3 the BDG only generates varying Blocks for the hull and thus the superstructure including chimneys is left out of scope.

Table 5.6: Deck table columns

Column name	Data Type	Unit	Constraints
Frame ID	Character	-	PK
Frame Name	Character	-	-
z Coordinate	Real	[mm]	-
Starboard Reference Line	Real	[mm]	-
Starboard Center Line	Real	[mm]	-
Center line	Real	[mm]	-
Port side Centre Line	Real	[mm]	-
Port side	Real	[mm]	-
Curve Indicator	Integer	-	-

5.2.4. Compartments and Equipment

Compartments and long lead time equipment are all represented by rectangular blocks, just as the resulting Blocks of the BDG. Next to the coordinates there is extra information required to take the Compartments and long lead time equipment into account according to the Block division principles.

Compartments In a ship many different Compartments can be found or defined. Appendix J.6 shows an overview of all present Compartments in the test case ship. This long list of Compartments is categorized in a shortlist that can be found in Table 5.8. Appendix J.6 also shows the defined Compartment Category for each individual original found and defined Compartment.

To be able to determine which Compartment should be preferred to split over another Compartment, a hierarchy of splitting preference has to be constructed. Based on the interviews with Royal IHC and DAMEN Schelde Naval shipyard, added in Appendix G, it was concluded that this hierarchy depends on the following three Compartment characteristics. The first characteristic is the amount of outfitting pieces that are present in a Compartment, this can be predicted by the Compartment Category. For example, in an Engine Room a lot more pieces of outfitting are expected than in a Technical Room in which more pieces of outfitting are expected than in a Workshop. The second characteristic is if there are any large pieces of outfitting or equipment present in a Compartment that require a lot of aligning when split, for example the rudder shafts or the bow thruster tubes. The third and final characteristic that creates this separability hierarchy of Compartments is the amount and quality of the finish in a Compartment. For example a Watertank requires a very high quality conservation finish to prevent oxidation and to be able to comply with strict regulations. Another example are Accommodation rooms which contains many different finishes such as woodwork, carpeting and paint. If any of these characteristics is found in to a greater or less extent are present in a Compartment, the less preferred it is to split this Compartment. Table 5.7 shows the range of parameters to indicate to what extent a certain characteristic applies to a certain Compartment.

Table 5.7: Parameters to indicate applicability of characteristics

Characteristic	Not/low	Medium	High
Amount of outfitting	1	2	3
Amount of Aligning	1	2	3
Finish Quality	1	2	3

Every characteristic is provided with a weight that can be changed to be able to distinguish between the importance of the different characteristics. Table 5.8 shows the results as they were concluded from the various interviews with the shipyard's experienced engineers and as they are used in the verification of the BDG. Note that these weights per characteristic can be defined as Design Variables and may differ per shipyard or even ship type. The applicability parameters per Compartment category and the chosen weight are qualitatively based on interviews, literature and reason based on common sense of what can be expected in certain Compartments and to reflect the results of the actual Block division plan developed by Royal IHC. The total hierarchical weights (w_{total}) are calculated according Equation 5.1, for Compartment Category s and referred to as Compartment Separability Weight in this report.

$$w_{total} = w_{outfitting} * c_{outfitting_s} + w_{aligning} * c_{aligning_s} + w_{finish} * c_{finish_s} \tag{5.1}$$

Aligning is considered the most important Compartment characteristic because in increases the amount of work exponentially when splits are made through very sensitive aligned systems. Splitting finishes is also considered to result in more work than to split outfitting, because of the difficult circumstances and for example drying times of paint at the slipway. Outfitting is also not preferred to split when not necessary but when a seam has to be placed and a split has to be made, outfitting can me more easily be decomposed in multiple smaller pieces of outfitting which results in having to link the outfitting from one Block to the other rather than having to work on the finish of the entire Compartment after erection of the Block on the slipway.

Table 5.8: Categorized Compartments Separability Hierarchy

Compartment Category	Outfitting	Aligning	Finish	Total
Weight	2	4	3	w_{total}
Steering Room	3	2	2	20
Engine Room	3	2	2	17
Pump Room	3	2	2	17
Navigation Room	3	1	1	13
Watertank	1	0	3	11
Accommodation	2	0	2	10
Technical Room	2	0	0	4
Workshop	0	0	1	3
Oiltank	1	0	0	2
Void	0	0	0	0

All living areas are equally non preferred to be split, so they are categorized and modelled as one Compartment with one particular hierarchical separability constraint, adding the individual rooms does not result in another Block division plan or higher accuracy of this plan. other circumstances/nearby Compartments dictate the Block division significantly more than the differences between certain accommodation areas and are not taken into account in the separability hierarchy. Table 5.9 and 5.10 show the relevant data columns for the Compartments and Separability Hierarchy used in the BDG. The constructed Compartments Tables of the test case ship can be found in Appendix J.6, the constructed Separability Hierarchy of the test ship used for verification of the BDG can be found in Table 5.8.

Table 5.9: Separability Weight table columns

Column name	Data Type	Unit	Constraints
Compartment Category ID	Character	-	PK
Compartment Category Name	Character	-	FK
Separability Weight (w_{total})	Integer	-	-

Table 5.10: Compartments table columns

Column name	Data Type	Unit	Constraints
Compartment ID	Character	-	PK
Compartment Name	Character	-	-
Coordinate 1x	Real	[mm]	-
Coordinate 1y	Real	[mm]	-
Coordinate 1z	Real	[mm]	-
Coordinate 2x	Real	[mm]	-
Coordinate 2y	Real	[mm]	-
Coordinate 2z	Real	[mm]	-
Compartment Category Name	Character	-	FK

The constraint indication "FK" is an abbreviation for Foreign Key, representing the constraint of the Compartment Category Name in Table 5.10 must be equal to the defined Compartment Categories in Table 5.8. Appendix I shows an overview of all relations between tables of the BDG database.

Next to having longitudinal deck reference lines for placing seams, these lines isolate Compartments. This creates a table of hierarchical weight separability parameters that can be used to asses the potential impact of placing a seam through the sum of these Compartments by simply adding up all separability parameters for a particular seam position, as elaborated upon in Sub Section 5.3.4

Equipment and erection direction As mention at the beginning of this Sub Section, also long lead time equipment requires extra information next to the simple six coordinate system that represents the volume and location of this equipment. All long lead time equipment is necessary to look into when developing the detailed production planning, not all of this equipment however directly influences the Block division plan. For example, the hopper floor doors, or conical valves, are erected from the bottom's up into the ship's hopper. This production technique results in no required closing Blocks or decks to leave open area to be able to erect this equipment. Other equipment may fit through transits in the covering Blocks, like for example the pumps that are installed on the bow thrusters. In such a case, also no closing Blocks or decks need to be taken into account to make sure the production planning does not get influenced by delays in the delivery of such equipment. To be able to take these different kinds of equipment into account extra erection information for each equipment installation is noted. This erection information is stated as from which direction the piece of long lead time equipment will be erected. There are six possible directions, negative and positive x direction, negative and positive y direction or negative and positive z direction. All of these are stated as equipment characteristic by either a "1" representing the positive erection direction for a certain axis, or "-1" representing the negative erection direction for a certain axis. For some equipment "2" is returned as an indication of Integrated Equipment, more information about these can be found in Sub Section 5.3.1. So for example "1" for the z direction means the equipment will be lowered from the top down. When a "0" is stated for a piece of long lead time equipment no considerations are made for this piece of equipment regarding the Block division, which does not exclude the piece of equipment being relevant for the detailed production planning. Table 5.11 shows the relevant data columns for the long lead time equipment used as input for the in the BDG.The constructed Equipment Table of the test case ship can be found in Appendix J.5.

Table 5.11: Long Lead Time Equipment table columns

Column name	Data Type	Unit	Constraints
Equipment ID	Character	-	PK
Equipment Name	Character	-	-
Coordinate 1x	Real	[mm]	-
Coordinate 1y	Real	[mm]	-
Coordinate 1z	Real	[mm]	-
Coordinate 2x	Real	[mm]	-
Coordinate 2y	Real	[mm]	-
Coordinate 2z	Real	[mm]	-
Erection Direction in x	Integer	-	-
Erection Direction in y	Integer	-	-
Erection Direction in z	Integer	-	-

5.3. Mechanisms

The following Sub Sections elaborate on the several mechanisms and underlying logic to find and return conditions as specified in Chapter 3 and Section 4.1.4. These found conditions need to be represented in the Optional Seam Position string as mentioned in Sub Section 5.1.3, and need be compared to each other to find the most suitable final seam placing position as will be elaborated upon in Section 6.1.

5.3.1. Integrated Equipment

As mentioned above, stated equipment can be erected form every axis' direction or have an Erection Direction value returning "2". This represents the equipment being so called Integrated Equipment. When a piece of equipment or system has this indication, it is never considered to be split. For example, the bow thruster of the test case ship is considered an Integrated Equipment by Royal IHC, as they never split it for producibility reasons. Figure 5.10 shows the Optional Seam Position considerations regarding Integrated Equipment.

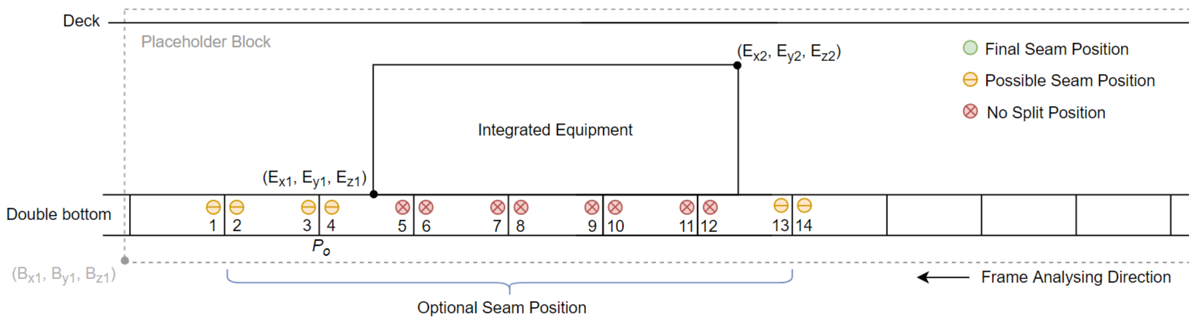


Figure 5.10: Schematic side view of Optional Seam Position considerations at Integrated Equipment

It can be seen in the Figure that at the Optional Seam Positions where Integrated Equipment is present, the position will be marked as No Split Position and therefore will not be taken into consideration when determining which of the 14 Optional Seam Positions the final seam has to be places. Because only Integrated Equipment is considered in this example no Final Seam Position can be chosen, only optional ocations can be excluded. In The No Split Position returned value is a Design Variable. Integrated Equipment will only be taken into consideration in this matter when the coordinates comply with Equations 5.2, 5.3, 5.4, 5.5 and 5.6. Where E_{x1} is the smallest x coordinate of the Integrated Equipment, and B_{x1} is the Placeholder Block coordinate notation. Next to the bow thruster complex pieces of structure can also be considered Integrated Equipment, even though these are not actual pieces of equipment.

$$E_{x1} <= Deck_{x2} \tag{5.2}$$

$$E_{x2} >= Deck_{x1} \tag{5.3}$$

$$E_{z1} > B_{z1} \tag{5.4}$$

$$E_{z2} < B_{z2} \tag{5.5}$$

$$ErectionDirection_E == 2 \tag{5.6}$$

5.3.2. Frames and Bulkheads

As mentioned in Sub Section 3.2.3 also the structural system must be translated into preferred or non preferred seam positions. The BDG checks for each Optional Seam Position if any frame or bulkhead is found. If a frame or bulkhead is found the side on which the stiffeners are present is found by looking for the "Stiffeners on side" characteristic as shown in Table 5.3. Figure 5.11 shows the Optional Seam Position considerations when a stiffened bulkhead is found within range. Because a general preference for placing seams at bulkheads is found, as mentioned in Sub Section 3.2.3, position 10 of the Option Seam Position in this example without any other arguments is marked as the Final Seam Position. However, in the BDG the weight of the of the Bulkhead Preference seam position can be varied and therefore is a Design Variable. The Optional Seam Position where stiffeners are found is replaced with a No Split Position Design Variable, and the position on the other side of the frame or bulkhead a preferred bulkhead split position Design Variable is added. The same principle goes for decks and girder seams, that have to be in front or over a stiffened piece of construction. Bulkheads are defined by the structure type in the structural parts table.

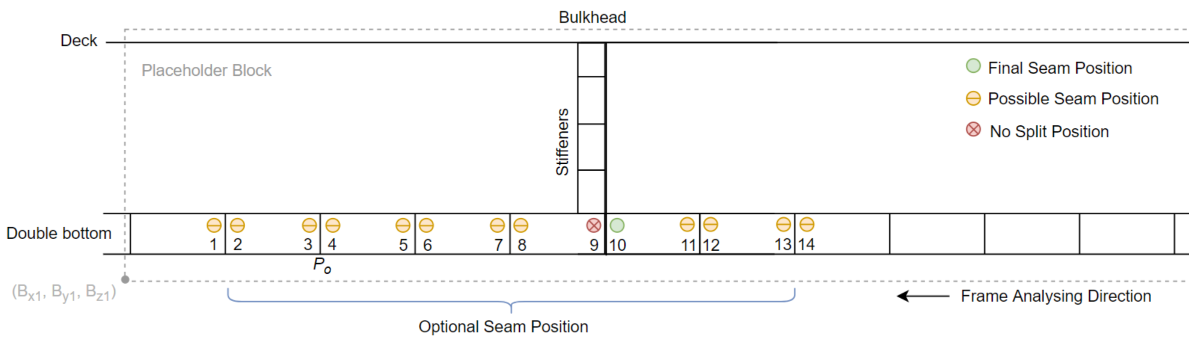


Figure 5.11: Schematic side view of Optional Seam Position considerations at stiffened bulkhead

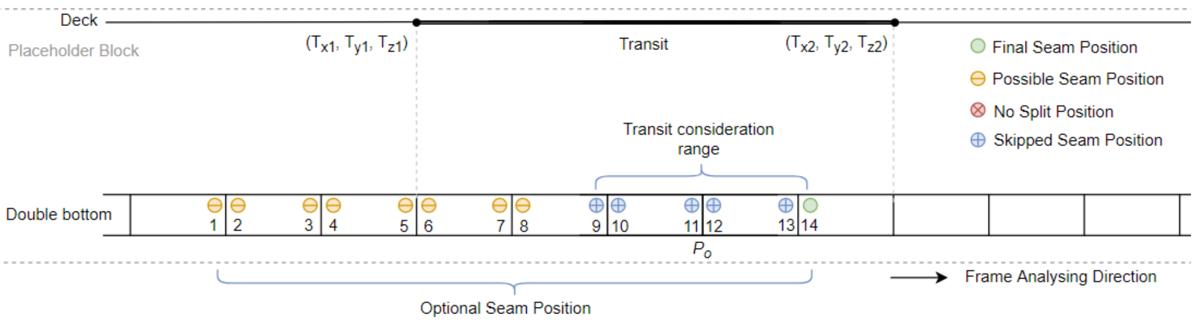


Figure 5.13: Schematic side view of Optional Seam Position considerations at mid of transit

5.3.3. Transit Maximization

As mentioned in Sub Section 3.3.3, Transits also influence the chosen splitting seam. Because of a small correction in the seam position can already result in opening or closing a transit by the seam, see also Figure 3.5, only six Optional Seam Positions are checked for transits around P_o. There are two situations of finding a transit by checking each frame. The first case is when a checked frame position equals the start or end of a transit. Depending on the frame analyzing direction and the found x_1 or x_2 position of the transit the Optional Seam Position is chosen to be within the Transit as shown in Figure 5.12, including the chosen seam position since no other arguments are taken into account. This mechanism only enters into operations when Equations 5.7 or 5.8 are satisfied and the to be returned Design Variable weight is referred to as Transit Preference.

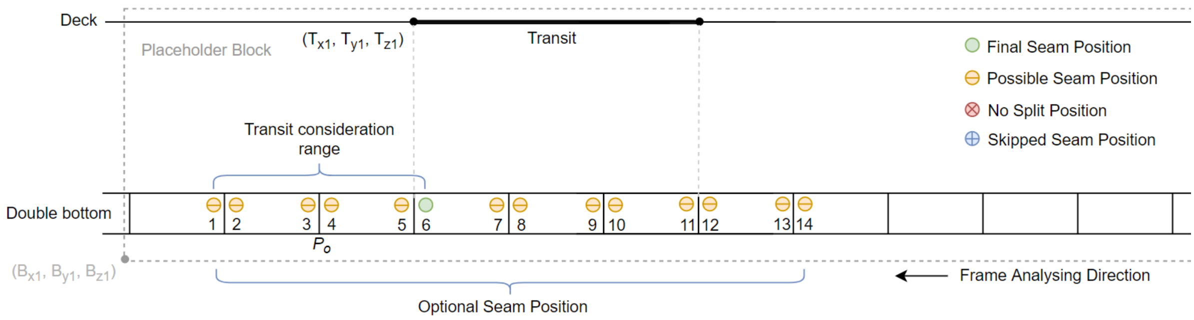


Figure 5.12: Schematic side view of Optional Seam Position considerations at start of transit

$$T_{x1} == OptSeamPos \tag{5.7}$$

$$T_{x2} == OptSeamPos \tag{5.8}$$

The second case is when a frame crosses the mid of a transit. Because the BDG checks each frame and Optional Seam Position after each other, depending on the analysis direction, the conditions as described above are met multiple times. To be able to distinguish these positions within the Transit, each time the conditions are met the Transit Preference Design Variable is increased by a small amount. In case of the x_2 position of the Transit is passed by the Optional Seam position regarding backwards analyzing direction, the Transit Position Design Variable will be decreased. This results in the lowest Transit Position Design Variable to maximize the Transit's length within the to be chosen Block. Figure 5.13 shows an example of this multiple Optional Seam Considerations analysis and a final chosen seam position, since no other arguments are taken into account. Note that the frame analysis direction differs from the previous examples. The above mechanism only enters into operations when Equations 5.9 and 5.10 are satisfied. Equation 5.11 shows the calculations for the Transit Position Design Variable to create a distinction between the skipped and final seam position. In the case of a forward frame analyzing direction the Transit Position is increased by the number skipped Optional Seam Positions, and in the case of a backward frame analyzing direction the Transit Position is decreased by the number of skipped Optional Seam Positions.

$$[H]T_{x2} > OptSeamPos > T_{x1} \tag{5.9}$$

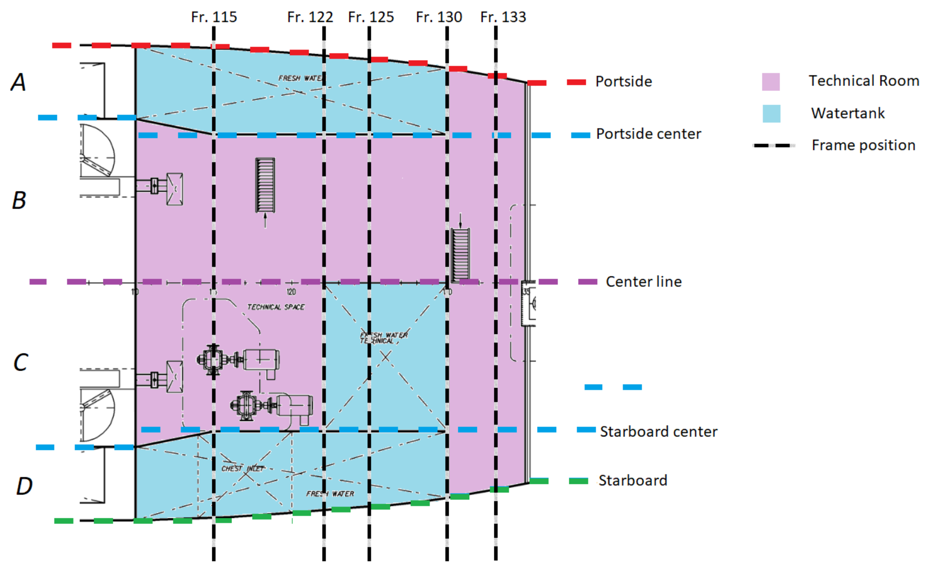


Figure 5.14: Deck reference line hierarchical Compartment Areas

$$[H]T_{x2} >= Deck_{x1} \tag{5.10}$$

$$[H]TransitPosition == TransitPosition + / - SkippedCount \tag{5.11}$$

5.3.4. Sum of Compartments Separability Weight

As mentioned in Sub Section 5.2.4 and shown in Table 5.8, Compartments are arranged by the separability weight variable w_total to be able to determine which Compartment will have the least negative effects on the producibility of the ship when split compared to another Compartment. Because over the breadth of a ship most of the times multiple Compartments are found, these have to be analyzed together. As also mentioned the longitudinal reference lines separate compartments and can create a table of local separability weights as an representation of found Compartments per frame position. The five reference lines as shown in Figure 5.14 create four enclosed Compartment Areas from a top view, referred to as A, B, C and D. The Figure show the considered frames in this example. Generally Compartments end and start at a frame, therefore Compartments weights are added to a particular frame position are checked 350mm behind the frame. Table 5.12 shows the resulting separability table for these frame positions, including the total sum of separability weight to be considered when to be split. If only Compartments are taken into consideration, and only the exampled frame positions from Table 5.12 are in range of an Optional Seam Position string, frame 133 would be the the final seam position because of the lowest sum of separability weights and therefore can be augmented to have the least amount of negative impact on the producibility of the ship, compared to frames 115, 122 and 125.

Table 5.12: Deck reference line hierarchical Compartment Areas example

Area	Fr. 115-350	$w_{tot_{115}}$	Fr. 122-350	$w_{tot_{122}}$	Fr. 125-350	$w_{tot_{125}}$	Fr. 133-350	$w_{tot_{133}}$
A	Watertank	11	Watertank	11	Watertank	11	Tech Room	4
B	Tech Room	4	Tech Room	4	Tech Room	4	Tech Room	4
C	Tech Room	4	Tech Room	4	Watertank	11	Tech Room	4
D	Watertank	11	Watertank	11	Watertank	11	Tech Room	4
Total Sum		30		30		37		16

The example shown above only includes the bottom deck. Sub Section 3.3.1 mentions all transverse seams to be directly positioned above each other for assembly optimization by erection condition minimization and Sub Section 4.1.3 explains how for the chosen Block division approach this results having to take seam placing arguments into consideration for each deck combines. For the sum of separability weights of Compartments this results in having to add up the total sum of separability weights of Compartments Areas together for all lower decks to compare Optional Seam Position's that spread across all these decks, all decks of the hull except the main deck in case of the test ship.

5.3.5. Equality Break

Whenever there are multiple equal sums of Separability Weights the BDG initially can not find one minimum value in the Optional Seam Position. Two Design Variables are incorporated that will chose on which Optional Seam Position of multiple equal positions will be the Final Seam Position. The first Design Variable indicates whether the to be chosen Block must be maximized or minimized in length, and will be referred to as the Equality Break. the Equality Break can be varied per frame direction analysis. Figure 5.15 shows the two remaining Option Seam Positions in the range of the Technical Room, which in the test case has a lower separability weight than the Watertanks as shown by Table 5.9. Optional Seam Position 6 in the Figure's example will be determined the final seam position when only Compartments are taken into consideration and the Equality Break Design Variable aims to minimize the to be chosen Block length when equal separability weights are found. In the case the Equality Break Design Variable aims to maximize the to be chosen Block length Optional Seam Position 11 will be found as final seam position.

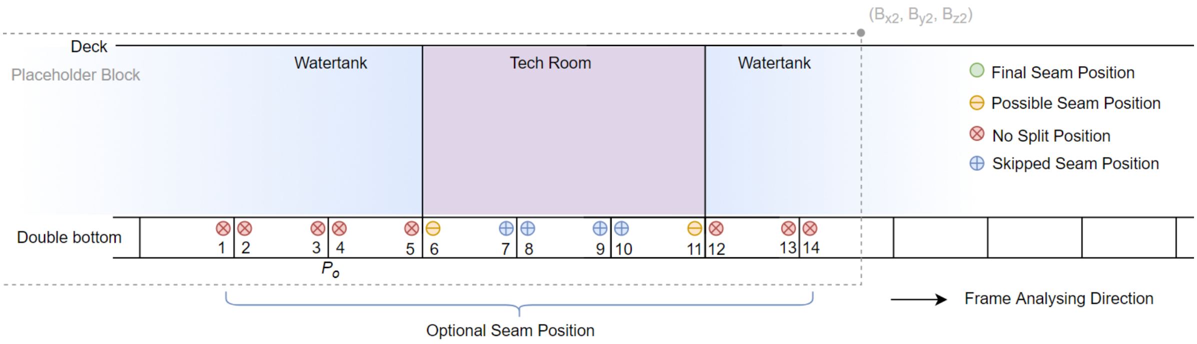


Figure 5.15: Remaining Optional Seam Positions at multiple equal separability weights by the Equality Break

The mechanism to determine either to maximize or to minimize the to be chosen Block length works as follows. At the equal separability weight Optional Seam Positions a replacement value is inserted which varies over the different equal positions. The Equality Break determines whether this replacement value increases or decreases per equal position. The result is that there are no longer equal values in the Optional Seam Position string and the minimum value in this string can be found, indicating the final chosen seam position. Table 5.13 gives an example of the Optional Seam Position string for the situation as described by Figure 5.15, before and after the Equality Break mechanism. In this example it is assumed that over the whole breadth of the ship the same Compartment is found. This results, for the minimum value in the Optional Seam Position string, in the minimizing Equality Break that position 6 is returned with value "0" and when the Equality Break aims for maximizing the to be chosen Block Optional Seam Position 11 is returned with value "-5".

Table 5.13: Separability Weight table columns

Optional Seam Position	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Sum of separability weight	44	44	44	44	44	16	16	16	16	16	16	44	44	44
After Equality Break minimizing	44	44	44	44	44	0	1	2	3	4	5	44	44	44
After Equality Break maximizing	44	44	44	44	44	0	-1	-2	-3	-4	-5	44	44	44

The second set of Design Variables influence the seam placing logic when all present sums of separability weight are equal to each other. In this case first the total length of the Placeholder Block is checked to determine in how many comparable Blocks it should be split. The first Design Variable is the Maximum Block Length of these identical Blocks ($L_{B_{max}}$) when no other arguments are found to split the Placeholder Block. The second Design Variable thresholds the length of the Placeholder Block ($L_{B_{max}}$) as a condition for this mechanism to start working. Equation 5.12 up until 5.16 is followed step by step and repeated until a final optimal Block length is found. In these equations B_{count} represents the amount of Block the Placeholder Block will be split into by the to be constructed Maximum Block Length ($L_{B_{max}}$) and c_B is a control variable indicating this initial ceiling. Equation 5.15 is repeated up until Equation 5.16 is true.

$$Fr_{count} = \frac{(B_{x_2} - B_{x_1})}{L_{Fr}} \tag{5.12}$$

$$B_{count} = \frac{Fr_{count}}{L_{B_o}/L_{Fr}} \tag{5.13}$$

$$c_B = \frac{roundup(Fr_{count})}{L_{B_{max}}} \tag{5.14}$$

$$L_{Bo} = L_{Bo} + 1 \tag{5.15}$$

$$c_B <= B_{count} \tag{5.16}$$

Figure 5.16 shows a Placeholder Block with indicated by the different arrows several solutions that the model would take into consideration to split the Placeholder Block into several smaller but feasible Blocks. It can be seen that for example L_{0-1} and L_{0-2} looks for too long optimal Block lengths, which results in three not close to comparable Blocks. L_{0-4} uses a too short optimal Block length resulting in the control variable c_B that is expecting three Blocks is surpassed and four too small Blocks would be created. The best result is L_{0-3} which results in the expected amount of three Blocks which are all comparable, in this case identical, in length. The Optional Seam Positions string will be capped by the optimal Block length when of the remaining positions, in combination with the Equality Break, the final seam position will be chosen.

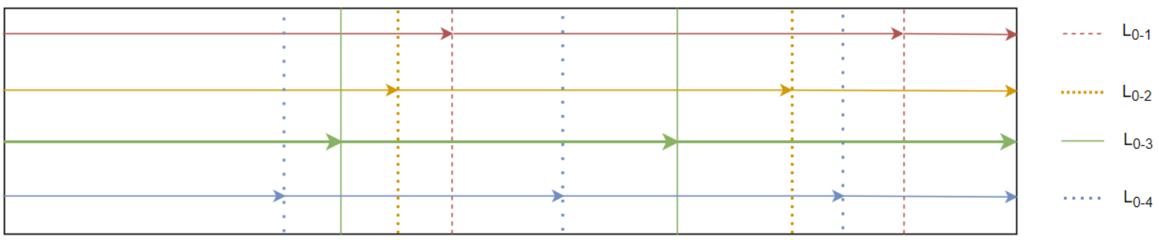


Figure 5.16: Several considered optimal Block lengths of which one result with three comparable Blocks

5.3.6. Longitudinal Splitting

All previous mechanisms are used to determine the transverse seams to split the Placeholder Blocks. The next step is to chose longitudinal splits to find Blocks that are comply with the feasibility constraints in terms of size and weight. The first step is to correct the Placeholder Breadth to the maximum size of the structural parts that are included by the individual Placeholder Blocks. Figure 5.17 shows the result of this operation for an example aft ship Module. Note that only the hull or the Blocks up until main deck are shown and taken into consideration.

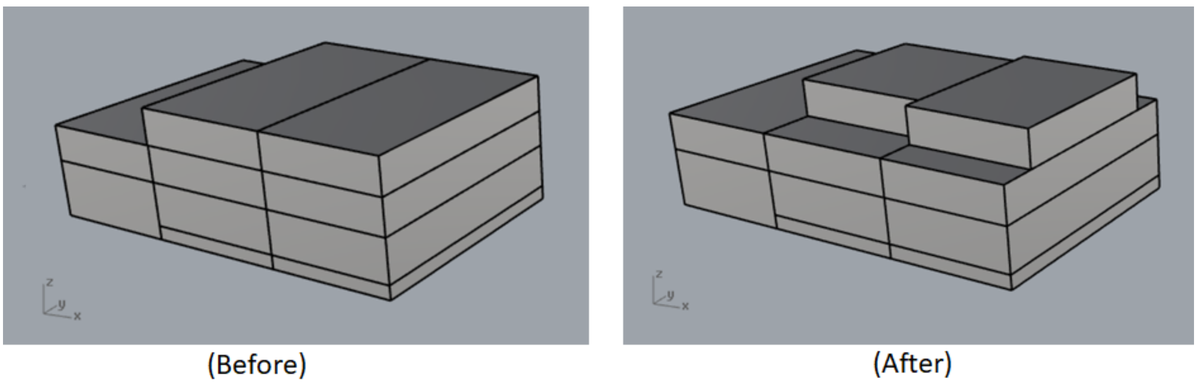


Figure 5.17: Breadth correction of Placeholder Block for aft ship Module by included structural parts

Symmetrical Split Before getting into the several conditions of longitudinal splitting, first the two types of splits will be elaborated upon. The first type of longitudinal split is the single Symmetrical Split, which will split the Placeholder Block in two comparable symmetrical Blocks. The same principle for longitudinal girders goes for frames, mentioned in Sub Section 5.3.2. The model only allows one default longitudinal seam position side per Block division generating run. The Design Variable "Default Center Line Side" indicates the position of the y coordinate of the seam. The seam will be placed on the side of the girder where no stiffeners are expected.

Closing Deck Split The second type of longitudinal split is in case long lead time equipment is present within a Placeholder Block that requires a closing deck. This is done by splitting the Placeholder Block two times. These seams are placed 75mm towards the center line from the longitudinal deck reference lines "Starboard Center" and "Port Side Center" of the applicable deck where the placeholder block is situated. Figure 5.18 shows an example of the before mentioned two types of longitudinal splits.

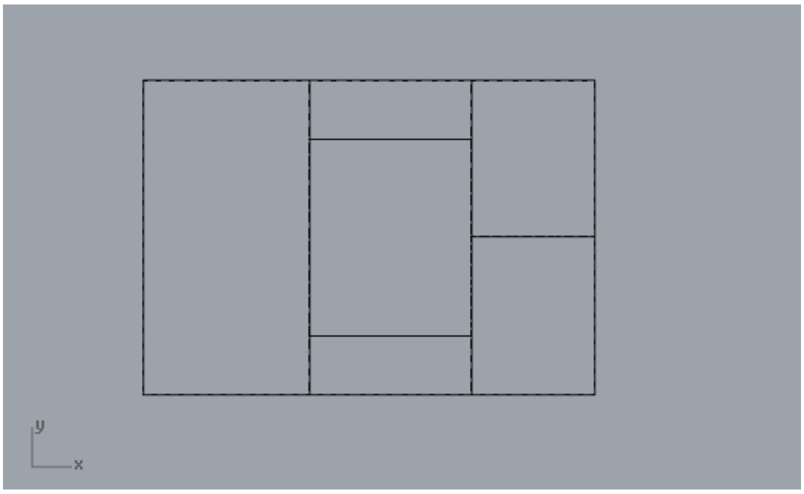


Figure 5.18: Top view of the two types of longitudinal splits next to a Block without a longitudinal split

Equipment Characteristics The next step is to look for equipment that is within the assessed Placeholder Block. Certain conditions have to be met before this influences the decision making process. Figure 5.19 shows a visualization of the Equation representation of these conditions as can be found in Equation 5.17 up until 5.22. Equation 5.21 checks if the equipment is crossing the longitudinal center line of the ship. When this is the case, there will be checked for the Erection Direction characteristic being equal to "2", as Equation 5.22 states. When this is the case, the equipment accounts as an Integrated Equipment and as mentioned in Sub Section 5.3.1 there will not made any split through an Integrated Equipment. Only in case the Erection Direction characteristic from the z direction equals "1" the equipment triggers a longitudinal split. This split will be a closing deck split because of the erection characteristic and aim to remove the equipment from the critical path of the production planning, as elaborated upon in Sub Section 3.3.1. In every other case, the default approach is to create symmetrical resulting Blocks, unless there are constrains that withhold any split to be made, such as the presence of Integrated Equipment. The resulting center Blocks that are pierced by equipment are labeled as a closing deck in the output information structure, to be able to comply with the requirements of the erection sequence schedule input data as mentioned in Sub Section 4.2.

$$E_{z1} <= B_{z1} \tag{5.17}$$

$$E_{z2} >= B_{z2} \tag{5.18}$$

$$E_{x1} >= B_{x1} \tag{5.19}$$

$$E_{x2} <= B_{x2} \tag{5.20}$$

$$E_{y1} <= 0 <= E_{y2} \tag{5.21}$$

$$E_{ErectDir} == 2 \tag{5.22}$$

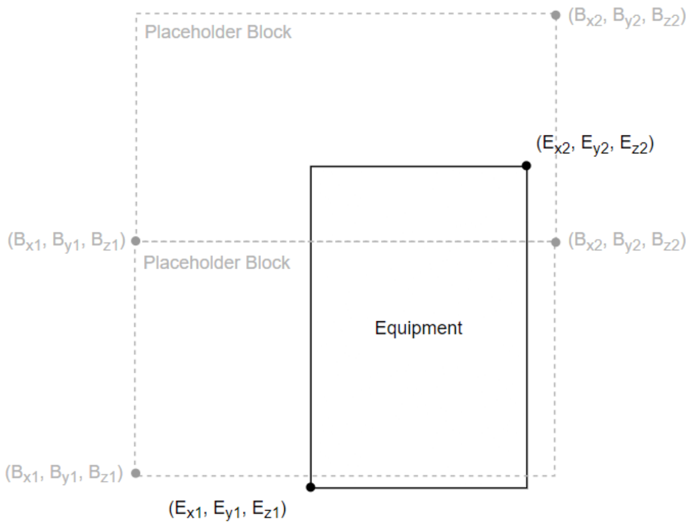


Figure 5.19: Equipment conditions for longitudinal Placeholder Block split

Longitudinal Split Constraints There are two Design Variables that can create a threshold to withhold the BDG to split a Placeholder Block in longitudinal direction. The first one is a maximum of the sum of the Compartment separability weights that would be split. This maximum, referred to as Split Boundary, needs to be surpassed in order to create the split. For example, if the Split Boundary equals 22, or according to Table 5.9 for example two watertanks, this Split Boundary will prevent the longitudinal split to be placed. The other Design Variable is referred to as Max Breadth and represents a breadth threshold value. When a Placeholder Block is smaller than the Max Breadth Design Variable no longitudinal split will be made. This value is a representation of creating Blocks that are still feasible to handle at the shipyard, as discussed in Sub Section 3.3.4. The Maximum Breadth constraint is not necessarily a representation of the door size constraint as mentioned in Sub Section 4.3.1. The Max Breadth parameter can be overruled, in case of Separability Weight Boundaries or Integrated Equipment, and the resulting Block will still fit through the door sizes of a shipyard. Because only the hull is taken into consideration, this together with the Maximum Block Length Design Variable will most of the time result in Blocks with maximum one dimension in excess of the maximum size. If only a Block is too big in only one dimension, it can be turned to still fit through doors at the shipyard.

Minimum Block Length Because the ship is assessed in Modules, there may be resulting Blocks at the end of a Module, opposite from where the Analyzing Direction starts, that are smaller than the minimum resulting Block length ($L_{B_{min}}$ by the Optional Seam Position mechanism. This only occurs when there are preferred seam placing arguments within two frames from a considered p_0 position as a result of the Maximum Block Length starting point. A small Block is defined by Equation 5.23, where the Minimum Block Length is a Design Variable for the BDG.

$$B_{x2} - B_{x1} <= L_{B_{min}} \tag{5.23}$$

To increase applicability of Grouping operations, as will be elaborated upon in Sub Section 5.3.8, Blocks that are smaller than the Minimum Block Length constraint will be split in every longitudinal seam position that is mentioned above. The Block will thus be split at center line, and at the Starboard Center en Port Side Center reference lines.

5.3.7. Weight Calculations

Once all seams are placed per deck in transverse and longitudinal direction a weight calculation is made for the resulting Blocks. As mentioned in Section 3.4.2, this can be done by calculating the steel panel weight of stiffened plates such as frames and decks. Figure 5.20 shows an example of a Block enclosing the steel coaming structure at the coaming deck of the test case ship created by the BDG. In this Figure the white lines are a representation of the Block boundaries or seams.

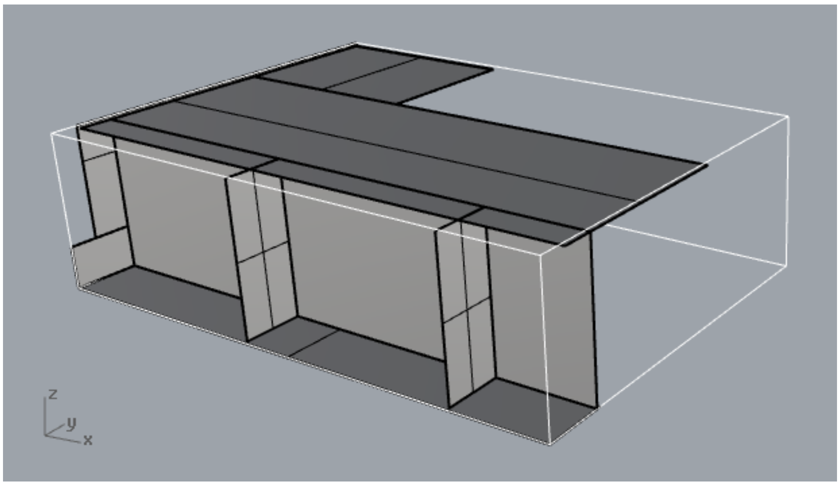
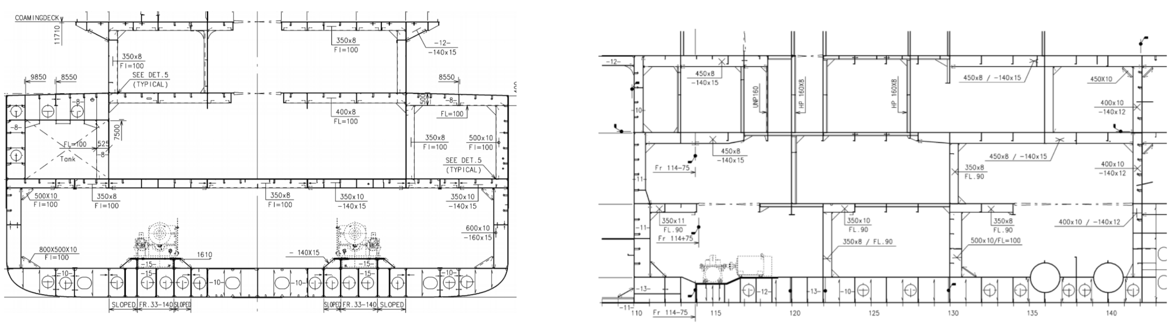


Figure 5.20: Example of enclosed structural parts by white lined coaming Block

The BDG uses the seams or boundaries of the chosen Block to calculate the amount of square meters present of each structural part within the Block. Using the structure type characteristic defined per structural part as shown in Table 5.2, which represents the thickness of each steel structural part, and the density of ship building steel [10] the weight is calculated. Because not all detailed structural design information is available at the early design stage the information about the structural design is limited. The result is that only major structural parts are part of the BDG and the primary and secondary stiffeners are not included in the structural parts table as referred to in Sub Section 5.2.2. Therefore the BDG includes Design Variable correction factors that can correct for this simplification.

There are three correction factors directly attributed of the different major structural parts and one general correction factor. The correction factors for decks and frames is a representation of the primary stiffeners that are not included in the structural parts table but are expected on these major structural parts, an example of these stiffeners are shown by Figures 5.21a and 5.21b which is a representation of a detailed structural design at a later design stage. For girders no correction for primary stiffeners is incorporated since girders are considered primary stiffeners. Finally a correction factor is incorporated that corrects for all the secondary stiffeners present throughout the ship, also shown by Figures 5.21a and 5.21b.



(a) Decks (b) Frames

Figure 5.21: Examples of primary and secondary stiffeners as part of major structural parts

5.3.8. Grouping

Because the BDG starts with Placeholder Blocks per deck, as explained in Sub Section 5.1.2, the resulting Blocks after transverse and longitudinal seam placing will never be Side Blocks stretching over multiple decks, which is a preferred way of chosen Blocks as mentioned in Sub Section 3.3.2. In order for the BDG to be able to create cross decks (side) Blocks the principle of Grouping is introduced. Because the model is simplified by using and creating rectangular Blocks only, Blocks can only be grouped if they line up perfectly in a particular direction. If Blocks do not line up perfectly a non-rectangular Block would be created that can not be described by the six coordinate system required for the erection planning generator. Next to lining up perfectly, a resulting Block after Grouping can not be longer than the maximum resulting size of the Optional Seam Position mechanism, being the defined p_0 plus one frame spacing length L_{fr}. Also, the resulting Blocks can not be heavier than the shipyard's maximum crane capacity, in order to still be able to lift the Block onto the slipway. The grouping process consists of several grouping operations that are executed in a particular order.

Vertical Side Blocks In order to create the before mentioned Side Blocks a vertical Grouping operations has to be executed. Figure 5.22 shows the coordinates of two different Blocks that are perfectly lining up in vertical direction. Equation 5.24 up until 5.28 show the lining up conditions to comply with. Because Side Blocks are a preferred Block Type, the vertical Side Block grouping operation is the first step of the several grouping processes. To only consider Side Blocks for this grouping operation, Equation 5.29 must also be satisfied. To be grouped Blocks are looked for from the bottom deck up, because of the general erection order of lower deck Blocks before higher deck Blocks defined by the "Vertical Feasibility" erection constraint.

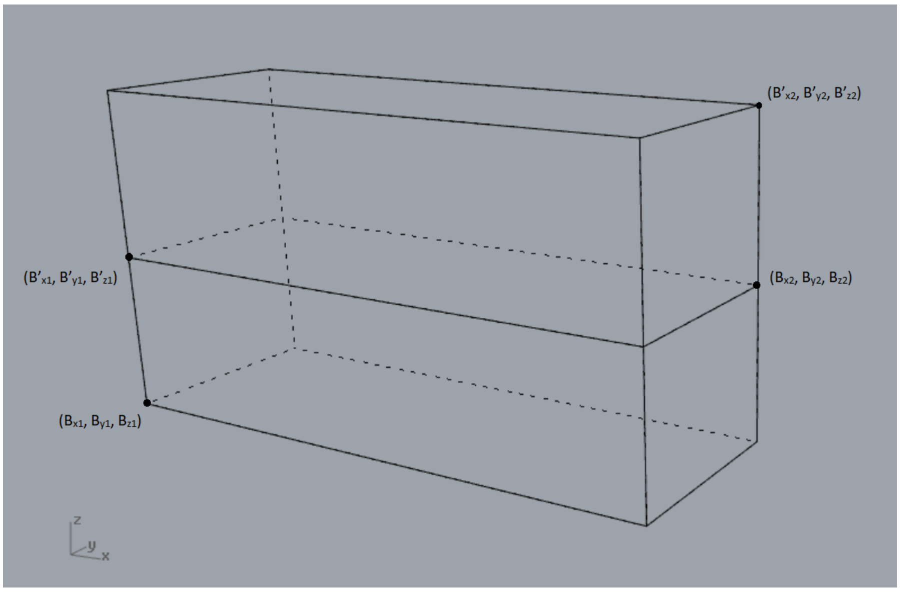


Figure 5.22: Coordinates of Blocks per deck for Grouping in vertical direction

$$B_{x1} == B'_{x1} \tag{5.24}$$

$$B_{y1} == B'_{y1} \tag{5.25}$$

$$B_{x2} == B'_{x2} \tag{5.26}$$

$$B_{y2} == B'_{y2} \tag{5.27}$$

$$B_{z2} == B'_{z1} \tag{5.28}$$

$$B_{y1} < 0 > B_{y2} \tag{5.29}$$

$$w_{Block_I} + w_{Block_{II}} + w_{Block_{III}} < w_{capacity} \tag{5.30}$$

Next to lining up, the to be grouped Side Blocks only need to comply with the weight constraint, shown in Equation 5.30, which is a representation of the situation in Figure 5.23. The longitudinal size constraint does not apply in this case due to the absent of situations where a resulting Block is elongated after the vertical grouping process. Figure 5.23 shows an example of the resulting vertically grouped Side Block.

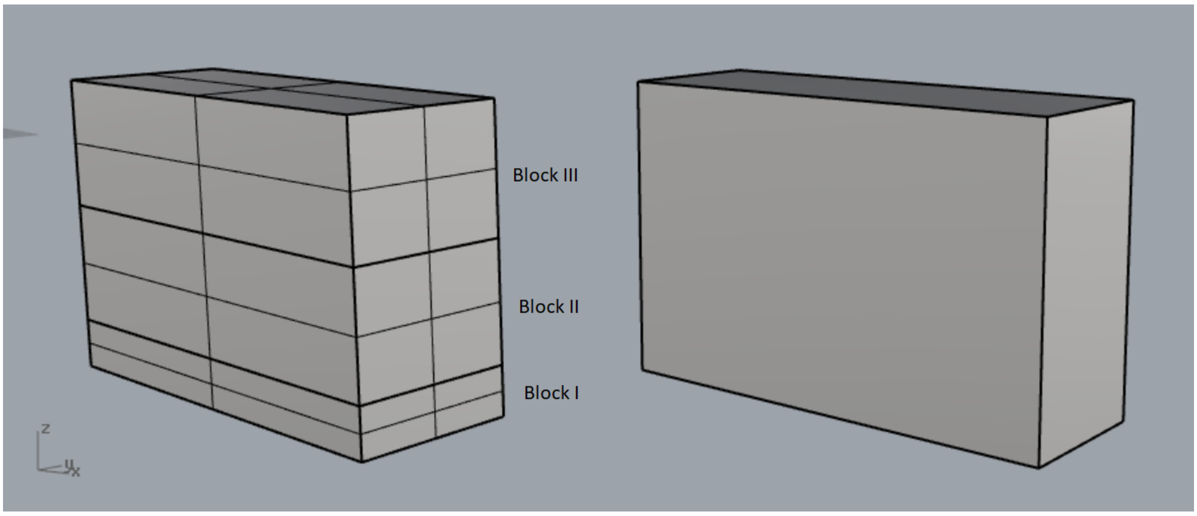


Figure 5.23: Example of Blocks per deck grouped as a Side Block

Longitudinal Bottom Blocks Next to Side Blocks, bottom Blocks are important Blocks for the erection process because these create the initial work area when a ship's erection has started onto the slipway, as mentioned in Sub Section 3.3.1. To maintain the transverse seams over the lower decks, other decks are excluded from this longitudinal grouping operation. Because of the Placeholder Blocks per deck, a bottom Block incorporates the double bottom. Because the ship is initially analyzed by ship's Modules, there can be situations where two shorter Blocks are next to each other in different Modules.

Because of the aim of creating as large and heavy Blocks as possible, this situation of two relative small Blocks must be excluded of the final results. This is done initially by the longitudinal grouping of bottom Blocks. Only bottom Blocks are analyzed in this second operational step of the total grouping process because of the importance of these Blocks for the erection process. Figure 5.24 shows the coordinates of two different bottom Blocks that are perfectly lining up in longitudinal direction. Equation 5.31 up until 5.35 show the lining up conditions to comply with. Equation 5.29 results in only center line bottom Blocks to be taken into consideration and excludes side Blocks.

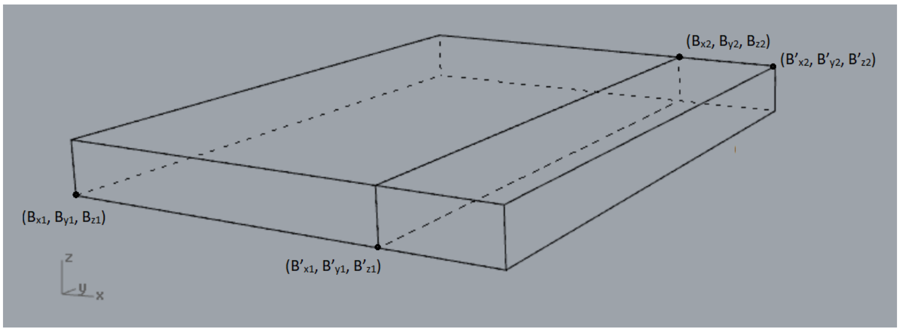


Figure 5.24: Coordinates of bottom Blocks deck for Grouping in longitudinal direction

$$B_{x2} == B'_{x1} \tag{5.31}$$

$$B_{y1} == B'_{y1} \tag{5.32}$$

$$B_{z1} == B'_{z1} \tag{5.33}$$

$$B_{y2} == B'_{y2} \tag{5.34}$$

$$B_{z2} == B'_{z2} \tag{5.35}$$

$$B_{y1} < 0 < B_{y2} \tag{5.36}$$

$$w_{Block_I} + w_{Block_{II}} < w_{capacity} \tag{5.37}$$

$$B_{x1} + B'_{x2} < L_{max} \tag{5.38}$$

Next to lining up, the to be grouped bottom Blocks need to comply with the weight and maximum length constraints, as shown in Equations 5.30 and 5.38, which is a representation of the situation in Figure 5.25. The longitudinal size constraint is controlled by the L_{max} Design Variable. Figure 5.23 shows an example of how multiple bottom Blocks will result in a single grouped bottom Block.

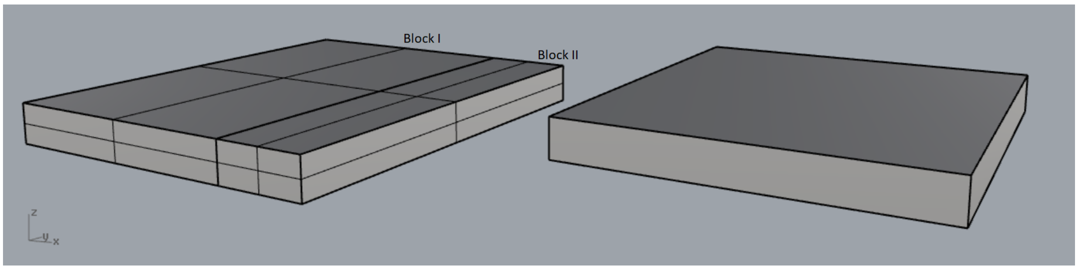


Figure 5.25: Example of multiple bottom Blocks grouped as a single bottom Block

Vertical Center Blocks After the vertical Side Blocks and the longitudinal bottom Blocks are grouped, there is one final grouping operation that can be be performed. As mentioned before, to maintain the transverse seams over the lower decks, other decks are excluded from longitudinal grouping operations. Also Closing Blocks are excluded from vertical grouping because of the importance of closing Blocks in the erection process. Before grouping center Blocks vertically, Blocks that are shorter than the Minimum Block Length will be grouped transversely to form true center Blocks, after this step the vertical grouping operation will be started. The vertical line up conditions as illustrated by Equations 5.24 up until 5.28 must be met including 5.36 to together define only keep center Blocks in scope. Next to the before mentioned conditions, also Equation 5.39 must be met. As shown earlier by Figure 4.5, in the case of an unsupported aft no double bottom is present to use as a basis for erection. Equation 5.39 therefore only complies within the frame positions over the length of the ship where Equation 5.40 holds up.

$$B_{x1} > z_{2DoubleBottom} \tag{5.39}$$

$$z_{1DoubleBottom} == 0 \tag{5.40}$$

5.3.9. Overview Model Variables

As elaborated upon in Sub Section 4.3.3, to be able go generate multiple Block division solutions, Design Variables have had to be incorporated in the BDG. Next to these Design Variables there are some parameters that can be deducted from the concept design or shipyard facilities.

Input Parameters Input parameters are a representation of a particular part of the ship or situation at a shipyard, rather than a range such as the Design Variables. However, these parameters are of high importance for the resulting Block division. Table 5.14 shows a list of the parameters used in the previously described BDG mechanisms but can not be changed for a specific Block division solution for a specific shipyard. When these parameters are changed a no longer viable Block division for the given circumstances could be the result. For example, the crane capacity at a shipyard is fixed. In case this parameter would change, a resulting Block division maybe not be able to be built at that shipyard because the Blocks have been grouped in too heavy resulting final Blocks. Also, different shipyards handle Integrated Equipment in their own way, which may result in different pieces of equipment receiving different characteristics in the BDG.

Table 5.14: Overview of input parameters

Parameter	Type	Unit
Frame Spacing	Real	[mm]
Equipment Characteristics	Integer	[-]
Weight Correction Factors	Real	[-]
Crane Capacity	Real	[ton]

Incorporated Design Variables The Design variables that influence the seam placing mechanisms can be broken into two sets of variables for the two major steps in the Block division process. These may also be shipyard and Block division approach specific, but when varied within a specific range will still result in feasible Block division solutions. The first set are the variables that influence the transverse seam placing results are shown in Table 5.15.

Table 5.15: Overview of Transverse seam placing Design Variables

Design Variable	Type	Unit
Maximum Block Length ($L_{B_{max}}$)	Real	[mm]
Equality Break	Integer	[-]
No Split Position	Integer	[-]
Bulkhead Preference	Integer	[-]
Transit Preference	Integer	[-]
Separability Weight	Integer	[-]

The second set of Design Variables are the variables that influence the longitudinal seam placing are shown in Table 5.16. Where the Split Boundary is a longitudinal seam placing threshold of the Separability Weight.

Table 5.16: Overview of Longitudinal seam placing Design Variables

Design Variable	Type	Unit
Split Boundary	Integer	[-]
Max Breadth	Real	[mm]
Default Center Line Side	Real	[mm]
Minimum Block Length ($L_{B_{min}}$)	Real	[mm]

Maximum weight is not incorporated as a design variable but as a constraint. The reason for this is that by the single seam placing mechanisms the model operates, in the intermediate steps such as transverse seam placing, the resulting (Placeholder) Blocks can not be assessed for final weight as they require another seam to be places anyway due to the size constraints. However, the Maximum Block Length can be considered a weight Design Variable. The weight of a Block is directly related to its size [26], therefore this suits the chosen Optimization Algorithm since this relies on changes in weight and size of Blocks.

5.4. Used Software

Because the goal of this research is not to develop a model that for example is as CPU efficient as possible, there was chosen to use software packages that were available and licensed by the TU Delft at the moment of writing. Depending on the developed scripts and results of this research, it may be concluded whether these software packages are suitable to fulfill the (future) requirements of the model.

5.4.1. Database

At the basis of the BDG lies a database system where the data can be called from and stored at. A conventional PostgreSQL relational database is used to be able to use relations between different data to be able to make varying the input parameters possible. Postgre SQL can be managed by an open source database manager pgAdmin making it easily availble, version 4 of pgAdmin was used during this research. Next to the availability, the TU Delft default database structure is PostgreSQL so it is easy to maintain compatibility of the created and calculated data from this research.

5.4.2. Visualization

To be able to visualize the data input and the results of the BDG, visualization software is needed. Because the TU Delft has a license for Rhinoceros 5 and experience with creating models using different software languages to visualize results, this was chosen as the visualization software. Also the data structure used by the erection sequence model of *Meijer*(2008)[16] is suitable to visualize in Rhinoceros 5.

5.4.3. Logic Functions

The actual model that needs to modify and search through the data to be able to create a Block division plan, needs to be compatible with PostgreSQL and Rhinoceros. Python 3.6 was used because this is also open source software with existing packages that make it compatible with PostgreSQL and Rhinoceros 5 and has an easy to learn syntax. Furthermore, is a complete software system that is able to do all sorts of operations through different table structures and therefore ideal to use when developing a new model.

6
Analysis

This chapter discusses the verification of the BDG by recreating the existing Block division of the test case ship as mentioned in Sub Section 4.1.2. Also other Block division solutions are generated, discusses and assessed using the erection sequence generator by *Meijer*(2008)[16]. The results are discussed as is the validation of the developed model using the Validation Square as developed by *Seepersad*(2005)[3].

6.1. Verification of the Block Division Generator

To assess the model's capability of generating one or more feasible Block division solutions, the first step is to reproduce an existing Block division solution. In this manner it is shown that for a specific shipyard and a specific ship, all with a resulting specific Design Variables based on the Block division approach suitable for that shipyard, the model can recreate the actual results and therefor this result verifies the model's ability of generating feasible Block division solutions.

6.1.1. Data set Test Case Ship 1

As mentioned in Sub Section 4.1.2 a test case ship is chosen. As shown in Section 5.2, several tables have to be constructed to make this ship available as input for the BDG. The constructed information tables can be found in Appendix A, where this Section will only introduce the visual representation of this data. Because the BDG only takes into account the hull for the automatic generation of Blocks, only the hull information can be found in either Appendix A and below.

Hull Structural System Figure 6.1 shows the hull structure system as converted from the GA in Appendix H.1, all individual structural parts are listed in Appendix J.2, including all structure types of these structural parts as can be found in Appendix J.1. More information about the structural types for this test case ship can be found in Sub Section 6.1.2. As mentioned in Sub Section 5.2.1, all structural parts and Compartments are simplified as rectangular blocks.

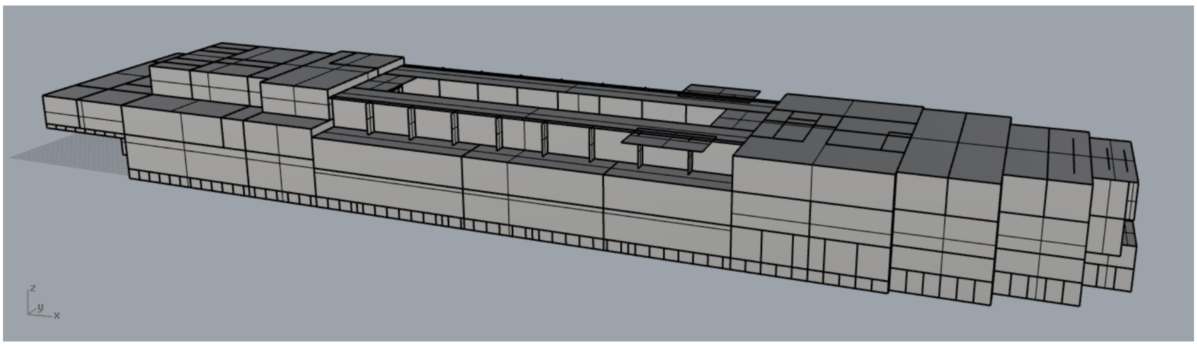


Figure 6.1: Hull structure system defined from test case ship

Hull Compartments Figure 6.2 shows the Compartments as these can be defined in the hull from the GA found in Appendix H.1. The different present Compartments types as defined in Sub Section 5.2.4 can are represented using different colors and shown in the legend. All individual Compartments including characteristics are listed in Table J.6 in Appendix A. Bow ballast tanks, the Void Hopper and aft Module of the test case ship can easily be recognized.

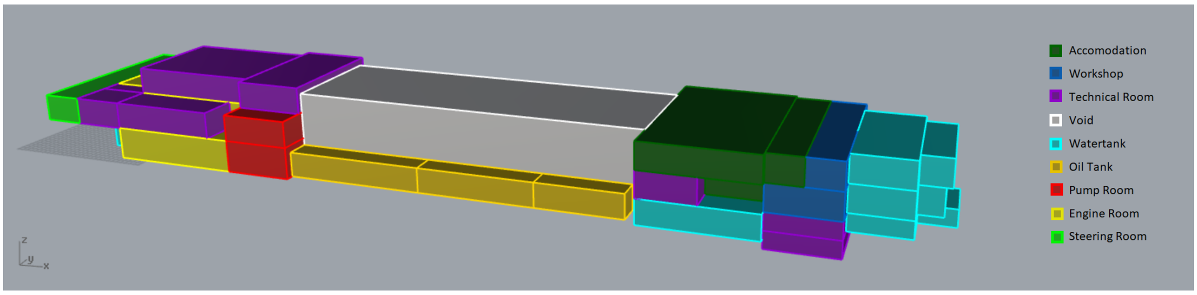


Figure 6.2: Compartments defined from test case ship

Equipment Figure 6.3 shows the Equipment as converted from the GA in Appendix H.1. Without the context of the ship's shape some parts are hard to recognize. On the right side of the Figure the bow thruster can be found, in the middle the Conical Valves including driving mechanisms, and on the left side the two engines and Skeg of the ship. All individual pieces of Equipment, including characteristics, are listed in Table 6.1. Whether each piece of Equipment is either characterized as Integrated Equipment or has a specific Erection Direction is based on the interviews with the experienced engineer at Royal IHC, and is a result of the chosen Block division approach and ship building techniques as they are used at the shipyard in Kinderdijk.

Table 6.1: Equipment defined from test case ship 1

Name	Amount
Skeg	1
Main Engine	2
Suction tube	2
Suction Tube Inlet	2
Conical Valve	18
Conical Valve tube	18
Life Boat Platform	2
Bow Pump	1
Bow Thruster	1

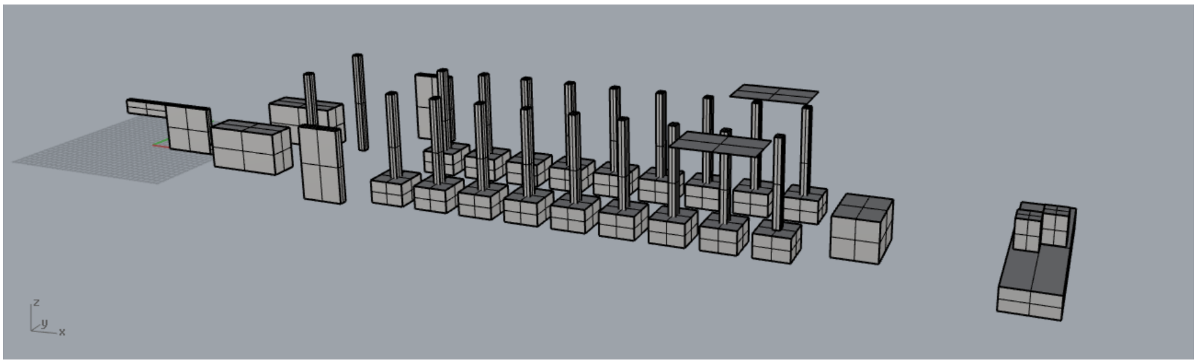


Figure 6.3: Equipment defined from test case ship 1

6.1.2. Applied Input Parameters

The already discussed input parameters suitable for this test case ship are shown in Table 6.2. As mentioned above, the Equipment characteristics can be found in Table J.5 as these are chosen individually per piece of equipment. The Weight Correction factors are discussed below.

Table 6.2: Test case input parameters

Parameter	Value	Unit
Frame Spacing	700	[mm]
Crane Capacity	140	[ton]

Steel Weight Calculation As mentioned in Sub Section 5.3.7, the weight of each individual Block is based on the amount of square meter plate of particular structure types is found within a defined Block. To determine which different structure types are required to model the steel weight of a ship, the detailed structural design of the test case ship was analyzed. The first step was to check the range of plate thickness of the decks over the length of the ship, Figure 6.4 shows the results. To construct this graph the average thickness of the different deck plates over the breadth of the ship was set out against the frame position over the length of the test case ship. The plate thickness varies less and more extensively per deck per ship Module because of the expected stresses and bending moment the ship will endure over its lifetime. In the early design stage this detailed information is not available for a newly designed ship, but reference ships, as mentioned in Sub Section 3.2.2, can provide a magnitude of the expected plate thicknesses. Because the goal of this research is not to be able to calculate the steel weight of Blocks as accurate as possible, a general approximation will suffice to be able to use the Block weight as a constraint in for example the grouping of Blocks.

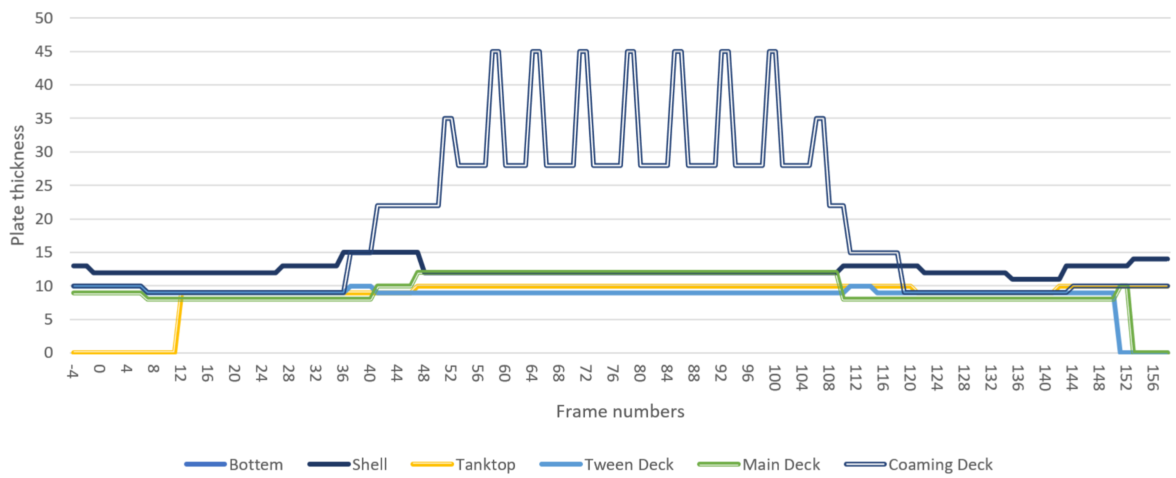


Figure 6.4: Thickness of plates of different decks over the length of the test case ship

Figure 6.4 shows a clear segmentation and differences of the average plate thicknesses in the different Modules of the ship. Therefore it was chosen to create three sets of structure types for the found major structural parts. The categorization of these structure types per Module can be found in Table 6.3 and the list of chosen structure types for the whole test case ship analysis can be found in Appendix J.1. Next to the categorized structure types per module, some general structure types are defined, such as the shell, bulbous shell, walls and frames in the double bottom. The transit structure type is a negative value that corrects the steel weight of deck plate. This structure type is created for the decks only where transits are found per Module.

Table 6.3: Categorized Structure types per Module

Structure Type	Unit
Frame	[mm]
Girder	[mm]
Tanktop	[mm]
Tween Deck	[mm]
Main Deck	[mm]
Coaming Deck	[mm]
Bottom Shell	[mm]
Transit	[mm]

Deck Weight Correction Factor To add the primary stiffener's weight to the Blocks which contain steel plates of the structure type of any of the decks, the primary transverse stiffeners have to be taken into account. The longitudinal primary stiffeners, girders, are in this test case ship already part of the steel structure system. Figure 6.5 shows an example of the deck between frame 110 and 120 of the main deck, which consist of a consistent deck plate thickness as can be seen in Figure 6.4. Therefore this length of example deck is assumed to be representative for all the decks over the whole length. The arrows point at the transverse primary stiffeners that need to be taken into account in the weight calculation by the deck weight correction factor.

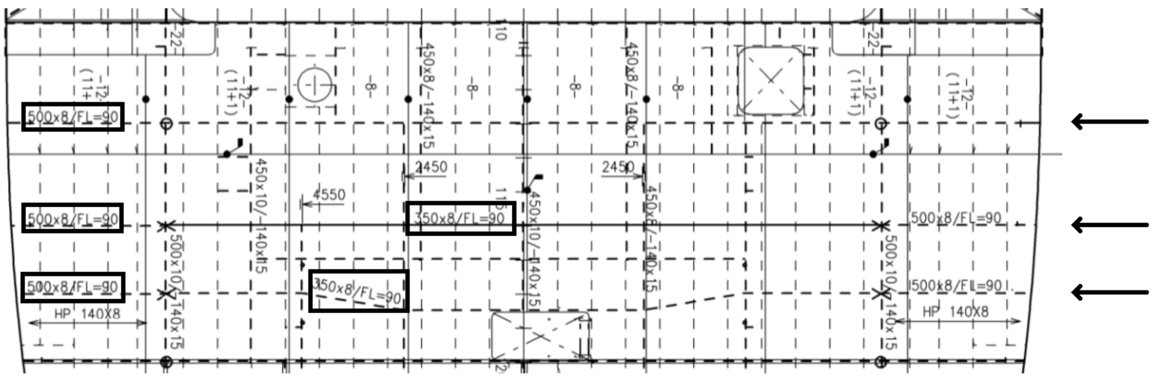


Figure 6.5: Transverse primary stiffeners on deck, indicated with arrows

The following Equations 6.1 up until 6.3 present the calculation of the deck's weight correction factor($f_{w_{deck}}$), where $L_{110-120}$ is the distance between the 110^{th} and the 120^{th} frame, B is the breadth of the ship, d_{steel} the density of steel[10], t the plate thicknesses and $_{deck}$ and $w_{transverse}$ the weights of respectively the deck and the transverse stiffeners present as shown in Figure 6.5. When these calculations are made, the resulting deck's weight correction factor is equal to 1.18 [-]. This factor is used in the test case to correct the weight of each plate with the characteristic of deck structure type for the primary transverse stiffeners.

$$f_{w_{deck}} = \frac{w_{tot_{transverse}}}{w_{deck}} + 1 \tag{6.1}$$

$$w_{deck} = t_{deck} * L_{110-120} * B * d_{steel} \tag{6.2}$$

$$w_{transverse_1} = L_{transverse_1} * t_{transverse_1} * h_{transverse_1} * d_{steel} \tag{6.3}$$

Bulkhead Weight Correction Factor Bulkheads are the main frames of the ship and therefore include many primary vertical stiffeners and secondary stiffeners in vertical and horizontal direction. The primary vertical stiffeners have different sizes over the depth of the bulkhead, due to be able to withstand the great bending moments. This progression in size of primary stiffeners is simplified by the bulkhead weight correction factor ($f_{w_{bulkhead}}$) as a single addition in calculated weight equally for all the positions of the bulkhead. The bulkhead weight correction factor is calculated by the following Equations 6.4 up until 6.6 which calculate the situation shown in Figure 6.6. Where h_1 is the height from the bottom until the main deck, h_2 is the height from the bottom up until the coaming deck, $B_{coaming}$ is the breadth of the coaming and V_1, v_2 and V_3 are the volumes (thickness times length times width) of the primary vertical stiffeners as marked in Figure 6.6. This Figure shows an watertight bulkhead and therefore without transits. Because of this, the plate area is easily calculated and no extra stiffeners are found to create sufficient strength to allow for the transits. This results in a bulkhead that is suitable for an easy calculation of the primary vertical stiffeners weight correction factor that can be projected on every square meter of bulkhead present in the test case ship. The resulting bulkhead weight correction factor is equal to 1.25 [-] and will be used in the test case ship's Block division to correct for the vertical primary stiffeners of all bulkhead plates. Next to the correction factor, also the bulkhead at frame 142 of the test case ship is categorized as a thicker frame due to impact Resistance demands at this location in the ship.

$$f_{w_{bulkhead}} = \frac{w_{tot_{primary}}}{w_{bulkhead}} + 1 \tag{6.4}$$

$$w_{bulkhead} = t_{bulkhead} * h_1 * B * d_{steel} + t_{bulkhead} * h_2 * B * d_{steel} \tag{6.5}$$

$$w_{tot_{primary}} = (V_1 + V_2 + V_3) * d_{steel} \tag{6.6}$$

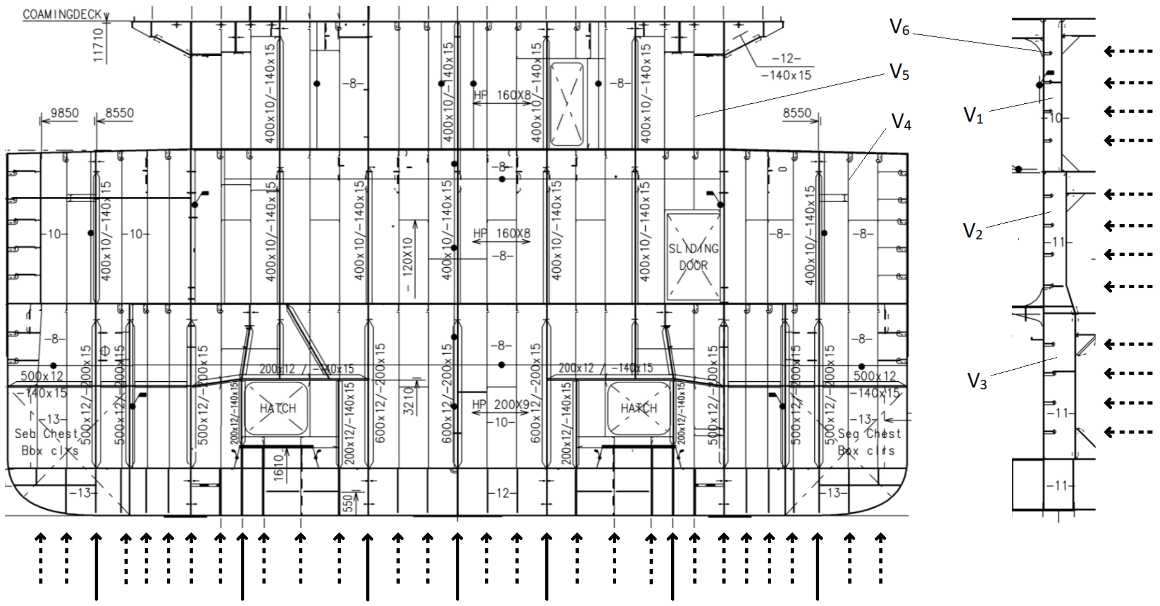


Figure 6.6: Vertical primary stiffeners (line arrows) on bulkhead and secondary stiffeners (dotted arrow)

Secondary Stiffeners Weight Correction Factor Next to the weight corrections for the primary stiffeners, also for the added weight of secondary stiffeners must be corrected. Because the bulkhead example from Figure 6.6 is a whole plate with an average plate thickness of around 9 [mm], which is comparable to the average plate thickness of most of the decks as shown in Figure 6.4, the secondary weight correction factor ($f_{w_{secondary}}$) can be deducted from this bulkhead frame. In this Figure V_4, V_5 and V_6 are the volumes of the vertical secondary stiffeners from the bottom up to the main deck, the vertical stiffeners from the bottom up to the coaming deck and the transverse stiffeners over the breadth of the bulkhead respectively. Equation 6.7 up until 6.9 show the steps to calculate the secondary stiffener weight correction factor. The resulting secondary weight correction factor is 1.30 [-] and will be used in the test case ship's Block division to correct for the horizontal and vertical secondary primary stiffeners of all plates. This correction factor is also in the same range as was suggested by the interview with Royal IHC as can be found in Appendix G.2.

$$f_{w_{secondary}} = \frac{w_{tot_{secondary}}}{w_{bulkhead}} + 1 \tag{6.7}$$

$$w_{bulkhead} = t_{bulkhead} * h_1 * B * d_{steel} + t_{bulkhead} * h_2 * B * d_{steel} \tag{6.8}$$

$$w_{tot_{secondary}} = (V_4 + V_5 + V_6) * d_{steel} \tag{6.9}$$

6.1.3. Applied Design Variables

For the chosen Design Variables for recreating the Block division plan as created by Royal IHC, the interviews with the engineers from Royal IHC are used as a reference point. The Maximum Block Length is based on material and the building beds of 12,000 [mm], with 100 [mm] to spare for shrinkage margins and seam placing margins. Next, the Equality Break represents maximization of to be chosen Blocks in case of equal Compartment splitting separability weights, for the aft-forward analyzing direction this means maximizing Blocks and for the fore-back words analyzing direction this means minimizing to be chosen Blocks. The value of the No Split Position is higher so that in no case will it will be lower than a sum of Compartments separability weights. Also the Bulkhead Preference is preferred over Compartments Separability weights. The Transit End preference is most preferred except if the Transit Mid preference is found, because the Transit Mid mechanism will also find the Transit End positions. This hierarchy of Design Variables represents the information found in the interviews in Appendices G.1, G.3 and G.2. Separability weight varies and can be found in Table 5.9, also based on the described situation at Royal IHC by the engineers.

Table 6.4: Verification Transverse seam placing Design Variables

Design Variable	Value	Unit
Maximum Block Length ($L_{B_{max}}$)	11,900	[mm]
Equality Break	-1	[-]
No Split Position	900	[-]
Bulkhead Preference	-100	[-]
Transit End Preference	-200	[-]
Transit Mid Preference	-300	[-]
Separability Weight	Table 5.8	[-]

The same goes for the Split Boundary, which is set be equal to two watertank separability weights. The Max Breadth is the maximum found breadth size of Blocks in the test case Block division, as another example from Royal IHC. The Default Center Line Side is chosen to recreate the Block division, but no other arguments are found. Also, as mentioned in Sub Section 3.2.3 this can still change over time as the detailed structural design is worked out further. The Minimum Block Length is equal to 11 frames, as this is the minimum size a resulting Block will be. This still is longer than the resulting minimum Block size developed by the Optional Seam Placing mechanism. In case the mechanism creates minimum Block sizes of 8,400 [mm], or 12 frames long, these Blocks will hardly be able to be grouped due to the Maximum Block Length constraint while grouping. For this reason the Minimum Block Length is set as half the Maximum Block Length and is equal to 6,300 [mm] or 9 frames. Regarding the Default Center Line Side variable, the model picks starboard as default side for the seam to be placed in longitudinal direction at the center line. The reason for this is that in the early design phase detailed information about stiffeners on longitudinal girders is not yet know.

Table 6.5: Verification Longitudinal seam placing Design Variables

Design Variable	Value	Unit
Split Boundary	22	[-]
Max Breadth	15,400	[mm]
Default Center Line Side	75	[mm]
Minimum Block Length ($L_{B_{min}}$)	6,300	[mm]

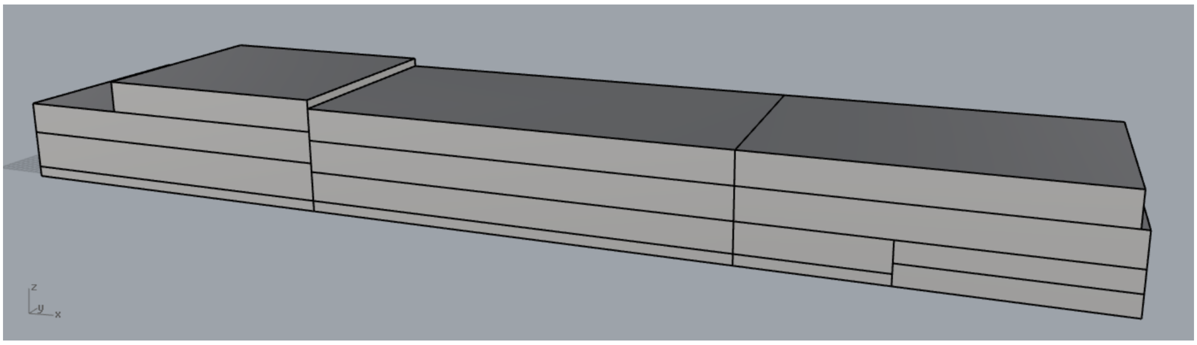


Figure 6.7: Verification results of the Placeholder Blocks for the hull of the test case ship

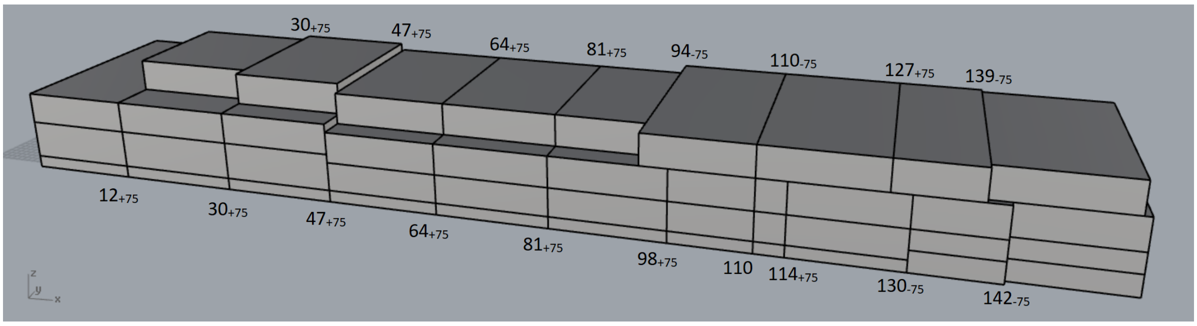


Figure 6.8: Verification results of the transverse seam placing for the hull of the test case ship

6.1.4. Block Division Reproduction Test Case Ship 1

The before mentioned applied Design Variables result in a Block division which is elaborated upon in this Sub Section. Next to an overview of the resulting Block division the deviations from the original Block division plan as developed by Royal IHC are discussed.

Placeholder Blocks Figure 6.7 shows the generated resulting Placeholder Blocks. As at Royal IHC the model starts by analyzing the ship in Modules. For each Module separate Placeholder Blocks are created per deck, where deck heights change the Placeholder Block stops and a new Placeholder Block is created.

Transverse Seams Figure 6.8 shows the chosen transverse seams by the BDG. Because this assessment is before the Grouping operations, some seams are preliminary and will disappear after some Blocks are grouped. Next to the transverse seam placing also the Placeholder Blocks are scaled to fit the steel structure in a Placeholder Block. Table 6.6 describes the arguments of the final chosen seams decision by the BDG. Appendix E shows all created and considered Optional Seam Position strings that support the results of the Table below. The final column of Table 6.6 "deviation" states whether the seam of the model is equal to the chosen seam of provided Block division plan. All deviations are discussed below. Table 6.6 only elaborated on the chosen seams, all seams below deck are equal to the chosen seams on the bottom deck as elaborated upon in Sub Section 3.3.1.

Seam numbers 4 up to 6 are chosen 700 [mm] from the original seam position, this is due to the fact that there are hardly any leads regarding definite positions of the final seam, the model divides the whole mid Module Placeholder Block in as comparable as possible Blocks, the actual Block division is less constant but the result is not materially different. Seam number 8 is at the same position for the center block, but the actual Block division places the outer seams 150 [mm] backwards. The model does not allow different transverse seam positions over the breadth of the ship. For the coaming deck again several chosen seams are different from the original Block division, the same argument of the limitation of leads goes for these Blocks as for the lower decks. Finally seam number 18 is off one frame, the model chooses to minimize the to be chosen Block as Equality Break for equal separability weights, where the original Block division picks the seam one frame extra towards the stern of the ship for no addressable reason.

Table 6.6: Final chosen Optional Seam Placing arguments

#	Decks	Seam positions	Decisive Argument	Deviation	Unit
1	Bottom-main	12_{+75}	Bulkhead	0	[mm]
2	Bottom-main	30_{+75}	Mid Transit max	0	[mm]
3	Bottom-main	47_{+75}	Placeholder Block / Bulkhead	0	[mm]
4	Bottom-main	64_{+75}	Compartments Equality Break Comparable	+700	[mm]
5	Bottom-main	81_{+75}	Compartments Equality Break Comparable	+700	[mm]
6	Bottom-main	98_{+75}	Compartments Equality Break Comparable	+700	[mm]
7	Bottom-main	110	Preliminary Placeholder Block seam	-	[-]
8	Bottom-main	114_{+75}	End Transit	150	[mm]
9	Bottom-main	130_{-75}	Bulkhead	0	[mm]
10	Bottom-main	142_{-75}	Minimum Compartments Split	0	[mm]
11	main-coaming	30_{+75}	Compartments Equality Break max	0	[mm]
12	main-coaming	47_{+75}	Placeholder Block / Bulkhead	0	[mm]
13	main-coaming	64_{+75}	Compartments Equality Break Comparable	-275	[mm]
14	main-coaming	81_{+75}	Compartments Equality Break Comparable	+2,525	[mm]
15	main-coaming	94_{-75}	Equality Break max	+275	[mm]
16	main-coaming	110_{-75}	Placeholder Block / Bulkhead	0	[mm]
17	main-coaming	127_{-75}	Equality Break max	+700	[mm]
18	main-coaming	139_{-75}	End Transit	0	[mm]

Longitudinal Seams Figure 6.9 shows an exploded view per deck of the longitudinal placed seam positions. In Appendix K is added which analyzes all Blocks indicated in this Figure for the longitudinal split that the BDG created. All the created longitudinal seams represent the same created Blocks as the original Block division plan. Because the main driver for longitudinal splitting in more than two Blocks is equipment with an positive z Erection Direction, the characteristics given to the equipment plays a crucial roll in the resulting Block division. The chosen characteristics are based on the multiple interviews with experienced engineers at Royal IHC, found in Appendix A.

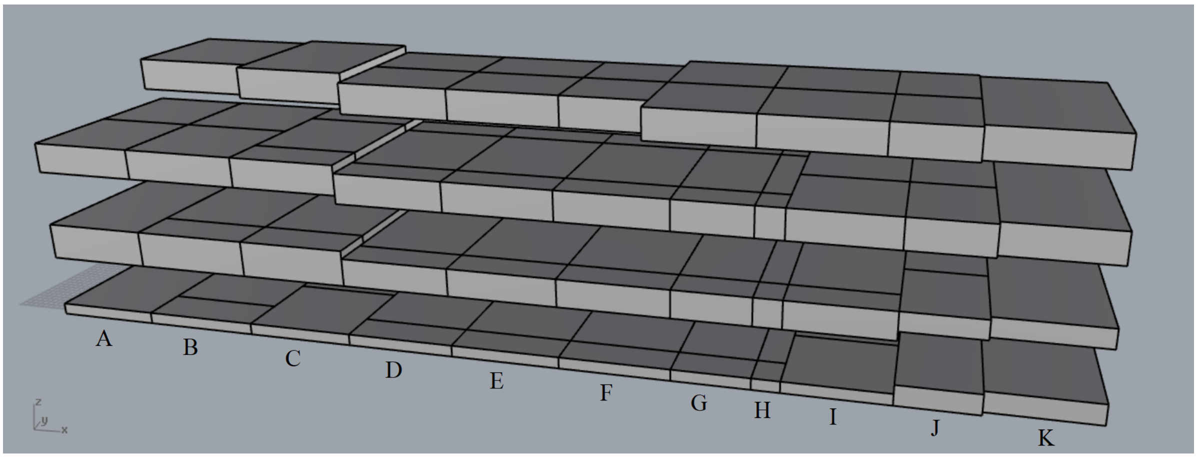
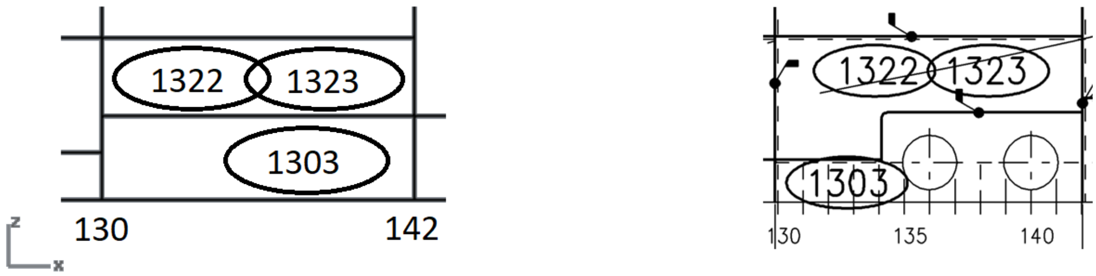


Figure 6.9: Verification results of the longitudinal seam placing for the hull of the test case ship per deck

Weight Calculations The results of the weight of all resulting Blocks can be bound in Appendix **??**. This weight per Block is calculated as described in Sub Section 5.3.7 with the Input Parameters as calculated in Sub Section 6.1.2. A deviation of 10% from the original Block division actual weights is considered reasonable per Block, because the weight calculation is only a way of generating a complete input for the erection sequence generator. Table 6.7 shows a summary of all the Blocks of which the weight has a deviation of more than 10%. All deviations are discussed below. In column "Name" of Table 6.7 the names of the reference Blocks from the original Block division are added for comparison, also in the Tables of Appendix **??**. Block

Table 6.7: Deviations of weight calculation results of verification Blocks

#	x_1	y_1	z_1	x_2	y_2	z_2	w_b	Name	w_0	Deviation
1	90925	-10725	-75	99325	10725	2175	75.80	1303	66	15 %
2	90925	75	2175	99325	10725	4275	10.53	1323	14	-25 %
3	90925	-10725	2175	99325	75	4275	10.60	1322	15	-29 %
4	8475	-5925	1195	21075	5925	5175	16.21	1251	12	35 %
5	21075	-10725	1195	32975	-5925	8475	47.33	1220	41	15 %
6	56775	-6696	1195	68675	6696	7575	15.21	1412	22	-31 %
7	68675	-6696	1195	76925	6696	7575	7.96	1413	7	14 %
8	56775	-8075	7575	65875	75	10875	21.83	1444	33	-34 %
9	56775	75	7575	65875	8075	10875	21.83	1445	35	-38 %
10	65875	-10725	7575	76925	75	10875	47.09	1446	38	24 %
11	65875	75	7575	76925	10725	10875	46.82	1447	38	23 %



(a) Block Division Generator

(b) Actual Block Division

Figure 6.10: Side view of simplified seam by BDG that results in different resulting weight of Blocks

1303 is 15% too heavy and Blocks 1322 and 1323 are 29% and 25% too light, compared to the original Block division. This can be explained by the chosen simplified seam by the BDG, as shown in Figure 6.10a compared to the original seam in Figure 6.10b. However, the total weight of these three Blocks calculated by the BDG only deviates 2% compared to the three original Block weights. Therefore it can be concluded that the different seam position results in the high deviation of the calculated weights. Block 1251 has the highest relative deviation, although the absolute weight of the Block is rather low. This deviation is also the result of a different chosen seam position. The port side and starboard center reference lines are chosen directly above these reference lines at the bottom deck. In the actual Block division Block 1222 and 1223 are not rectangular, so the change of reference line position is a way to simplify this with the deviation as a result.

Also Block 1220 (and 1221) are heavier than the original Block division, because the Tube Inlet including some steel structure are not automatically generated, as elaborated upon in Sub Section 4.1.4. The same goes for Block 1221 although the weight of this Blocks remains within 10% deviation from the original Block.

The Blocks 1412 and 1413 in the mid ship Module are chosen a little different from the original Block division by the BDG, as shown in Table 6.6. Therefore the hopper floor Blocks deviate in weight (m). Table 6.8 shows how this is only a deviation on the individual Block level rather than the whole mid ship Module. This deviation as a result of different chosen seams in the mid ship Module also goes for the Blocks at coaming deck, 1444, 1445, 1446 and 1447. Table 6.9 shows how this is again a deviation of the weight of the individual Block rather than the whole coaming for example. Therefore this can be directly related to the difference in seam placing. And as the total weight of the BDG calculation equal 2628 tonnes and the original actual measured weight by Royal IHC of the developed Block division plan equals 2647 for the Blocks in scope of the model. These results only deviate 0.72% from the original measured weight and therefore it is safe to say that the weight calculation is accurate enough to use also for other Block division solutions of the BDG and that the Correction Factors chosen in Sub Section 6.1.3 are valid.

Table 6.8: Compare hopper floor Blocks calculated by BDG to actual Block weights

Block name	m_{BDG}	m_{actual}	Deviation
1410	15.21	14	9%
1411	15.21	14	9%
1412	15.21	22	-31%
1413	7.96	7	14%
Total	53.59	57	6%

Table 6.9: Compare coaming Blocks calculated by BDG to actual Block weights

Block name	m_{BDG}	m_{actual}	Deviation
1444	21.38	33	-34%
1445	21.38	35	-38%
1446	47.09	38	24%
1447	46.82	38	23%
Total	136.67	144	5%

Resulting Block division The grouping mechanisms as described in Sub Section 5.3.8 creates a final Block division consistent with the original Block division. Appendix B shows the top view of the final resulting Blocks, including the Placeholder Blocks after transverse seam placing, longitudinal seam placing and grouping. Figure 6.11 shows the final Block division as created by the BDG for the hull of test case ship 1, consisting of 61 Blocks. Note that the grouping operations create cross Module Blocks between the mid and fore ship Module.

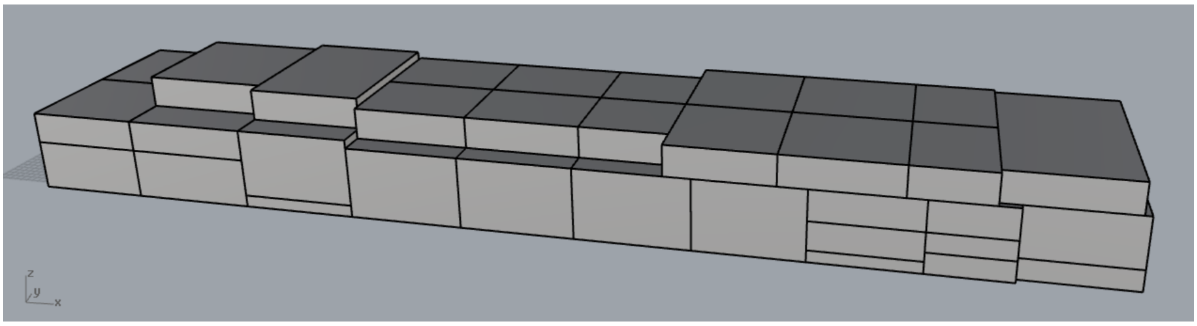


Figure 6.11: Final results of the verification of the BDG for the hull of the test case ship

Due to the simplifications of not taking into account special Blocks, some deviations compared to the manually created Block division is found. The castings of the suction tube inlet manifolds are not isolated and included in separate Blocks. Originally, these are integrated in block 1220 and 1221 in the manually created Block division plan. Since the simplification is made to generate only rectangular Blocks, it is not possible to generate such separate yet integrated Block.

6.1.5. Block Division Reproduction Fore Module Test Case Ship 2

Next to reproducing the Block division of Test Case Ship 1, the fore ship Module of another trailing suction hopper dredger built at Royal IHC is ran through the BDG. The previous described verification results of the BDG are a solution of the ship the BDG was based on. To be able to create a broader understanding of the functionality of the implemented Block division mechanisms it should be used on another test case ship. Only the fore ship Module was chosen because in this part of a dredger generally many different arguments are found that are considered by the BDG. Also, the input information has to be created manually from the 2D GA. The GA of Test Case Ship 2 can be found in Appendix H.3. Test Case Ship 2 was also built at Royal IHC in Kinderdijk. The same Block division approach and Design Variables as used for the reproduction of the Block division of Test Case Ship 1 should apply.

Data Set Test Case Ship 2 As mentioned in Sub Section 5.2.3 the deck height is simplified. The hull structural system of the fore ship Module is not created to the extend as shown for Test Case Ship 1, because of the labour intensive process of doing so. Also, the added value of doing this is to be able to calculate the weight per resulting Block after seam placing to be able to decide which Blocks can or can not be grouped due to the facility constraints. A manual assessment of the potential Grouping actions will be made at the end of this Sub Section. This can be done because the expected results of the Grouping logic can easily be recreated by analyzing the resulting Blocks and consulting with the systematic approach, as elaborated upon in Sub Section 5.3.8. Figure 6.12(1) shows the minimum amount of defined structural system the BDG requires to be able to create a Block division solution. Figure 6.12(2) shows the defined Compartments are shown and Figure 6.12(3) the two found pieced of equipment, where (a) represents a bow pump and (b) represents the bow thruster. The created and used input data of for the BDG can be found in Appendix J..

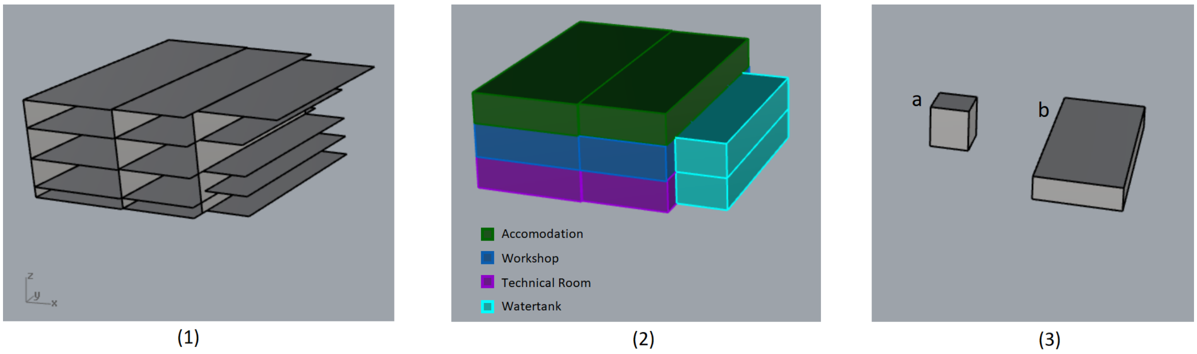


Figure 6.12: (1) Defined decks and bulkheads (2) Compartments and (3) Equipment of test case ship 2

Resulting Block division Solution Test Case Ship 2 Figure 6.13(1) shows the initial created Placeholder Blocks. Figure 6.13(2) shows the two created transverse seams, these are also discussed in Table 6.10. It is shown that the final transverse seams as found by the BDG are equal to the original Block division transverse seams. The original Block division solution for the fore ship Module of Test Case Ship 2 can be found in Appendix **??**. Whether the bow pump results in a closing deck Block can be a subjective decision by the Block division engineer. In the case of Test Ship 2 the bow pump does not require a closing deck because it is easily fit trough the broad transit in the deck. Where in Test Case Ship 1 this is not the case. However, this decision is hard to reproduce using a mathematical model because it can also depend on the type of equipment, the weight and size of the transit compared to the size of the equipment. This results in the longitudinal seams at position *A* of the tween deck to be split at the CL position, as shown in Figure 6.13(3).

Table 6.10: Final chosen Optional Seam Placing arguments

#	Decks	Seam positions	Decisive Argument	Deviation	Unit
1	Bottom-main	119_{-75}	Bulkhead	0	[mm]
2	Bottom-main	131_{-75}	Bulkhead	0	[mm]
3	main-coaming	119_{-75}	Bulkhead	0	[mm]
4	main-coaming	131_{-75}	Bulkhead	0	[mm]

Figure 6.13(4) shows the final Block division solution by the BDG, without having run the grouping logic due to the absence of a proper weight calculation. The Grouping logic will not reproduce the original Block division solution. The reason for this is the approach of the BDG to only attempt to group Blocks above the double bottom, and not include the double bottom in this consideration. The BDG's Grouping logic can easily be tailored to reproduce the exact original Block division solution.

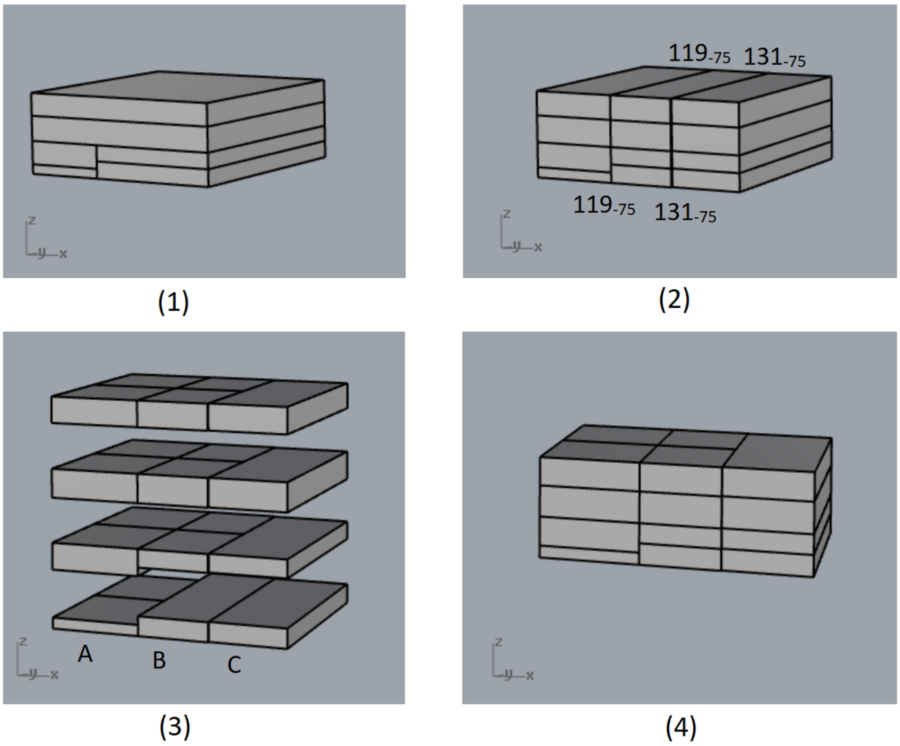


Figure 6.13: (1) Placeholder Blocks (2) Transverse and (3) longitudinal and the (4) resulting Block division of test case ship 2

6.1.6. Limitations

The developed model is not required to incorporate an exact reality of changing shipyard conditions because initially only the effectiveness of different Block division solutions is to be researched. Therefore simplifications were made that result in limitations of the applicability beyond the scope it was developed for. These limitations are listed below.

- Ships with a significant higher breadth, to the point where Blocks that after all splitting operations still are not feasible by the crane capacity constraint
- Seams can not change between perpendiculars of other seams because only rectangular resulting Blocks are created
- Blocks can only be rectangular, also the Grouping logic does not allow for multiple rectangular Blocks to create a resulting non-rectangular Block
- The Equality Break Design Variable can only be assigned for the whole ship and can not vary per analyzed Module
- In the case of equal Separability weights the BDG will minimize or maximize the to be created Block. The Placeholder Block can be split in such a way that the resulting Block has dimensions smaller than the Minimum Block Length. This is not a redundant mechanism, since it can result in a very small Block at the other end while by no hard constraint this split position was chosen.
- Only the frames within range of the Optional Seam Position will be considered to determine the Final Seam Position
- The model can not make exceptions in case of for example Blocks being heavier than the maximum crane capacity, the feasibility constraints are hard constraints while actually these can be overruled
- Because only the hull is taken into account resulting Blocks will never be too high for the door sizes at Royal IHC but no constraint is incorporated that can limit this size
- Every frame position can only be analyzed by one argument. Figure 5.4 shows the order of checking for seam placing arguments. When one of these arguments is found, the corresponding Design Variable will be inserted in the Optional Seam Position string. In case an argument is ruled out, for example the preferred seam position at Bulkheads, this Optional Seam Position where a bulkhead is found can not be considered regarding Compartment Separability weight because the position is already filled with a Design Variable that excludes this position from consideration

6.2. Multiple Solutions

Next to the reproduction of the existing Block division of Test Case Ship 1, referred to as Case 0, other Design Variable sets for the same ship are defined as appropriate test cases for which Block divisions are generated.

6.2.1. Design Variable Sets

The test cases of varying Design Variable sets can be categorized in three cases. Next to looking into the possible effects of different Design Variables on the Block division and resulting erection planning, these test cases are used to validate the efficiency of the model in Section 6.4. The chosen Design Variables sets are summarized below, referred to as Case 0, Case 1a-1g and Case 2.

- **Case 0 -** Verification by reproducing existing Block division solution by Royal IHC
- **Case 1a -** Equality Break creating minimum size Blocks in case of equal Separability Weight
- **Case 1b -** No preference for Bulkheads compared to other arguments
- **Case 1c -** No preference for transits, either split at mid or end
- **Case 1d -** Separability Weight hierarchy in reverse order compared to Case 0
- **Case 1e -** Never split longitudinally in symmetrical Blocks, prevented by Split Boundary
- **Case 1f -** Always split longitudinally in symmetrical Blocks
- **Case 1g -** Place symmetrical longitudinal seam on other side of center line compared to Case 0
- **Case 2 -** Attempt to model the Block division approach of DAMEN Schelde Naval by trying to create Mega-Ring-Blocks

Table 6.11: Sets of Transverse and Longitudinal seam placing Design Variables

Design Variables	Case 1a	Case 1b	Case 1c	Case 1d	Case 1e	Case 1f	Case 1g	Case 2	Unit
Maximum Block Length	11,900	11,900	11,900	11,900	11,900	11,900	11,900	9,100	[mm]
Equality Break	1	-1	-1	-1	-1	-1	-1	-1	[-]
No Split Position	900	900	900	900	900	900	900	900	[-]
Bulkhead Preference	-100	100	-100	-100	-100	-100	-100	-100	[-]
Transit End Preference	-200	-200	900	-200	-200	-200	-200	900	[-]
Transit Mid Preference	-300	-300	900	-300	-300	-300	-300	900	[-]
Separability Weight	Table 5.8	Table 5.8	Table 5.8	Reverse	Table 5.8	Table 5.8	Table 5.8	Table 5.8	[-]
Split Boundary	22	22	22	22	0	900	22	100	[-]
Max Breadth	15,400	15,400	15,400	15,400	15,400	15,400	15,400	15,000	[-]
Default CL Side	75	75	75	75	75	75	-75	75	[-]
Minimum Block Length	6,300	6,300	6,300	6,300	6,300	6,300	6,300	3,500	[-]

The before mentioned Design Variable sets are only those representing the Block division approach. However, there are also characteristics of the input data that may vary per shipyard because of different production techniques or Block division approaches. Mainly the conditions indicating Integrated Equipment and Erection Directions of long lead time equipment influence the Block division solution. Because only one Block division approach at IHC is taken into account, these input characteristics are not varied or changed to create different Block division solutions.

6.2.2. Block Division Solutions

All sets of Design Variables are run to see if the results differ from the manually created Block division and verification Case as presented in Sub Section 6.1.4. The average run time of the Erection Sequence Scheduler is 1:40 minutes. The average runtime of the BDG was less than 10 seconds. All test case runs are executed using the software mentioned in Section 5.4, on a Dell XPS13 computer, with Intel Core i7-5500U dual-core CPU (Broadwell) @ 2.4 GHz (boosted 2.9GHz), and 8GB RAM. The operating system is Windows 10 x64. This computer is also used as the database server using pgAdmin 4. All Design Variable sets resulted in feasible solutions, the weight constraint is never surpassed. Below the different results of the cases as shown in Table 6.11 are discussed.

Case 1a Case 1a differs from the verification Case 0 by a reversed Equality Break Variable. In this case the BDG prefers to minimize the length Blocks in case there are multiple equal separability weights found. The BDG creates a Block division solution consisting of 69 Blocks. Figure 6.14 shows this solutions. The different transverse seam position compared to the verification case are indicated in the figure by mentioning the frame number and seam deviation next to the frame number. The model creates extra and smaller Blocks due to the preferred minimization of Block length.

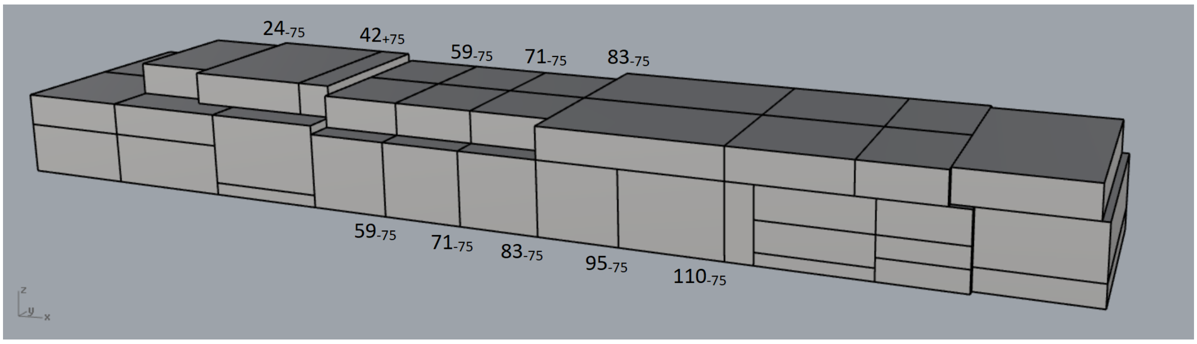


Figure 6.14: Final results of Case 1a of the BDG for the hull of Test Case Ship 1

Case 1b Figure 6.15 shows the resulting Block division solution of the Design Variable set of Case 1b. Compared to the verification Case 0 there is no preference for seams at bulkhead positions, as indicated by the Bulkhead Preference Design Variable. As can be seen in the Figure in the aft ship Module two transverse seams are chosen differently. This results in the aft Blocks to be longer and thus heavier, eliminating the grouping possibility due to the weight constraint that limits this operation. The Block that is not grouped in Case 1b but is in Case 0 is indicated with yellow. Because the lack of this single grouping operation this Block division solution counts a total of 62 Blocks, one in excess of the verification Case 0.

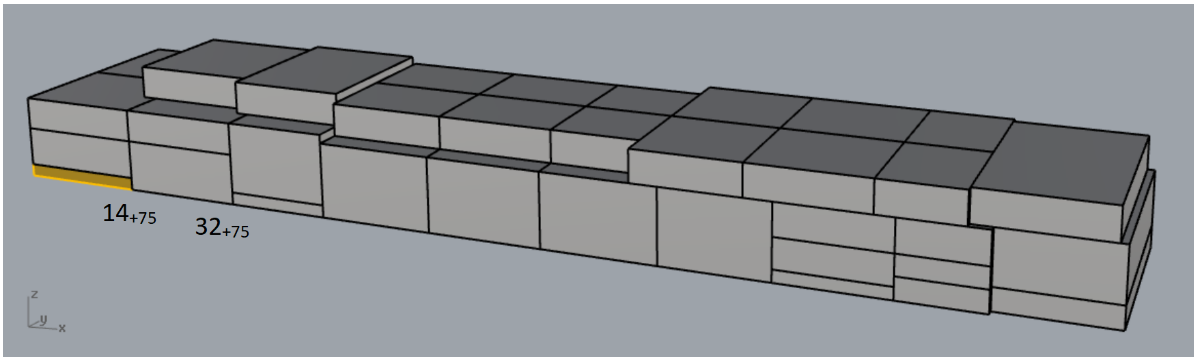


Figure 6.15: Final results of Case 1b of the BDG for the hull of Test Case Ship 1

Case 1c The Design Variable set of Case 1c eliminates the preference of transverse seams being placed at the location at the end or in the middle of a transit. In the fore ship Module this results in four seams to change position compared to the verification Case 0. The original seams thus were placed based on the found transit arguments. The Block division solution of Case 1c results in 64 Blocks. Figure 6.16 shows the resulting Block division solution, including the mentioned different transverse seam positions.

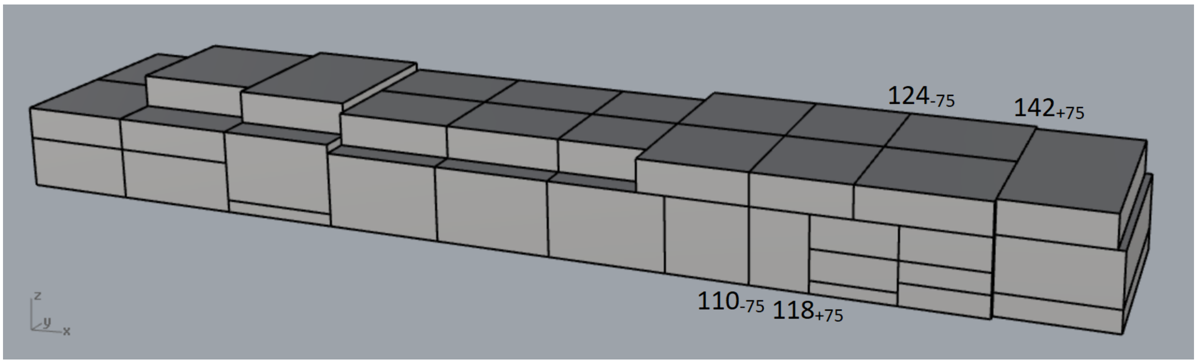


Figure 6.16: Final results of Case 1c of the BDG for the hull of Test Case Ship 1

Case 1d The next alteration of the set of Design Variables is to reverse the separability weight hierarchy of the Compartments types. This results in the Block division shown in Figure 6.17 and is referred to Case 1d. No different transverse seams are the result of this alteration compared to the verification Case 0. However, because the hierarchy weight of the Compartments differs but no different Compartments are found and the Split Boundary remains the same, the red Blocks in Figure 6.17 are not split longitudinally. The total amount of Blocks therefore is also reduced to a total of 55 Blocks.

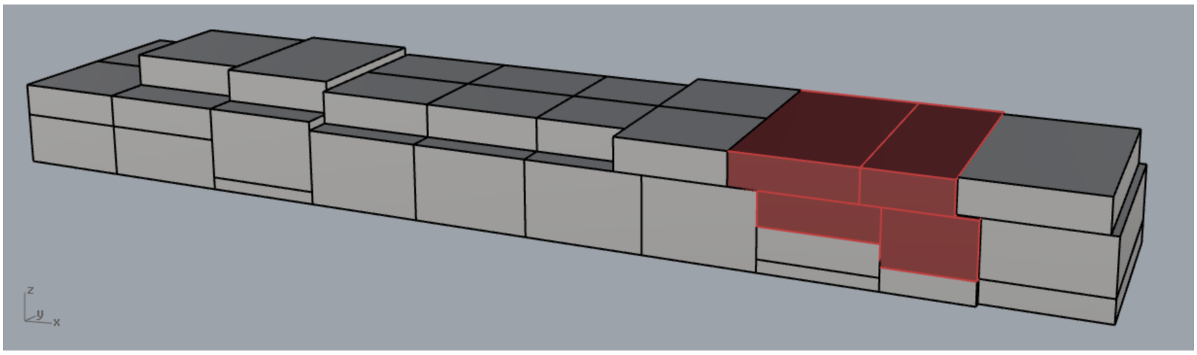


Figure 6.17: Final results of Case 1d of the BDG for the hull of Test Case Ship 1

Case 1e In the Design Variable set of Case 1e the separability hierarchy of Compartments is restored to the original hierarchy of verification Case 0 but the Split Boundary is set to zero. This means that no longitudinal split will be made unless the found Compartments at the center line are less than zero. No Compartment's separability weight can be zero so no longitudinal splits are made. All affected Blocks are indicated in red in Figure 6.18. Case 1e results in a Block division solution consisting of 47 Blocks.

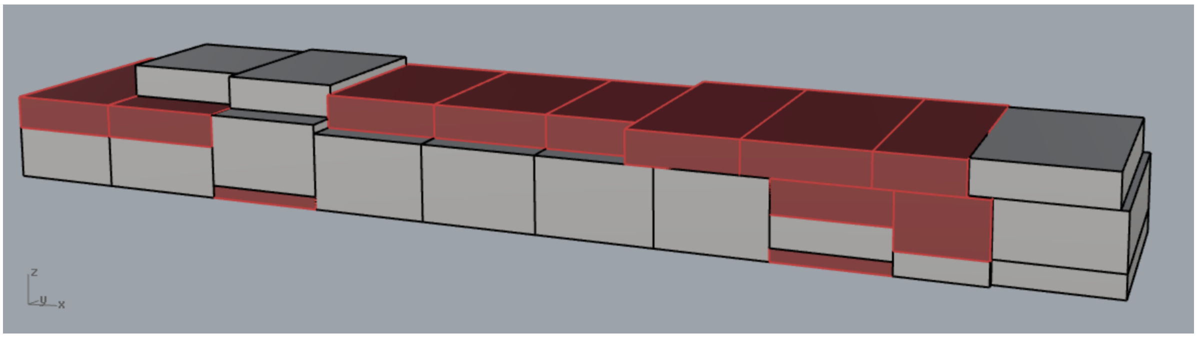


Figure 6.18: Final results of Case 1e of the BDG for the hull of Test Case Ship 1

Case 1f Case 1f reverts the Design Variable choice of Case 1e by making the Split Boundary Design Variable equal to 100. This results in no longitudinal splits being made unless the sum of the Compartments type hierarchy beside the center line is higher than 100. Figure 6.19 shows the affected Blocks. Only in the fore ship Module one longitudinal seam is chosen different from the verification Case 0, an extra seam is placed. The resulting Block division of the Design Variable set of Case 1f creates 62 Blocks.

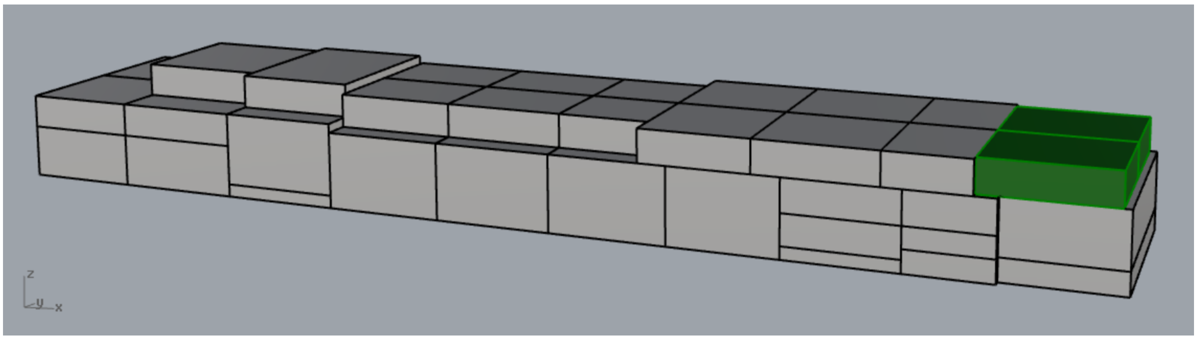


Figure 6.19: Final results of Case 1f of the BDG for the hull of Test Case Ship 1

Case 1g The change in the Design Variable set of Case 1g is the Default Center Line Position. Instead of the longitudinal seam over the center line being placed 75mm off the center line on the port side of the ship this is switched to 75mm off the center line on the starboard side of the ship. All green Blocks in Figure 6.20 are affected by this change of Design Variable, all Blocks that are split longitudinally on the center line in the verification Case 0. The resulting Block division solutions is visually very similar to verification Case 0 and also counts 61 Blocks.

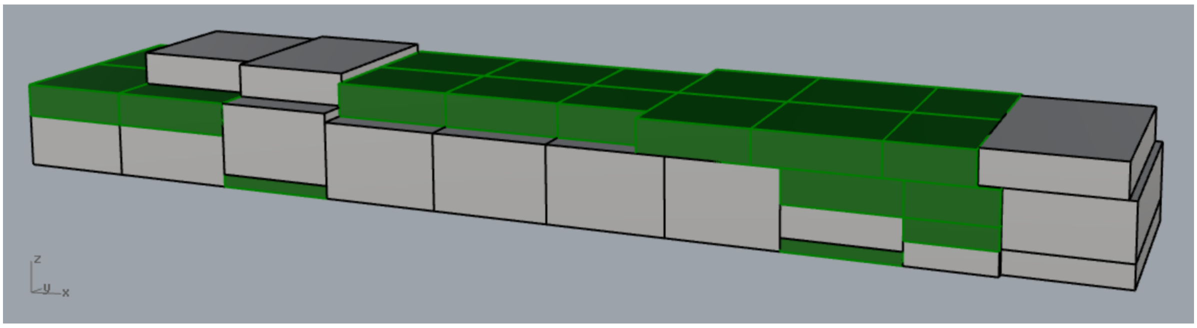


Figure 6.20: Final results of Case 1g of the BDG for the hull of Test Case Ship 1

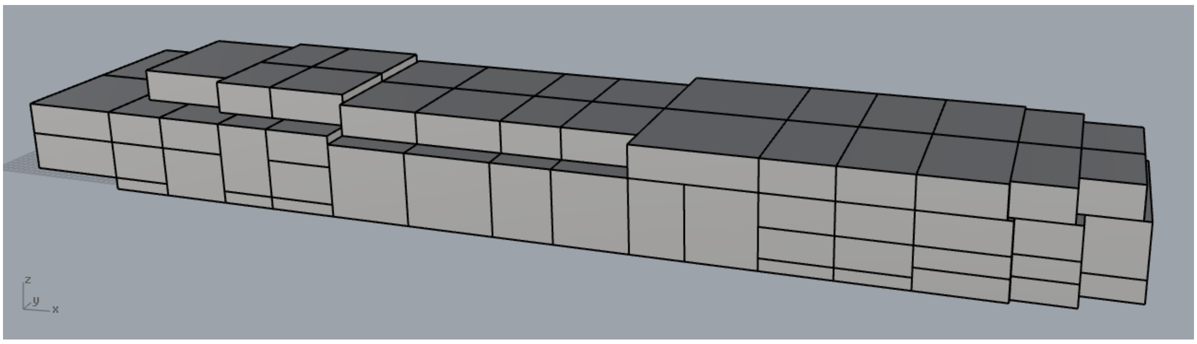


Figure 6.21: Final results of Case 2 of the BDG for the hull of Test Case Ship 1

Case 2 The final set of created Design Variables is referred to as Case 2, because this is not a simple alteration to the verification Case 0 Design Variable set. The Design Variable set of Case 2 attempts to recreate a Ring-Mega-Block erection strategy and thus supporting Block division approach. As can be seen in Figure 6.21 most transverse seams are aligned on top of each other allowing Ring-Mega-Blocks to be assembled prior to erecting the Mega-Block on the slipway. The amount of Blocks increases significantly compared to the verification Case 0. The Block division solution of Case 2 results in 101 individual Blocks.

Different Block division results test case ship 2 For the fore ship Module of test case ship 2 it was also attempted to create different Block division solutions. The same Design Variable sets as defined for Case 1a up to Case 1g are applied to Test Case Ship 2, these Design Variable sets can be found in Table 6.11. Figure 6.22 shows the results. It can be seen that for Design Variable set c, f and g different Block division solutions than the original Block division solution created manually are found. The manually created Block division solution for Test Case Ship 2 can be found in Appendix **??**. The red Blocks are not split longitudinally compared to the original solution and the green Blocks have different longitudinal splits. Case 2c is the only resulting Block division where different transverse seams where chosen, compared to the original Block division solution.

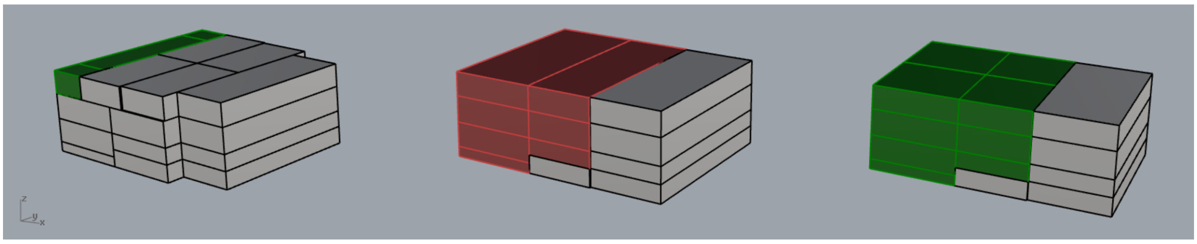


Figure 6.22: Block division solutions of the fore Module of Test Case Ship 2c, 2e and 2g

6.2.3. Input for the Erection Planning

Block Types, as elaborated upon in Sub Section 3.3.6, are not taken into account. All Blocks therefore are characterized as the same Block Type and only the man hours per ship Module differ. The default man hours per tonnes characteristics as defined by *Meijer*(2008)[16] are used. When an assessment is to be made to determine the absolute quality of a Block division solution regarding the possible erection plannings it is important to chose parameters in such a way they are representative for the actual situation. Since this research only is looking for different Block division solutions and if this impacts the erection planning, a set of constant parameters is all that is required to be able to compare the results. Note that in this case no attempt is made to recreate the actual situation at a shipyard but solely create erection schedules under the same conditions so they can be compared to each other.

Block names are generated per ship Module because per Module different lead times for Block building apply, as Table 6.12 shows. The reference numbers of *Meijer*(2008)[16] are used, where four digit Block names are defined. The Blocks present in the mid ship Module start with digits "11", the for ship Module Block names start with "12" and the aft ship Module Block names start with digits "13". Beside from these first two digits the Block names are appended randomly to the Blocks in the order of which the BDG generates them, which is generally per deck from aft to front. Also Case 0 is renumbered, because as mentioned the first two digits of the Block number represent a particular lead time of the Module of which the Block is part of. Because the superstructure and funnel Blocks are out of scope of the BDG, these are also not taken into account for the erection sequence and planning generation.

Because of the current strategy of Royal IHC to outsource all to be built Blocks, this is also the conditions used for the generation of the erection plannings for the test cases. This is also supporting to a simple test case for the Block division solutions in the optimization algorithm since no unnecessary constraints are taken into account such as used Floor space and planning of the panel lanes for steel pre-fabrication. The remaining objectives that can be assessed in this setting are throughput time for erection on the slipway, number of erected Blocks per week and the required personnel for mounting and welding the Blocks on the slipway.

The initial Block to be erected was chosen by iterating automated erection scheduling runs of the Erection Sequence Scheduler. Regardless of the initial Block designated as input, the model would have a preferred Block to start with. The date on which the slipway is available remains consistent for each planning run and case to have consistent working days, weekends and holidays. Table 6.12 shows an overview of all general input parameters that remain constant over all test cases and are required input for the erection sequence generator.

Table 6.12: Overview general input values Erection Sequence Generator

Input Parameter	Value	Unit
Mid Ship Module Lead time	9,00	[mh/ton]
Mid Ship Module Lead time	17,00	[mh/ton]
Mid Ship Module Lead time	10,00	[mh/ton]
Slipway Available	12/12/2011	[dd/mm/yyyy]
Work hours per day	16	[hrs]
Number of shifts per day	2	[#]
Max erection actions per day	4	[#]
Mid Ship Module Lead time	9,00	[mh/ton]
Breadth of test case ship	21,30	[m]
Frame spacing test case ship	700	[mm]

The final input files for Case 0, Case 1a up until 1g and Case 2 can be found in Appendix F. Note that the x position is in the unit of [Frames] and the y position is a factor of the total breadth of the ship. The indicated initial Block is shown on the first line of each Table of the input data set.

6.2.4. Table of Neighbours

To be able to create Block division solutions a table of neighbours must be created. As mentioned in Sub Section 4.2.3 the erection sequence schedule generator of *Meijer*(2008)[16] creates these individual erection constraints per Block automatically. Figure 6.23 shows an example of two Blocks, where each Block is described with the two created coordinates, as explained in Section 4.2.4. Because all Blocks are described using cubical blocks the erection constraints can be found fairly easy by using this six coordinate information structure.

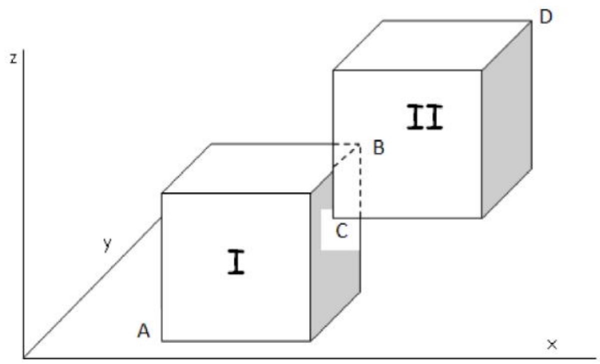


Figure 6.23: Example of two neighboring blocks [16]

Block I is defined by two three-dimensional points A and B, and Block II is defined by the three-dimensional points C and D. Each three-dimensional point consists of an x, y and z coordinate. The neighbour table for this example will show Block I and II to be neighbours, as the x coordinate of point B and C is equal to each other and the y and z coordinates of point B lie within the two y and z coordinates of Block I.

As mentioned, the erection sequence scheduler simplifies the set of actual erection constraints that influence the actual erection process at a shipyard. The following erection constraints are elaborated upon in Section 2.1.4. The constraints taken into account by the erection sequence scheduler are first of all what can be referred to as the "Vertical Feasibility Constraint". This constraint ensures that all Blocks geometrically directly below the following to be erected Block are already erected. The second constraint taken into account is the "No Placing Between Constraint", which is quantified by making sure all Blocks between the to be erected Block and the initial starting Block are all erected before. The third constraint equals the "Inside Out Constraint", which makes sure the ship is erected starting with a center Block before any side Blocks are erected. The fourth constraint, similar to the "Closing Deck Constraint", is the opposite of the "No Placing Between Constraint". This is the case when not a full Block is in between other Blocks, but when this is only a deck, referred to as closing decks. In the case of a closing deck, all other Blocks surrounding the closing deck must be erected before the closing deck can be erected. A Block will have a mark that it is considered a closing deck. The final constraint is the "Sister Block Constraint", resulting in two Blocks that are required to be erected directly after each other. In the case of the erection sequence scheduler this is given shape by requiring the prior erection of a mirrored starboard Block before the equal and opposite port side Block can be erected. In the erection sequence generator this choice is made with regard to Royal IHC Krimpen, who start erection with the starboard side due to configuration of the slipway in the production facility [16].

6.3. Erection Schedule Results

In this section the results of the different Block division test cases are analyzed by using them as input for the Erection Sequence Scheduler of *Meijer*(2008)[16]. The resulting planning schedules are compared using several objectives, already integrated in the Erection Sequence Scheduler.

6.3.1. Erection Planning Objectives

The Erection Sequence Scheduler its goal is to create a schedule with the shortest through put time on the slipway. Because all Blocks are outsourced, as mentioned in Sub Section 6.2.3, described objectives such as required floor area and the planning schedules in for example the steel pre-fabrication stage will not be assessed since these are zero. The total time the outsource partners require to build all the Blocks, the total erection time and the required personnel to erect the Blocks onto the slipway are still relevant optimization objectives and are used to compare the resulting erection schedules of the different Block division solutions. Also the number of erection constraints per Block is assessed, as this is currently an objective of the Block division engineers in creating a redundant erection schedule via the Block division plan, as mentioned in Sub Section 3.3.1.

6.3.2. Erection Schedules

The different erection sequences can, next to the input of the erection sequence generator, be found in Appendix F. A short summary of the results is shown in Table 6.13.

Table 6.13: Sets of Transverse and Longitudinal seam placing Design Variables

Results	Case 0	Case 1a	Case 1b	Case 1c	Case 1d	Case 1e	Case 1f	Case 1g	Case 2	Unit
First Erection Block	1303	1231	1301	1233	1301	1301	1102	1303	1243	[-]
Duration Erection	235	247	231	231	218	207	231	241	267	[days]
First Building Block	1301	1301	1307	1301	1301	1301	1301	1301	1243	[-]
Duration Block Building	276	288	264	279	260	249	264	267	267	[days]
Number of Blocks	61	69	62	64	55	47	62	61	101	[#]
Closing Decks	4	4	4	4	4	4	4	4	5	[#]
Erection Constraints	205	229	210	210	183	152	208	205	320	[#]
Constraints per Block	3.36	3.32	3.39	3.28	3.33	3.23	3.35	3.36	3.17	[#]

Duration Erection In Table 6.13 it can be seen that the original Block division plan result in an erection duration of 235 days for 61 blocks. The variations on this original Block division show comparable results. Case 1b, 1c and 1f show a lower throughput time of the ship on the slipway while the amount of Blocks to erect is higher. Also different erection starting Blocks are chosen. This shows that the general presumption of maximizing the Blocks size and weight to minimize the throughput time of the ship on the slipway is not necessarily true. The three mentioned cases realize a lower throughput with smaller and lighter Blocks. However, because this research focuses only merely attempting to show difference objective fitness by creating different feasible Block division solutions, no attempt or assessment was made if the resulting Erection Schedules are indeed the most optimal solutions of the erection planning problem. Also several simplifications are implemented that might influence this result. Therefore it can only be stated that regarding the throughput time of a ship on the slipway, different feasible Block division solutions can result in different erection sequence schedules. Appendix F shows that the Erection Sequence Scheduler also results in different erection sequences. Note that the reference names of the Block do not necessarily relate to the same Block, due to the difference in Block division solutions. However, comparable named Blocks will be found in comparable locations in the ship.

In the Erection Sequence Scheduler, the number of erection actions that can be performed every week is limited. Case 2 has a significantly higher amount of Blocks to be erected. For this reason, Case 2 is taking significantly longer to erect than the other cases.

Duration Block Building As a result of the different erection duration and erection sequence, also the Block building process is influenced. It can be seen in Table 6.13 that the duration of the Block Building process varies. Not necessarily does a lower erection duration result in a lower Block building duration. Case 1b shows a shorter erection duration and also a decreased Block building duration. However Case 1c also shows a shorter erection duration but an increased Block Building duration. These results indicate that varying the Block division plan can result in different Block division solutions, perhaps even without influencing the total throughput time of the ship on the slipway. This means that in the case of Royal IHC, where all Blocks are build by outsource partners, depending on the occupation and conditions at outsource partners the Block division plan could be optimized to fit these circumstances. For example, it may be possible to build more Blocks at a cheaper outsource partner by using a different Block division solution, compared to what another Block division solution that results in a production planning where there are less Blocks built at this outsource partner.

Erection Constraints Table 6.13 also shows that the erection constraints per Block vary with the different Block division solutions. This supports the idea of Block division engineers to minimize the amount of erection constraints to have an as redundant as possible erection schedule. However, it can not be stated that a lower amount of erection constraints per Block does result in a more redundant erection schedule. To be prove the relation between the amount of erection constraints per Block and the redundancy of an erection schedule a critical path analysis of the resulting erection schedules have to be made. This research focuses on the potential difference in the erection schedule by different Block division solutions and therefore no critical path analysis of the resulting erection schedules is made.

6.3.3. Required Erection Personnel

The ideal resource leveling curve is defined by [20]. The diagonal lines at the start and end of the production period have a duration of the average time it takes to mount a Block, as shown in Figure 6.24. The total area below the ideal resource level equals the area below the required resource level. It is more ideal to have a flat required resource level due to the inflexibility in the change in the amount of workers available. For example, you can not hire workers for only one day, so more spikes is less efficient.

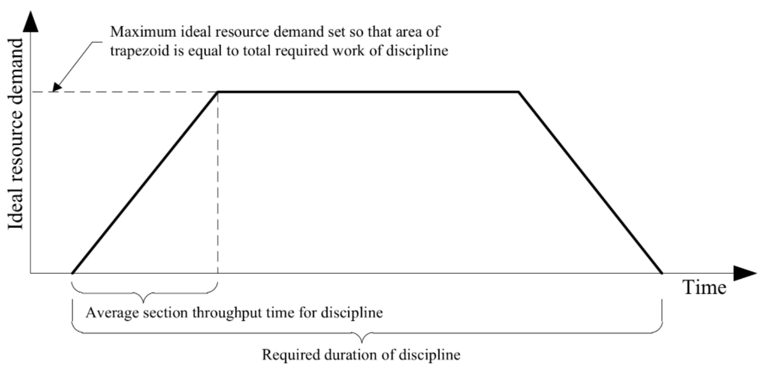


Figure 6.24: Example ideal resource objective curve[20]

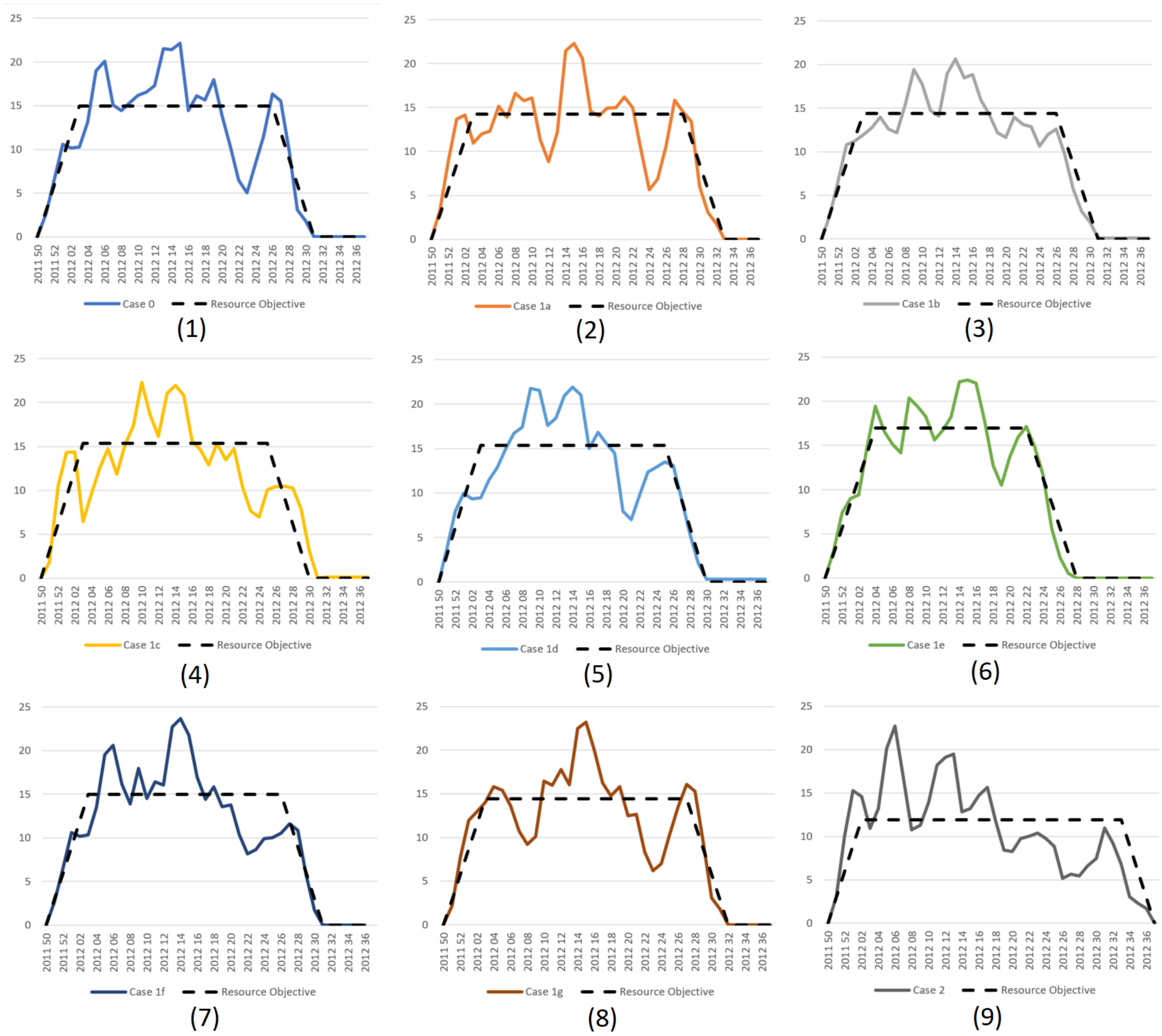


Figure 6.25: Required personnel over time (in weeks) for the erection of all test cases, including the ideal resource objective

Figure 6.25 shows clearly the change in required personnel for the different Block division solutions. The most optimal production plan for a Block division solution is Case 1e with a deviation of 15.73 %. Case 2 is the most unfavourable with a total deviation of 33.56%. Note that the this deviation is only the absolute deviation and no translation to the actual situation at the shipyard can be made. The total deviation for the erecting discipline per Block division solution case is shown in Table 6.14.

Table 6.14: Overview general input values Erection Sequence Generator

	Average Erection time per Block	Deviation from ideal Resource objective
Unit	[workdays]	[%]
Case 0	5.13	22.89
Case 1a	4.79	22.64
Case 1b	5.12	16.90
Case 1c	5.12	27.45
Case 1d	5.34	22.79
Case 1e	5.66	15.73
Case 1f	5.10	22.41
Case 1g	5.11	23.62
Case 2	4.42	33.56

6.4. Validation of the Block Division Generator's Methodology

Because the Block division generator is a design tool, and not an optimization algorithm, the validation square is an applicable method to assess the validity of the developed model [3]. Figure 6.26 shows the structure of the validation square method. A design method's validity is considered proven by the combination of how useful the method is with respect to a predefined purpose. Where usefulness is defined as a combination of effectiveness and efficiency, based on qualitative and quantitative measures respectively. The effectiveness of the developed model is assessed in Sub Section 6.4.1 and 6.4.2. The efficiency of the developed model is assessed in Sub Section 6.4.3 and 6.4.4.

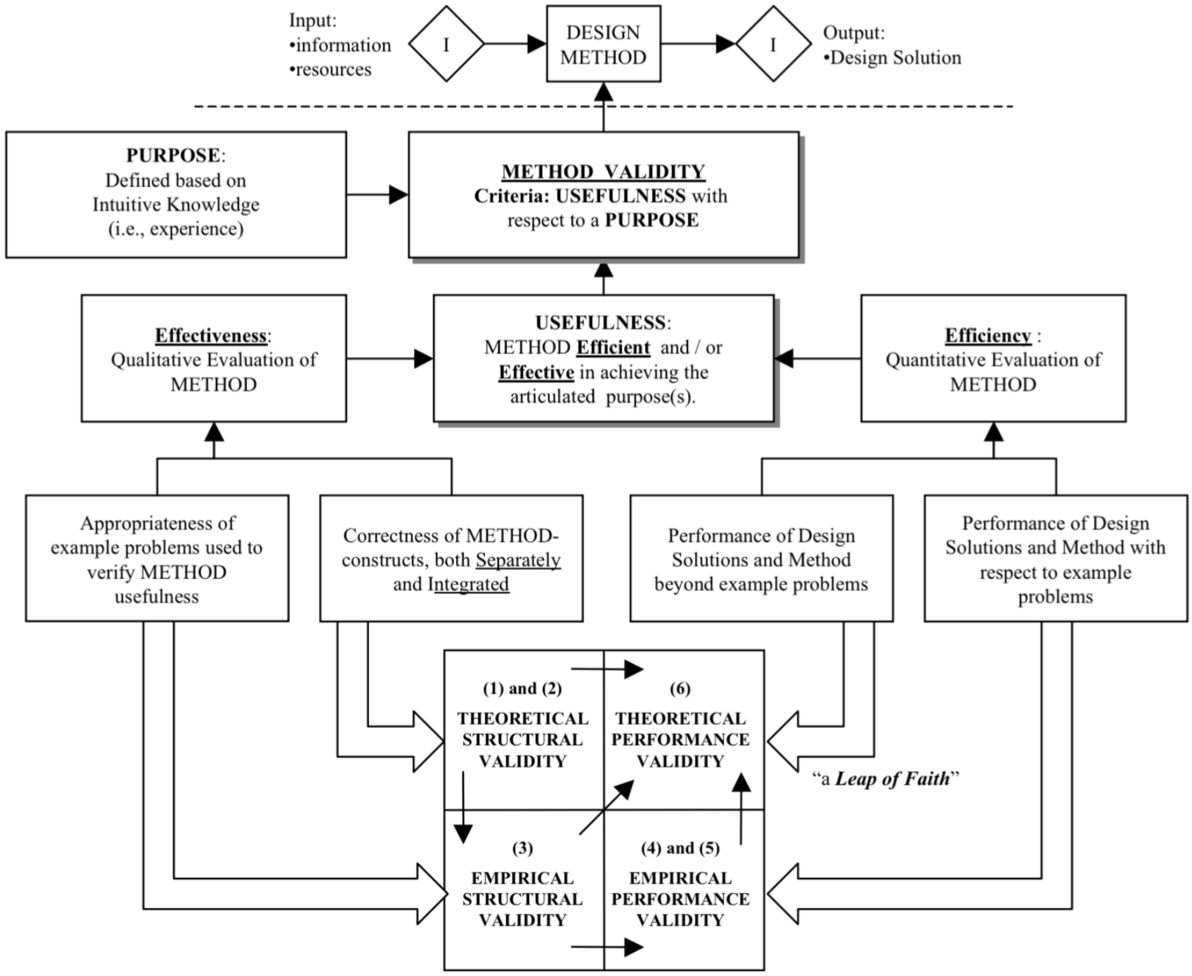


Figure 6.26: The validation square[3]

6.4.1. Theoretical Structural Validity

As suggested by *Seepersad*(2005)[3], the first step to measure build confidence in the validity in the individual constructs of the model is to critically evaluate literature. however, no literature was found that accurately describes the Block division process of complex ships at European shipyards, as discussed in Section 1.2. The Seam Placing Logic is based on the information gathered from these experienced engineers, and the developed mechanisms are a mathematical representation of this decision making process. Therefore, the individual constructs that compose the BDG are validated using the interviews conducted with experienced Block division engineers from Royal IHC and DAMEN Schelde Naval, found in Appendix G.

Because the information gathered in the interviews is the basis for the Seam Placing Logic and all constructs are confirmed to be of relevance in the Block division process by the conducted validation interviews, it can be stated that the constructs composing the BDG are widely accepted. Depending on the Block division approach used by a shipyard, the different constructs may be valued less or more relevant for the total Block division process. This is incorporated in the BDG as the different Design Variables per construct. Therefore the BDG's constructs are considered to be theoretical structural valid.

The second step is to validate the consistency of the developed method. This is done by showing the input required for each construct or step is always available from a previously called method. This is done using the flow chart method, as proposed by *Seepersad*(2005)[3]. The flowcharts in Figure 5.3 and 5.4 show which input is available for each step of the Seam Placing Logic and how the anticipated output is a result if the used input. All used mechanisms in these flows are discusses in Section 5.3 and require all data structured as shown in Section 5.2. Example data sets in this information structure for test ship 1 are extracted from the design information and included in Appendix A.

The conducted interviews at Royal IHC and DAMEN Schelde Naval provided feedback on the available information to make sure that the information the model uses will be readily available at the stage where the Block division plan is created. The direct information, such as the GA, can be found in Appendix H and general Block Division approach knowledge can be found in Appendices G.1 and G.4. The in-direct or implicit knowledge can be found in Appendices G.1, G.2, and G.3. All this information is discussed in Chapter 3 and 4. The information used to do determine the weight correction factors for the weight calculation must be deducted from reference ships, which are available at the early design stage and the general methodology information was provided by the interview found in Appendix G.3. In the verification of the test case ship the detailed structural design information of the completed test case ship was used. The Grouping Logic does only requires available information about shipyard facilities, no other external information is needed. Therefor, the methods constructs are considered to be consistent.

6.4.2. Empirical Structural Validity

The BDG method's constructs are created to simulate the Block division approach of Royal IHC at their shipyard in Kinderdijk. The example problems of the verification test ship 1 and test ship 2 are of ships built at this shipyard. This means that the Block division approach by the shipyard is equal to the Block division approach as developed into the BDG. Because of this, the same set of Design Variables is valid for each test case. Because of the previous, the example problems are considered similar enough to the problems for which the method-constructs are generally accepted.

The method is intended to potentially increase global production optimization objectives for complex ships that are engineered-to-order and build at a European Shipyard. The model must be applicable in the preliminary design stage. Contracts of engineered-to-order ships are awarded when a ship's design is only developed to the preliminary design stage, and the same stage a Block division plan must be created, it can be stated that the example verification Block division problems represent the actual problem for which the BDG is intended. Also because the verification Block divisions as described in Section 6.1 are considered to potentially have multiple feasible Block division solutions by the Block division engineer at Royal IHC. Therefore the example problems also comply with the initial defined problem of ship production optimization through changing the Block division solution for a ship. These different feasible Block division solutions are discussed in Sub Section 6.2.2 and assess in Section 6.3. There is no formal definition of a trailing suction hopper dredger is the most representative complex ship. However, these ships carry high amounts of complex systems on board, are generally build in Europe[20], are regularly used in academic research as test cases such as cost estimation and shipyard planning optimization [6][16][20][26]. Based on this, it is concluded that the selected example problem represents the actual problems for which the BDG is intended.

Finally, to show that the data associated with the example problems is adequate to support a Block division solution, the preliminary design data of the test case ships are shown in Appendix H.1 and H.3. Next to this design data, the implicit knowledge of Block division engineers is considered to be available and thus incorporated into the BDG. For the weight calculations of a Block, in the verification case of the first test case ship, the detailed hull structural design is used to determine the weight correction factors. This detailed hull structural design is not yet available in the preliminary design stage. However, the detailed information of reference ships is available at this stage. This information might lead to deviations in the weight calculations due to the differences between the reference ship and the ship taken into consideration for the creation of a Block division plan. Because information about the weight of each ship Module is present during the preliminary design stage, as stated in Sub Section 3.2, the weight correction factors can be altered and big deviations can be prevented. When taking this all into account it can be stated that also for the weight calculations sufficient information is available at the moment of creating the Block division plan for the BDG to come up with different solutions. In the conducted interviews, everybody agreed that indeed previous mentioned information is available in the preliminary design stage. This shows that the information associated with the example problem is adequate to support the Block division solutions.

6.4.3. Empirical Performance Validity

In order to accept the usefulness of the developed BDG, it should be applied to a Representative example problem. As mentioned above, the BDG was applied to test case ships build at Royal IHC in Kinderdijk. To determine the usefulness of the method, metrics must be defined that are linked to the degree to which the purpose of the BDG has been achieved. Chapter 1 states the purpose of the model in the main research question. The model is considered useful if it can be effectively used in optimization algorithms. As mentioned in Chapter 4, to be able to assess the effectiveness of the BDG in optimization algorithms it must be able to generate $n+1$ feasible solutions to a Block division problem. The Block division generator is considered effective in optimization algorithms if the $n+1$ solutions affect the optimization objectives of the used optimization algorithm.

Usefulness Metrics The main objective of the BDG is to find $n+1$ feasible Block division solutions. Section 4.3 states the feasibility constraints to assess the feasibility of these Block division solutions. The two defined facility constraints are listed below. The first constraint is the size of the Blocks. to be able to fit Blocks through the doors of the halls they can only have a maximum size. The second constraint is the weight of the Blocks, in order for the crane facilities to lift the them. If a Block division solution does not comply with either of these constraints it is considered unfeasible to build at the specific shipyard to which the constrains are applicable. Next to be able to generate feasible solutions, the optimization objectives of the used optimization algorithm have to be defined in order to analyze the affect of the different Block division solutions on these objectives. Sub Section 6.3.1 discusses the optimization objectives that can be analyzed in the chosen test case and these are listed below, including the before mentioned feasibility constraints.

1. Block maximum size
2. Block maximum weight
3. Erection duration
4. Block building duration
5. Erection Constraints
6. Required erection personnel

Usefulness of Applying the Method The usefulness metrics as stated above are all assessed in Section 6.2 and 6.3. The different developed Block division solutions are all feasible. The results on the usefulness metrics are compared to the results of the original Block division which is created manually by the Block division engineers at Royal IHC. It is shown that the different solutions affect the erection duration, Block building duration, amount of erection constraints per Block and the required erection personnel. This comparison proves that the usefulness is linked to the utilization of the BDG.

6.4.4. Theoretical Performance Validity

The purpose of going through the validation square is to present circumstantial evidence to substantiate the claim of generality of the proposed method, as stated by *Seepersad*(2005)[3]. Generality in this sense means confidence in the applicability and usefulness of the method for domains that are broader. In order to identify the applicable broader domain the main objective of this research is divided in two parts. The main objective is to find out whether the Block division process can be atomized and if this can be effectively used in shipyard planning optimization algorithms.

The first part is to find out if it is possible to identify the expertise of Block division engineers and translate it into an algorithm to generate these Block division solutions automatically. This is done by reproducing a single Block division approach of a shipyard following a particular erection strategy, as mentioned in Sub Section 4.1.1. Based on this, it can be deducted that if the BDG is able to reproduce the Block division solution created by this shipyard's engineers, it must be able to be do the same for another ship being build according to the same erection strategy and Block division approach. Sub Section 6.1.5 shows to what extend the BDG is able to create a Block division solution for the fore ship Module of Test Case Ship 2. The result of applying the BDG regarding another ship following similar building principles are also discussed in the before mentioned Sub Section. It can be concluded that the BDG is useful to apply this broader domain. However, some small corrections to the initial model have to be made to exactly reproduce the original Block division solution of Test Case Ship 2.

The second part of the main objective is to see if the generated feasible Block division solutions can be effectively used in shipyard planning optimization algorithms. This is done by using different Design Variable sets to alter the chosen Block division approach as shown in Case 1a up until 1g, as shown in Sub Section 6.2.1. These different Design Variable sets consequently create varying results on the erection sequence schedule and corresponding shipyard planning optimization algorithms, as discussed in Section 6.3. A broader domain in this regard would be to be able to apply a different Block division approach to the same test case ship, by means of generating a Block division solution as if the ship would be built at another shipyard. Case 2 from Sub Section 6.2.1 shows this is possible to a limited extend. However, the BDG can be tailored or expanded with some functionalists to be able to cope with these situations of modelling other Block division approaches.

The two identified broader domains for the BDG methodology are discussed by applying the BDG to different ships regarding the same the Block division approach conditions as it was developed by. Also, it was shown that the BDG is able to apply different Block division approach conditions to the same test case ship to a certain extend. These domains are proven to be applicable to the BDG or expected to be applicable after tailoring the model implementing the methodology. These argument combined prove the developed BDG methodology is indeed applicable in domains that are broader and relevance to this research.

7 Conclusion

This report describes the developed methodology and model for the automatic generation block division plans for complex ships build at European shipyards, during the preliminary production planning stage. In this Chapter the results of this research will be discussed and the research questions as stated in Chapter 1 will be answered. These conclusions build upon the results of the requirements of the developed model and the model itself, discussed in Chapter 4 and 5 respectively. The created model was verified and validated in Chapter 6. Next to the conclusion of this research, recommendations for future research are described.

7.1. Conclusion

Automatic generation of block division plans has the potential of obtaining superior production plans compared to the current way these are developed. The block division plan is essentially a design process, which is created for the sole purpose of being able to produce the ship in the shortest amount of time possible. The owner of the ship has no interest in a specific block division plan other than it being supportive to a low price or faster production time, but in no way it results in a better or worse to operate ship. For this reason, the main objective of a block division engineer is to optimize the block division plan towards an optimal production process from the perspective of producibility of the ship. This is achieved by means of an iterative process. Altering the design of a ship for improved producibility may not be in the interest of a shipowner, but if altering the block division for the same reason results in higher quality production processes, it needs to be taken into account. Defining a ship's constituent blocks is an important prerequisite for generation of the production planning of a ship. Furthermore it dictates the decomposition of engineering work, manufacturing of panels and assembly of blocks to a large extent. The rationale for where to put the boundaries between blocks is often dictated by a shipyard's maximum hoisting capacity, the independent strength and stiffness of the resulting block and experience of the responsible engineer, based on preliminary design information. But other criteria might be of relevance such as choosing a block division that is most effective in terms of overall cost, or outfitting cost,or more robust in terms of disruption of the critical path, in levelling resources such as required floor space and outsourcing

This thesis explored the possibility of developing an automated model to generate these block division plans and researched if these different feasible block division solutions have the potential to improve the quality of the total production plan, regarding optimization objectives of interest to a shipyard. The following research question was defined to guide this research.

Research Question: Is it possible to automatically generate block division plans in the preliminary production planning stage that can be effectively used in ship production optimization algorithm?

To answer this question, three sub-questions are stated. The first and second sub-questions examined the required implementation of the to be created model in order to be provide the plan of requirement of this model. The third sub question examines how to reflect on the created results by the model that is created in order to answer the main research question.

Research Sub-question #1: What is the available preliminary design information input and what is the required information output to incorporate an automated block division plan into automated ship production optimization algorithms?

Research Sub-question #2: What are the constraints and design variables that determine possible block division plans in a shipyard, and how can these be captured by a model or algorithm?

Research Sub-question #3: How can the quality of automatically generated block division plans be assessed to determine their potential effectiveness in ship production optimization algorithms?

The answers to the first sub-question is found in literature and by conducting interviews with engineers at shipbuilding companies. The available preliminary design input at the preliminary production planning stage is the general arrangement of a ship. Next to these drawings indirect knowledge of the hull structural design is available in the form of detailed drawings of comparable reference ships and implicit knowledge from experienced engineers. This information was gathered by conducting interviews with several engineers at Royal IHC and DAMEN Schelde Naval Shipyard. The output of the developed model was chosen based on the required input of ship production optimization algorithms, developed in previous research. To find connection with the chosen erection sequence scheduler the output of the Block Division Generator had to be in the form of rectangular blocks, described by two coordinates. Every block must have a weight and a location in order for the erection sequence model to generate the production schedules.

To be able to develop the automated block division method various literature was consulted and interviews with engineers at Royal IHC and DAMEN Schelde Naval Shipyard were conducted to define the general approach to block division. The transformation of this general approach to block division into a mathematical model is used to answer the second sub-question, by defining parameters and variables that can be considered input to the model. Two feasibility constraints are defined, the block weight and size constraints. If the created blocks are too heavy the facilities of a shipyard can not erect the block on the slipway. If the block is too large it will not fit through the shipyard's facility doors as for example the conservation hall.
Also design variables are defined which represent a different approach to chosen the block division as was found from conducting the interviews. The Block Division Generator considers different seam positions in order to create the blocks and the final position is a result of found structure, compartments (rooms in combination with outfitting and finish) and equipment. Test case ships are chosen to verify the results of the created model. A set of different design variables is implemented as for example the preferred block length, importance or weight per seam placing argument and exceptions to seam placing can be changed in order to find alternative block division solutions to the manually created block division.

The third sub-question is answered by choosing different sets of design variables varying block division solutions can be created of this test case ship, which are compared by the ability to comply with the defined optimization objectives set by the erection sequence scheduler. In order for the Block Division Generator to be effective in affecting the achieved optimum in ship production planning it must create $n+1$ block division solutions. The used erection sequence scheduler that creates ship production plannings for the created block division solutions has implemented several optimization objectives such as total duration of erection, total duration of block building and the required amount of personnel. The fitness of the results are compared to be able to find deviations compared to the original manually created block division plan. The Block Division Generator proved to be able to create multiple block division solutions and showed deviations in the resulting optimization objectives.

The Block Division Generator methodology presented in this research satisfies the main constructs of the validation square, resulting in circumstantial evidence that builds confidence in the usefulness of the method. The developed Block Division Generator is able to generate $n+1$ different block division solutions for the same ship by altering the Design Variables that represent a certain block division strategy and the relevant supply and facility constraints. The different block division solutions result in different results on the optimization objectives of the erection sequence schedule optimization algorithm that represent the general objective of a shipyard. Several different block division solutions result in a superior result than the original block division solution on these optimization objectives. However, because this research focuses only merely attempting to show difference objective fitness by creating different feasible block division solutions, no attempt or assessment was made if the resulting Erection Schedules are indeed the most optimal solutions of the erection planning problem. Also several simplifications are implemented that might influence this result. Therefore it can only be stated that regarding the throughput time of a ship on the slipway, different feasible block division solutions can result in different erection sequence schedules.

Therefore it can be concluded that the developed BDG and methodology is able to automatic generate block division plans based on preliminary design information that can be effectively in shipyard planning optimization algorithms to improve the results on relevant optimization objectives.

7.2. Recommendations

This Section presents recommendations for further research. Some recommendations will improve the applicability of the model to a broader domain, where others will improve the accuracy of the results. Therefore two categories are defined.

7.2.1. Applicability of the Method

- Research other shipyards and analyze the erection strategy and block division approach to determine applicable scope of the developed methodology. This can provide insight in the required additions to be able to also use the Block Division Generator as a potential tool to optimize ship production at a shipyard by assessing the effectiveness of different block division approaches
- Integrate the Block Division Generator with more advanced ship production optimization algorithms in order to be able to quantify the shown effectiveness. Because producibility is an important perspective to block division, this optimization algorithm should incorporate more of the stated block division arguments in this research. This should result in finding the actual optimal solution to a block division problem
- Integrate the Block Division Generator with more advanced ship production optimization algorithms that are able to automatically generate Mega-block configurations to be able to optimize towards optimal Mega-blocks
- Find connection with automated design tools such as packing approach to be able to find relations between the optimal ship design with respect to the optimal ship production planning and processes. In theory when finalizing the concept design the ship production time and costs could be taken into consideration when this is all automatically generated by design tools, the Block Division Generator and finally ship production optimization algorithm to create a whole integrated optimization model.
- Also integrating with automated detailed structural design tools can improve the weight calculation, lead time and cost estimations

7.2.2. Functionality of the Model

- Expand model to be more mutually applicable for other block division approaches by expanding the flexibility of the model by upgrading the mechanisms. Mainly the grouping logic has to be expanded in order to facilitate different grouping orders and thereby block division approaches.
- Expand Optional Seam analysis by not limit the 14 mentioned seam positions but every frame individually. This way more versatile analysis per to be placed seam can be created resulting in more different block division solutions
- Currently the Block Division Generator can only asses one argument per Optional Seam Positions. Ideally the model would be able to asses all arguments and analyze the found conditions individually based on the approach quantified by the Design Variables

A

Block Division Generator Input Tables Texst Case Ship 1

For the BDG ".txt" files were used as import files for the PostgreSQL database to be able to easily change the data, these tables are attached in this Appendix to this report.

A.1. Structural Types Table

Structural Type ID	Structural Type Name	Thickness [mm]
str-000	frame-db	11
str-001	frame	9
str-002	shell	12
str-003	girder	13
str-005	tanktop	10
str-006	tween-deck	9
str-007	tween-deck-transit	-6
str-008	wall	12
str-009	hopper-end	18
str-010	shell-bulbous	16
str-011	bulkhead-transit	-9
str-012	foundation	15
str-013	null	0
str-101	frame-aft	9
str-102	girder-aft	13
str-103	tanktop-deck-aft	9
str-104	tween-deck-aft	9
str-105	tween-deck-aft-transit	-5
str-106	main-deck-aft	9
str-107	main-deck-aft-transit	0
str-108	coaming-deck-aft	11
str-109	coaming-deck-aft-transit	-9
str-110	bottom-shell-aft	12
str-201	frame-mid	9
str-202	girder-mid	13

Structural Type ID	Structural Type Name	Thickness [mm]
str-203	tanktop-deck-mid	10
str-204	tween-deck-mid	9
str-205	tween-deck-mid-transit	-6
str-206	main-deck-mid	12
str-207	main-deck-mid-transit	-10
str-208	coaming-deck-mid	35
str-209	coaming-deck-mid-transit	-27
str-210	bottom-shell-mid	13
str-301	frame-fore	9
str-302	girder-fore	13
str-303	tanktop-deck-fore	9
str-304	tween-deck-fore	9
str-305	tween-deck-fore-transit	-7
str-306	main-deck-fore	9
str-307	main-deck-fore-transit	-6
str-308	coaming-deck-fore	12
str-309	coaming-deck-fore-transit	-9
str-310	bottom-shell-fore	11

A.2. Structural Parts Table

To be able to fit the tables below on the pages abbreviations for the column names have been used. In that perspective, "c1x" is an abbreviation for "Coordinate 1x" and "sx" is an abbreviation for "Stiffeners on side x".

Part ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	Type	s-x	s-y	s-z
sp-1010	frame–4	-2800	-10650	4600	-2800	10650	8400	hopper-end	1	0	0
sp-1020	frame-3	2100	-10650	5100	2100	10650	8400	frame-aft	0	0	0
sp-1030	bulkhead-12-td	8400	-10650	0	8400	10650	5100	frame-aft	0	0	0
sp-1040	buklhead-12-md	8400	-10650	5100	8400	-3500	8400	frame-aft	0	0	0
sp-1050	bulkhead-12-md	8400	3500	5100	8400	10650	8400	frame-aft	0	0	0
sp-1060	bulkhead-12-cd	8400	-6000	8400	8400	6000	11700	frame-aft	0	0	0
sp-1070	bulkhead-35-md	24500	-10650	1120	24500	10650	8400	hopper-end	-1	0	0
sp-1080	frame-35-cd	24500	-7450	8400	24500	7450	11700	hopper-end	0	0	0
sp-1090	bulkhead-47-md	32900	-10650	1120	32900	10650	8400	hopper-end	-1	0	0
sp-1100	bulkhead-47-cd	32900	-7450	8400	32900	7450	11700	hopper-end	-1	0	0
sp-1110	bulkhead-110	77000	-10650	1120	77000	10650	10800	hopper-end	1	0	0
sp-1111	frame-113	79100	-4600	7500	79100	4600	10800	frame-fore	1	0	0
sp-1112	frame-wt-114	79800	-10650	1120	79800	-6771	4200	frame-fore	0	0	0
sp-1113	frame-wt-114	79800	6771	1120	79800	10650	4200	frame-fore	0	0	0
sp-1114	frame-117-cd	81900	-4600	7500	81900	4600	10800	frame-fore	1	0	0
sp-1115	frame-wt-118-sb	82600	-10650	1120	82600	-6771	4200	frame-fore	0	0	0
sp-1116	frame-wt-118-ps	82600	6671	1120	82600	10650	4200	frame-fore	0	0	0
sp-1117	bulkhead-120-td	84000	-10650	4200	84000	10650	7500	frame-fore	1	0	0
sp-1118	bulkhead-120-cd	84000	-4600	7500	84000	4600	10800	frame-fore	1	0	0
sp-1119	frame-wt-120-sb	84000	-10650	1120	84000	-6771	4200	frame-fore	0	0	0
sp-1120	frame-wt-120-ps	84000	6671	1120	84000	10650	4200	frame-fore	0	0	0
sp-1121	frame-wt-122-sb	85400	-10650	1120	85400	-6771	4200	frame-fore	0	0	0
sp-1122	frame-wt-122-ps	85400	6671	1120	85400	10650	4200	frame-fore	0	0	0
sp-1123	frame-wt-124	86800	-6771	1120	86800	0	4200	frame-fore	0	0	0
sp-1124	frame-wt-126-sb	88200	-10650	1120	88200	-6771	4200	frame-fore	0	0	0

Part ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	Type	s-x	s-y	s-z
sp-1125	frame-wt-126-ps	88200	6671	1120	88200	10650	4200	frame-fore	0	0	0
sp-1126	frame-wt-128	89600	-6771	1120	89600	0	4200	frame-fore	0	0	0
sp-1127	bulkhead-130	91000	-9967	1120	91000	9967	10800	frame-fore	1	0	0
sp-1128	bulkhead-142	99400	-9967	0	99400	9967	10800	frame-db	0	0	0
sp-1129	frame-wt-147	102900	-7520	7500	102900	7520	10800	frame-fore	0	0	0
sp-1130	frame-wt-150	105000	-5000	2100	105000	5000	10800	frame-fore	0	0	0
sp-1132	frame-wt-154	107800	-3015	7500	107800	3015	10800	frame-fore	0	0	0
sp-1133	frame-wt-156	109200	-3015	7500	109200	3015	10800	frame-fore	0	0	0
sp-1230	frame-8-db	5600	-7079	1120	5600	-2500	4200	frame-db	0	0	0
sp-1240	frame-8-db	5600	2500	1120	5600	7079	4200	frame-db	0	0	0
sp-1253	frame-10-db	7000	-7079	1120	7000	-2500	4200	frame-db	0	0	0
sp-1254	frame-10-db	7000	2500	1120	7000	7079	4200	frame-db	0	0	0
sp-1257	frame-35-db	24500	-10650	0	24500	10650	1120	frame-db	-1	0	0
sp-1258	bulkhead-47-db	32900	-10650	0	32900	10650	1120	hopper-end	-1	0	0
sp-1259	bulkhead-110-db	77000	-10650	0	77000	10650	1120	hopper-end	1	0	0
sp-1260	frame-db-112	78400	-10650	0	78400	10650	1120	frame-db	0	0	0
sp-1261	frame-db-114	79800	-10650	0	79800	10650	1120	frame-db	0	0	0
sp-1262	frame-db-116	81200	-10650	0	81200	10650	1120	frame-db	0	0	0
sp-1263	frame-db-118	82600	-10650	0	82600	10650	1120	frame-db	0	0	0
sp-1264	frame-db-120	84000	-10650	0	84000	10650	1120	frame-db	0	0	0
sp-1265	frame-db-122	85400	-10650	0	85400	10650	1120	frame-db	0	0	0
sp-1266	frame-db-124	86800	-10650	0	86800	10650	1120	frame-db	0	0	0
sp-1267	frame-db-126	88200	-10650	0	88200	10650	1120	frame-db	0	0	0
sp-1268	frame-db-128	89600	-10650	0	89600	10650	1120	frame-db	0	0	0
sp-1269	bulkhead-130-db	91000	-9967	0	91000	9967	1120	frame-fore	1	0	0
sp-1270	frame-db-132	92400	-9967	0	92400	9967	2100	frame-db	0	0	0
sp-1271	frame-db-134	93800	-9967	0	93800	9967	2100	frame-db	0	0	0
sp-1272	frame-db-136	95200	-9967	0	95200	9967	2100	frame-db	0	0	0
sp-1273	frame-db-138	96600	-9967	0	96600	9967	2100	frame-db	0	0	0
sp-1274	frame-db-140	98000	-9967	0	98000	9967	2100	frame-db	0	0	0
sp-1275	frame-db-144	100800	-7520	0	100800	7520	2100	frame-db	0	0	0
sp-1276	frame-db-146	102200	-7520	0	102200	7520	2100	frame-db	0	0	0
sp-1277	frame-db-148	103600	-7520	0	103600	7520	2100	frame-db	0	0	0
sp-1278	frame-db-150	105000	-7520	0	105000	7520	2100	frame-db	0	0	0
sp-1280	bulkhead-152-db	106400	-3015	0	106400	3015	1120	frame-db	0	0	0
sp-1282	frame-db-154	107800	-3015	0	107800	3015	2100	frame-db	0	0	0
sp-1284	frame-db-156	109200	-3015	0	109200	3015	2100	frame-db	0	0	0
sp-1287	frame-db–2	-1400	-300	3600	-1400	300	4600	frame-db	0	0	0
sp-1289	frame-db-0	0	-300	3600	0	300	4600	frame-db	0	0	0
sp-1291	frame-db-2	1400	-300	3600	1400	300	4600	frame-db	0	0	0
sp-1293	frame-db-5	3500	-300	0	3500	300	4600	frame-db	0	0	0
sp-1294	frame-db-6	4200	-300	0	4200	300	4600	frame-db	0	0	0
sp-1295	frame-db-7	4900	-300	0	4900	300	4600	frame-db	0	0	0
sp-1296	frame-db-8	5600	-300	0	5600	300	4600	frame-db	0	0	0
sp-1297	frame-db-9	6300	-300	0	6300	300	4600	frame-db	0	0	0
sp-1298	frame-db-10	7000	-300	0	7000	300	4600	frame-db	0	0	0
sp-1299	frame-db-11	7700	-300	0	7700	300	4600	frame-db	0	0	0
sp-1300	frame-db-14	9800	-10650	0	9800	10650	1120	frame-db	0	0	0
sp-1301	frame-db-16	11200	-10650	0	11200	10650	1120	frame-db	0	0	0
sp-1303	frame-db-18	12600	-10650	0	12600	10650	1120	frame-db	0	0	0
sp-1304	frame-db-20	14000	-10650	0	14000	10650	1120	frame-db	0	0	0
sp-1305	frame-db-22	15400	-10650	0	15400	10650	1120	frame-db	0	0	0
sp-1306	frame-db-24	16800	-10650	0	16800	10650	1120	frame-db	0	0	0

Part ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	Type	s-x	s-y	s-z
sp-1307	frame-db-26	18200	-10650	0	18200	10650	1120	frame-db	0	0	0
sp-1308	frame-db-28	19600	-10650	0	19600	10650	1120	frame-db	0	0	0
sp-1309	frame-db-30	21000	-10650	0	21000	10650	1120	frame-db	0	0	0
sp-1310	frame-db-32	22400	-10650	0	22400	10650	1120	frame-db	0	0	0
sp-1311	frame-db-34	23800	-10650	0	23800	10650	1120	frame-db	0	0	0
sp-1312	frame-db-21	14700	-6020	0	14700	6020	1120	foundation	0	0	0
sp-1313	frame-db-22	15400	-6020	0	15400	6020	1120	foundation	0	0	0
sp-1314	frame-db-23	16100	-6020	0	16100	6020	1120	foundation	0	0	0
sp-1315	frame-db-24	16800	-6020	0	16800	6020	1120	foundation	0	0	0
sp-1316	frame-db-25	17500	-6020	0	17500	6020	1120	foundation	0	0	0
sp-1317	frame-db-26	18200	-6020	0	18200	6020	1120	foundation	0	0	0
sp-1318	frame-db-27	18900	-6020	0	18900	6020	1120	foundation	0	0	0
sp-1319	frame-db-28	19600	-6020	0	19600	6020	1120	foundation	0	0	0
sp-1320	frame-db-29	20300	-6020	0	20300	6020	1120	foundation	0	0	0
sp-1321	frame-db-30	21000	-6020	0	21000	6020	1120	foundation	0	0	0
sp-1322	frame-db-31	21700	-6020	0	21700	6020	1120	foundation	0	0	0
sp-1324	frame-db-33	23100	-6020	0	23100	6020	1120	foundation	0	0	0
sp-1326	frame-db-37	25900	-6020	0	25900	6020	1120	foundation	0	0	0
sp-1328	frame-db-39	27300	-6020	0	27300	6020	1120	foundation	0	0	0
sp-1330	frame-db-41	28700	-6020	0	28700	6020	1120	foundation	0	0	0
sp-1332	frame-db-43	30100	-6020	0	30100	6020	1120	foundation	0	0	0
sp-1335	frame-db-36	25200	-10650	0	25200	10650	1120	frame-db	0	0	0
sp-1336	frame-db-38	26600	-10650	0	26600	10650	1120	frame-db	0	0	0
sp-1337	frame-db-40	28000	-10650	0	28000	10650	1120	frame-db	0	0	0
sp-1338	frame-db-42	29400	-10650	0	29400	10650	1120	frame-db	0	0	0
sp-1339	frame-db-44	30800	-10650	0	30800	10650	1120	frame-db	0	0	0
sp-1340	frame-db-46	32200	-10650	0	32200	10650	1120	frame-db	0	0	0
sp-1341	frame-db-49	34300	-10650	0	34300	-6771	1120	frame-db	0	0	0
sp-1342	frame-db-49	34300	-3100	0	34300	3100	1120	frame-db	0	0	0
sp-1343	frame-db-49	34300	6771	0	34300	10650	1120	frame-db	0	0	0
sp-1344	frame-db-51	35700	-10650	0	35700	-6771	1120	frame-db	0	0	0
sp-1345	frame-db-51	35700	-3100	0	35700	3100	1120	frame-db	0	0	0
sp-1346	frame-db-51	35700	6771	0	35700	10650	1120	frame-db	0	0	0
sp-1347	frame-db-53	37100	-10650	0	37100	-6771	1120	frame-db	0	0	0
sp-1348	frame-db-53	37100	-3100	0	37100	3100	1120	frame-db	0	0	0
sp-1349	frame-db-53	37100	6771	0	37100	10650	1120	frame-db	0	0	0
sp-1350	frame-db-55	38500	-10650	0	38500	-6771	1120	frame-db	0	0	0
sp-1351	frame-db-55	38500	-3100	0	38500	3100	1120	frame-db	0	0	0
sp-1352	frame-db-55	38500	6771	0	38500	10650	1120	frame-db	0	0	0
sp-1353	frame-db-57	39900	-10650	0	39900	-6771	1120	frame-db	0	0	0
sp-1354	frame-db-57	39900	-3100	0	39900	3100	1120	frame-db	0	0	0
sp-1355	frame-db-57	39900	6771	0	39900	10650	1120	frame-db	0	0	0
sp-1356	frame-db-59	41300	-10650	0	41300	-6771	1120	frame-db	0	0	0
sp-1357	frame-db-59	41300	-3100	0	41300	3100	1120	frame-db	0	0	0
sp-1358	frame-db-59	41300	6771	0	41300	10650	1120	frame-db	0	0	0
sp-1359	frame-db-61	42700	-10650	0	42700	-6771	1120	frame-db	0	0	0
sp-1360	frame-db-61	42700	-3100	0	42700	3100	1120	frame-db	0	0	0
sp-1361	frame-db-61	42700	6771	0	42700	10650	1120	frame-db	0	0	0
sp-1362	frame-db-63	44100	-10650	0	44100	-6771	1120	frame-db	0	0	0
sp-1363	frame-db-63	44100	-3100	0	44100	3100	1120	frame-db	0	0	0
sp-1364	frame-db-63	44100	6771	0	44100	10650	1120	frame-db	0	0	0
sp-1365	frame-db-65	45500	-10650	0	45500	-6771	1120	frame-db	0	0	0
sp-1366	frame-db-65	45500	-3100	0	45500	3100	1120	frame-db	0	0	0
sp-1367	frame-db-65	45500	6771	0	45500	10650	1120	frame-db	0	0	0

Part ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	Type	s-x	s-y	s-z
sp-1368	frame-db-67	46900	-10650	0	46900	-6771	1120	frame-db	0	0	0
sp-1369	frame-db-67	46900	-3100	0	46900	3100	1120	frame-db	0	0	0
sp-1370	frame-db-67	46900	6771	0	46900	10650	1120	frame-db	0	0	0
sp-1371	frame-db-69	48300	-10650	0	48300	-6771	1120	frame-db	0	0	0
sp-1372	frame-db-69	48300	-3100	0	48300	3100	1120	frame-db	0	0	0
sp-1373	frame-db-69	48300	6771	0	48300	10650	1120	frame-db	0	0	0
sp-1374	frame-db-71	49700	-10650	0	49700	-6771	1120	frame-db	0	0	0
sp-1375	frame-db-71	49700	-3100	0	49700	3100	1120	frame-db	0	0	0
sp-1376	frame-db-71	49700	6771	0	49700	10650	1120	frame-db	0	0	0
sp-1377	frame-db-73	51100	-10650	0	51100	-6771	1120	frame-db	0	0	0
sp-1378	frame-db-73	51100	-3100	0	51100	3100	1120	frame-db	0	0	0
sp-1379	frame-db-73	51100	6771	0	51100	10650	1120	frame-db	0	0	0
sp-1380	frame-db-75	52500	-10650	0	52500	-6771	1120	frame-db	0	0	0
sp-1381	frame-db-75	52500	-3100	0	52500	3100	1120	frame-db	0	0	0
sp-1382	frame-db-75	52500	6771	0	52500	10650	1120	frame-db	0	0	0
sp-1383	frame-db-77	53900	-10650	0	53900	-6771	1120	frame-db	0	0	0
sp-1384	frame-db-77	53900	-3100	0	53900	3100	1120	frame-db	0	0	0
sp-1385	frame-db-77	53900	6771	0	53900	10650	1120	frame-db	0	0	0
sp-1386	frame-db-79	55300	-10650	0	55300	-6771	1120	frame-db	0	0	0
sp-1387	frame-db-79	55300	-3100	0	55300	3100	1120	frame-db	0	0	0
sp-1388	frame-db-79	55300	6771	0	55300	10650	1120	frame-db	0	0	0
sp-1389	frame-db-81	56700	-10650	0	56700	-6771	1120	frame-db	0	0	0
sp-1390	frame-db-81	56700	-3100	0	56700	3100	1120	frame-db	0	0	0
sp-1391	frame-db-81	56700	6771	0	56700	10650	1120	frame-db	0	0	0
sp-1392	frame-db-83	58100	-10650	0	58100	-6771	1120	frame-db	0	0	0
sp-1393	frame-db-83	58100	-3100	0	58100	3100	1120	frame-db	0	0	0
sp-1394	frame-db-83	58100	6771	0	58100	10650	1120	frame-db	0	0	0
sp-1395	frame-db-85	59500	-10650	0	59500	-6771	1120	frame-db	0	0	0
sp-1396	frame-db-85	59500	-3100	0	59500	3100	1120	frame-db	0	0	0
sp-1397	frame-db-85	59500	6771	0	59500	10650	1120	frame-db	0	0	0
sp-1398	frame-db-87	60900	-10650	0	60900	-6771	1120	frame-db	0	0	0
sp-1399	frame-db-87	60900	-3100	0	60900	3100	1120	frame-db	0	0	0
sp-1400	frame-db-87	60900	6771	0	60900	10650	1120	frame-db	0	0	0
sp-1401	frame-db-89	62300	-10650	0	62300	-6771	1120	frame-db	0	0	0
sp-1402	frame-db-89	62300	-3100	0	62300	3100	1120	frame-db	0	0	0
sp-1403	frame-db-89	62300	6771	0	62300	10650	1120	frame-db	0	0	0
sp-1404	frame-db-91	63700	-10650	0	63700	-6771	1120	frame-db	0	0	0
sp-1405	frame-db-91	63700	-3100	0	63700	3100	1120	frame-db	0	0	0
sp-1406	frame-db-91	63700	6771	0	63700	10650	1120	frame-db	0	0	0
sp-1407	frame-db-93	65100	-10650	0	65100	-6771	1120	frame-db	0	0	0
sp-1408	frame-db-93	65100	-3100	0	65100	3100	1120	frame-db	0	0	0
sp-1409	frame-db-93	65100	6771	0	65100	10650	1120	frame-db	0	0	0
sp-1410	frame-db-95	66500	-10650	0	66500	-6771	1120	frame-db	0	0	0
sp-1411	frame-db-95	66500	-3100	0	66500	3100	1120	frame-db	0	0	0
sp-1412	frame-db-95	66500	6771	0	66500	10650	1120	frame-db	0	0	0
sp-1413	frame-db-97	67900	-10650	0	67900	-6771	1120	frame-db	0	0	0
sp-1414	frame-db-97	67900	-3100	0	67900	3100	1120	frame-db	0	0	0
sp-1415	frame-db-97	67900	6771	0	67900	10650	1120	frame-db	0	0	0
sp-1416	frame-db-99	69300	-10650	0	69300	-6771	1120	frame-db	0	0	0
sp-1417	frame-db-99	69300	-3100	0	69300	3100	1120	frame-db	0	0	0
sp-1418	frame-db-99	69300	6771	0	69300	10650	1120	frame-db	0	0	0
sp-1419	frame-db-101	70700	-10650	0	70700	-6771	1120	frame-db	0	0	0
sp-1420	frame-db-101	70700	-3100	0	70700	3100	1120	frame-db	0	0	0
sp-1421	frame-db-101	70700	6771	0	70700	10650	1120	frame-db	0	0	0

Part ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	Type	s-x	s-y	s-z
sp-1422	frame-db-103	72100	-10650	0	72100	-6771	1120	frame-db	0	0	0
sp-1423	frame-db-103	72100	-3100	0	72100	3100	1120	frame-db	0	0	0
sp-1424	frame-db-103	72100	6771	0	72100	10650	1120	frame-db	0	0	0
sp-1425	frame-db-105	73500	-10650	0	73500	-6771	1120	frame-db	0	0	0
sp-1426	frame-db-105	73500	-3100	0	73500	3100	1120	frame-db	0	0	0
sp-1427	frame-db-105	73500	6771	0	73500	10650	1120	frame-db	0	0	0
sp-1428	frame-db-107	74900	-10650	0	74900	-6771	1120	frame-db	0	0	0
sp-1429	frame-db-107	74900	-3100	0	74900	3100	1120	frame-db	0	0	0
sp-1430	frame-db-107	74900	6771	0	74900	10650	1120	frame-db	0	0	0
sp-1431	frame-db-109	76300	-10650	0	76300	-6771	1120	frame-db	0	0	0
sp-1432	frame-db-109	76300	-3100	0	76300	3100	1120	frame-db	0	0	0
sp-1433	frame-db-109	76300	6771	0	76300	10650	1120	frame-db	0	0	0
sp-1434	frame-db-111	77700	-6671	0	77700	6671	1120	foundation	0	0	0
sp-1435	frame-db-112	78400	-6671	0	78400	6671	1120	foundation	0	0	0
sp-1436	frame-db-113	79100	-6671	0	79100	6671	1120	foundation	0	0	0
sp-1510	frame-54-hop	37800	-10650	0	37800	10650	1120	hopper-end	0	0	0
sp-1512	frame-61-hop	42700	-10650	0	42700	10650	1120	hopper-end	0	0	0
sp-1514	frame-68-hop	47600	-10650	0	47600	10650	1120	hopper-end	0	0	0
sp-1516	frame-75-hop	52500	-10650	0	52500	10650	1120	hopper-end	0	0	0
sp-1518	frame-82-hop	57400	-10650	0	57400	10650	1120	hopper-end	0	0	0
sp-1520	frame-89-hop	62300	-10650	0	62300	10650	1120	hopper-end	0	0	0
sp-1522	frame-96-hop	67200	-10650	0	67200	10650	1120	hopper-end	0	0	0
sp-1524	frame-103-hop	72100	-10650	0	72100	10650	1120	hopper-end	0	0	0
sp-1525	frame-db–2	-1400	-10650	4600	-1400	10650	5100	frame-db	0	0	0
sp-1526	frame-db-0	0	-10650	4600	0	10650	5100	frame-db	0	0	0
sp-1527	frame-db-2	1400	-10650	4600	1400	10650	5100	frame-db	0	0	0
sp-1528	frame-db-4	2800	-10650	4600	2800	10650	5100	frame-db	0	0	0
sp-1529	frame-db-6	4200	-10650	4600	4200	10650	5100	frame-db	0	0	0
sp-1530	frame-db-8	5600	-10650	4600	5600	10650	5100	frame-db	0	0	0
sp-1531	frame-db-10	7000	-10650	4600	7000	10650	5100	frame-db	0	0	0
sp-2001	bottom-12	8400	-10650	0	32900	10650	0	bottom-aft	0	0	0
sp-2002	bottom-6	4200	-7079	1120	8400	-2500	1120	bottom-aft	0	0	0
sp-2003	bottom-6	4200	2500	1120	8400	7079	1120	bottom-aft	0	0	0
sp-2004	bottom-47	32900	-10650	0	77000	10650	0	bottom-mid	0	0	0
sp-2005	bottom-110	77000	-10650	0	91000	10650	0	bottom-fore	0	0	1
sp-2006	bottom-130	91000	-9967	0	99400	9967	0	bottom-fore	0	0	1
sp-2007	bottom-142	99400	-7520	0	106400	7520	0	bottom-fore	0	0	1
sp-2008	bottom-152	106400	-3015	0	110600	3015	0	shell-bulbs	0	0	1
sp-2009	tanktop-12	8400	-10650	1120	24500	-6020	1120	tanktop-aft	0	0	-1
sp-2010	tanktop-12	8400	-6020	1120	24500	6020	1120	foundation	0	0	-1
sp-2011	tanktop-12	8400	6020	1120	24500	10650	1120	tanktop-aft	0	0	-1
sp-2012	tanktop-35	24500	-10650	1120	32900	10650	1120	tanktop-aft	0	0	-1
sp-2013	tanktop-47	32900	-10650	1120	77000	-6771	1120	tanktop-mid	0	0	-1
sp-2014	tanktop-47	32900	6771	1120	77000	10650	1120	tanktop-mid	0	0	-1
sp-2015	tanktop-47	32900	-6771	365	77000	-3100	365	tanktop-mid	0	0	-1
sp-2016	tanktop-47	32900	3100	365	77000	6771	365	tanktop-mid	0	0	-1
sp-2017	tanktop-47	32900	-3100	1120	77000	3100	1120	tanktop-mid	0	0	-1
sp-2018	tanktop-110	77000	-10650	1120	91000	10650	1120	tanktop-fore	0	0	-1
sp-2019	tanktop-130	91000	-9967	2100	99400	9967	2100	tanktop-fore	0	0	-1
sp-2020	tanktop-142	99400	-7520	2100	106400	7520	2100	tanktop-fore	0	0	-1
sp-2021	tanktop-152	106400	-3015	2100	110600	3015	2100	tanktop-fore	0	0	-1
sp-2201	tweendeck–4	-2800	-10650	5100	2100	10650	5100	tween-aft	0	0	-1
sp-2202	tweendeck-3	2100	-10650	5100	24500	10650	5100	tween-aft	0	0	-1
sp-2203	tweendeck-35	24500	-10650	5100	32900	10650	5100	tween-aft	0	0	-1

Part ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	Type	s-x	s-y	s-z
sp-2204	tweendeck-47	32900	-10650	4200	77000	-6771	4200	tween-mid	0	0	-1
sp-2205	tweendeck-47	32900	6771	4200	77000	10650	4200	tween-mid	0	0	-1
sp-2206	tweendeck-110	77000	-10650	4200	91000	10650	4200	tween-fore	0	0	-1
sp-2207	tweendeck-130	91000	-9967	4200	99400	9967	4200	tween-fore	0	0	-1
sp-2208	tweendeck-142	99400	-7520	4200	106400	7520	4200	tween-fore	0	0	-1
sp-2209	tweendeck-152	106400	-5725	4200	109200	5725	4200	tween-fore	0	0	-1
sp-2210	tweendeck-156	109200	-3015	4200	110600	3015	4200	tween-fore	0	0	-1
sp-2301	maindeck–4	-2800	-10650	8400	32900	10650	8400	main-mid	0	0	-1
sp-2302	maindeck-47	32900	-10650	7500	77000	-6771	7500	main-mid	0	0	-1
sp-2303	maindeck-47	32900	6771	7500	77000	10650	7500	main-mid	0	0	-1
sp-2304	maindeck-110	77000	-10650	7500	91000	10650	7500	main-fore	0	0	-1
sp-2305	maindeck-130	91000	-9967	7500	99400	9967	7500	main-fore	0	0	-1
sp-2306	maindeck-142	99400	-7520	7500	106400	7520	7500	main-fore	0	0	-1
sp-2307	maindeck-152	106400	-5725	7500	109900	5725	7500	main-fore	0	0	-1
sp-2401	coamingdeck-12	8400	-6000	11700	24500	6000	11700	coaming-aft	0	0	-1
sp-2402	coamingdeck-35	24500	-7450	11700	32900	7450	11700	coaming-aft	0	0	-1
sp-2403	coamingdeck-47	32900	-7450	10800	77000	-3100	10800	coaming-mid	0	0	-1
sp-2404	coamingdeck-47	32900	3100	10800	77000	7450	10800	coaming-mid	0	0	-1
sp-2405	coamingdeck-47	32900	-3100	10800	37250	3100	10800	coaming-mid	0	0	-1
sp-2406	coamingdeck-104	72650	-3100	10800	77000	3100	10800	coaming-mid	0	0	-1
sp-2407	coamingdeck-95	66500	-10650	10800	74200	-6000	10800	coaming-mid	0	0	-1
sp-2408	coamingdeck-95	66500	6000	10800	74200	10650	10800	coaming-mid	0	0	-1
sp-2501	foredeck-110	77000	-10650	10800	91000	10650	10800	coaming-fore	0	0	-1
sp-2502	foredeck-130	91000	-9967	10800	99400	9967	10800	coaming-fore	0	0	-1
sp-2503	foredeck-142	99400	-7520	10800	106400	7520	10800	coaming-fore	0	0	-1
sp-2504	foredeck-152	106400	-5725	10800	109900	5725	10800	coaming-fore	0	0	-1
sp-3001	shell-sb-152	77000	-10650	0	91000	-10650	10800	shell-bulb	0	0	0
sp-3002	shell-sb-130	91000	-9967	0	99400	-9967	10800	shell	0	0	0
sp-3003	shell-sb-142	99400	-7520	0	106400	-7520	10800	shell	0	0	0
sp-3004	shell-sb-152	106400	-7520	0	106400	-3015	4200	shell	0	0	0
sp-3005	shell-sb-152	106400	-7520	4200	106400	-5725	10800	shell	0	0	0
sp-3006	shell-sb-152	106400	-5725	4200	109200	-5725	10800	shell	0	0	0
sp-3007	shell-sb-152	106400	-3015	0	110600	-3015	4200	shell-bulb	0	0	0
sp-3008	shell-158	110600	-3015	0	110600	3015	4200	shell-bulb	0	0	0
sp-3009	shell-156	109200	-5725	7500	109900	-5725	10800	shell-bulb	0	0	0
sp-3010	shell-sb-156	109200	-5725	4200	109200	5725	7500	shell-bulb	0	0	0
sp-3011	shell-ps-110	77000	10650	0	91000	10650	10800	shell	0	0	0
sp-3012	shell-ps-130	91000	9967	0	99400	9967	10800	shell	0	0	0
sp-3013	shell-ps-142	99400	7520	0	106400	7520	10800	shell	0	0	0
sp-3014	shell-ps-152	106400	3015	0	106400	7520	4200	shell	0	0	0
sp-3015	shell-ps-152	106400	5725	4200	106400	7520	10800	shell	0	0	0
sp-3016	shell-ps-152	106400	5725	4200	109200	5725	10800	shell-bulb	0	0	0
sp-3017	shell-158	109900	-5725	7500	109900	5725	10800	shell-bulb	0	0	0
sp-3018	shell-ps-156	109200	5725	7500	109900	5725	10800	shell-bulb	0	0	0
sp-3019	shell-ps-152	106400	3015	0	110600	3015	4200	shell-bulb	0	0	0
sp-3100	shell-6	4200	-7079	1120	8400	-7079	4200	shell-bulb	0	0	0
sp-3101	shell-6	4200	-2500	1120	8400	-2500	4200	shell-bulb	0	0	0
sp-3102	shell-6	4200	-7079	4200	8400	-2500	4200	shell-bulb	0	0	0
sp-3103	shell-6	4200	2500	1120	8400	2500	4200	shell-bulb	0	0	0
sp-3104	shell-6	4200	7079	1120	8400	7079	4200	shell-bulb	0	0	0
sp-3105	shell-6	4200	2500	4200	8400	7079	4200	shell-bulb	0	0	0
sp-3106	shell-6	4200	-7079	1120	4200	-2500	4200	shell-bulb	0	0	0
sp-3107	shell-6	4200	2500	1120	4200	7079	4200	shell-bulb	0	0	0

Part ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	Type	s-x	s-y	s-z
sp-3201	shell–4	-2800	-10650	4600	8400	10650	4600	shell	0	0	0
sp-3108	shell–4	-2800	-10650	4600	8400	-10650	8400	shell	0	0	0
sp-3109	shell–4	-2800	10650	4600	8400	10650	8400	shell	0	0	0
sp-3110	shell-12	8400	-10650	0	24500	-10650	8400	shell	0	0	0
sp-3111	shell-12	8400	10650	0	24500	10650	8400	shell	0	0	0
sp-3112	shell-35	24500	-10650	0	32900	-10650	8400	shell	0	0	0
sp-3113	shell-35	24500	10650	0	32900	10650	8400	shell	0	0	0
sp-3114	shell-47	32900	-2000	4500	74900	2000	4500	shell-bulb	0	0	0
sp-3115	shell-4	2800	-300	0	8400	-300	4600	shell-bulb	0	0	0
sp-3116	shell-4	2800	300	0	8400	300	4600	shell-bulb	0	0	0
sp-3117	shell-4	2800	-300	0	2800	300	4600	shell-bulb	0	0	0
sp-3118	shell-4	2800	-300	0	8400	300	0	shell-bulb	0	0	0
sp-3119	shell–4	-2700	-300	3600	2800	300	3600	shell-bulb	0	0	0
sp-3120	shell–4	-2700	-300	3600	2800	-300	4600	shell-bulb	0	0	0
sp-3121	shell–4	-2700	300	3600	2800	300	4600	shell-bulb	0	0	0
sp-3122	shell–4	-2700	-300	3600	-2700	300	4600	shell-bulb	0	0	0
sp-3123	shell-47-sb	32900	-10650	0	77000	-10650	7500	shell	0	0	0
sp-3124	shell-47-ps	32900	10650	0	77000	10650	7500	shell	0	0	0
sp-4001	girder-110-sb	77000	-6771	1120	91000	-6771	4200	girder-fore	0	0	0
sp-4002	girder-110-ps	77000	6771	1120	91000	6771	4200	girder-fore	0	0	0
sp-4003	girder-wtank-122	85400	0	1120	91000	0	4200	girder-fore	0	0	0
sp-4004	girder-main-122	84000	0	7500	91000	0	10800	girder-fore	0	0	0
sp-4005	girder-room-120	84000	-7100	4200	91000	-7100	7500	girder-fore	0	0	0
sp-4006	girder-room-120	84000	-5000	4200	91000	-5000	7500	girder-fore	0	0	0
sp-4007	girder-CL-120	84000	0	4200	91000	0	7500	girder-fore	0	0	0
sp-4008	girder-CL-142	99400	0	0	110600	0	2100	girder-fore	0	0	0
sp-4009	girder-110-sb	77000	-4600	7500	81900	-4600	10800	girder-fore	0	0	0
sp-4010	girder-110-ps	77000	4600	7500	84000	4600	10800	girder-fore	0	0	0
sp-4011	girder-110-cps	77000	700	7500	84000	700	10800	girder-fore	0	0	0
sp-4012	girder-110	79100	2100	7500	81900	2100	10800	girder-fore	0	0	0
sp-4013	girder-130	91000	0	0	99400	0	2100	girder-fore	0	0	0
sp-4014	girder-127	88900	1000	7500	91000	1000	10800	wall	0	0	0
sp-4015	girder-47	32900	-6771	0	77000	-6771	10800	girder-mid	0	0	0
sp-4016	girder-47	32900	6771	0	77000	6771	10800	girder-mid	0	0	0
sp-4017	girder-47	32900	-3100	0	77000	-3100	1120	girder-mid	0	0	0
sp-4018	girder-47	32900	3100	0	77000	3100	1120	girder-mid	0	0	0
sp-4019	girder-47	32900	0	0	77000	0	1120	girder-mid	0	0	0
sp-4020	girder-47-kk	32900	0	1120	74900	0	4500	foundation	0	0	0
sp-4024	girder-db-110	77000	0	0	91000	0	1120	girder-fore	0	0	0
sp-4025	girder-db-12	8400	0	0	24500	0	1120	girder-aft	0	0	0
sp-4026	girder-db-12	8400	-4200	0	24500	-4200	1120	girder-aft	0	0	0
sp-4027	girder-db-12	8400	4200	0	24500	4200	1120	girder-aft	0	0	0
sp-4028	girder-db-35	24500	-4200	0	32900	-4200	1120	girder-aft	0	0	0
sp-4029	girder-db-35	24500	0	0	32900	0	1120	girder-aft	0	0	0
sp-4030	girder-db-35	24500	4200	0	32900	4200	1120	girder-aft	0	0	0
sp-4031	girder-110	77000	0	1120	79800	0	2100	girder	0	0	0
sp-5001	wall-wtank-122	85400	-6771	1120	85400	0	4200	wall	0	0	0
sp-5002	wall-136	95200	-9967	7500	95200	9967	10800	wall	0	0	0
sp-5003	wall-120	84000	-4600	7500	91000	-4600	10800	wall	0	0	0
sp-5004	wall-120	84000	4600	7500	91000	4600	10800	wall	0	0	0
sp-5005	wall-127	88900	-4600	7500	88900	1000	10800	wall	0	0	0
sp-5008	wall-12	8400	-6000	8400	24500	-6000	11700	wall	0	0	0
sp-5009	wall-12	8400	6000	8400	24500	6000	11700	wall	0	0	0

Part ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	Type	s-x	s-y	s-z
sp-5010	wall-12	24500	-7450	8400	32900	-7450	11700	wall	0	0	0
sp-5011	wall-12	24500	7450	8400	32900	7450	11700	wall	0	0	0
sp-5101	wall-54-cd	37800	-8000	7500	37800	-6771	10800	foundation	0	0	0
sp-5102	wall-54-cd	37800	6771	7500	37800	8000	10800	foundation	0	0	0
sp-5103	wall-61-cd	42700	-8000	7500	42700	-6771	10800	foundation	0	0	0
sp-5104	wall-61-cd	42700	6771	7500	42700	8000	10800	foundation	0	0	0
sp-5105	wall-68-cd	47600	-8000	7500	47600	-6771	10800	foundation	0	0	0
sp-5106	wall-68-cd	47600	6771	7500	47600	8000	10800	foundation	0	0	0
sp-5107	wall-75-cd	52500	-8000	7500	52500	-6771	10800	foundation	0	0	0
sp-5108	wall-75-cd	52500	6771	7500	52500	8000	10800	foundation	0	0	0
sp-5109	wall-82-cd	57400	-8000	7500	57400	-6771	10800	foundation	0	0	0
sp-5110	wall-82-cd	57400	6771	7500	57400	8000	10800	foundation	0	0	0
sp-5111	wall-89-cd	62300	-8000	7500	62300	-6771	10800	foundation	0	0	0
sp-5112	wall-89-cd	62300	6771	7500	62300	8000	10800	foundation	0	0	0
sp-5113	wall-96-cd	67200	-8000	7500	67200	-6771	10800	foundation	0	0	0
sp-5114	wall-96-cd	67200	6771	7500	67200	8000	10800	foundation	0	0	0
sp-5115	wall-103-cd	72100	-8000	7500	72100	-6771	10800	foundation	0	0	0
sp-5116	wall-103-cd	72100	6771	7500	72100	8000	10800	foundation	0	0	0
sp-5117	wall-47-hfo	32900	-9650	1120	75600	-9650	4200	wall	0	0	0
sp-5118	wall-47-hfo	32900	9650	1120	75600	9650	4200	wall	0	0	0
sp-5119	wall-108-hfo	75600	-9650	1120	75600	-6771	4200	wall	0	0	0
sp-5120	wall-108-hfo	75600	6771	1120	75600	9650	4200	wall	0	0	0
sp-5121	wall-715-hfo	50050	-10650	0	50050	-6771	7500	wall	0	0	0
sp-5123	wall-715-hfo	50050	6771	0	50050	10650	7500	wall	0	0	0
sp-5124	wall-54-hfo	37800	6771	1120	37800	9650	4200	wall	0	0	0
sp-5125	wall-925-hfo	64750	-10650	0	64750	-6771	7500	wall	0	0	0
sp-5126	wall-925-hfo	64750	6771	0	64750	10650	7500	wall	0	0	0
sp-5127	wall-45-mdo	31500	-2100	5100	31500	6000	8400	wall	0	0	0
sp-5128	wall-45-mdo	31500	-2100	5100	32900	-2100	8400	wall	0	0	0
sp-5129	wall–4	-2800	-6000	5100	32900	-6000	8400	wall	0	0	0
sp-5130	wall–4	-2800	6000	5100	32900	6000	8400	wall	0	0	0
sp-5131	wall-3	2100	3500	5100	8400	3500	8400	wall	0	0	0
sp-5132	wall-3	2100	-3500	5100	8400	-3500	8400	wall	0	0	0
sp-5133	wall-15	10500	6000	5100	10500	10650	8400	wall	0	0	0
sp-5134	wall-31	21700	6000	5100	21700	10650	8400	wall	0	0	0
sp-5135	wall-31	21700	-10650	5100	21700	-6000	8400	wall	0	0	0
sp-5136	wall-20-cd	14000	-6000	8400	14000	6000	11700	wall	0	0	0
sp-5137	wall-31-cd	21700	-6000	8400	21700	6000	11700	wall	0	0	0
sp-5138	wall-12-cd	8400	-2000	8400	21700	-2000	11700	wall	0	0	0
sp-5139	wall-12-cd	8400	2000	8400	14000	2000	11700	wall	0	0	0
sp-5140	wall-12-cd	8400	-4000	8400	14000	-4000	11700	wall	0	0	0
sp-5141	wall-12-cd	8400	4000	8400	14000	4000	11700	wall	0	0	0
sp-5142	wall-20-cd	14000	0	8400	21700	0	11700	wall	0	0	0
sp-5143	wall-38-cd	26600	2000	8400	32900	2000	11700	wall	0	0	0
sp-5144	wall-39-cd	26600	2000	8400	26600	7450	11700	wall	0	0	0

A.3. Transit Table

Transit ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	Type
tr-001	tweendeck-114	79800	-6670	4200	84000	-1000	4200	tween deck fore transit
tr-002	tweendeck-134	93800	-3500	4200	99100	3500	4200	tween deck fore transit
tr-003	maindeck-20-sb	14000	-6020	5100	22400	-3220	5100	main deck aft transit
tr-004	maindeck-20-ps	14000	3220	5100	22400	6020	5100	main deck aft transit
tr-005	maindeck-35	24500	-5330	5100	30800	5330	5100	main deck aft transit
tr-101	coamingdeck-136	95200	-2000	10800	97300	100	10800	coaming deck fore transit
tr-102	tweendeck-136	95200	-2000	7500	97300	100	7500	tween deck fore transit

A.4. Decks Tables

A.4.1. Bottom Deck

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr–1	bulkhead–4	-2800	0	-7079	-2500	0	2500	7079	5
fr–2	frame–3	-2100	0	-7079	-2500	0	2500	7079	5
fr–3	frame–2	-1400	0	-7079	-2500	0	2500	7079	5
fr–4	frame–1	-700	0	-7079	-2500	0	2500	7079	5
fr-0	frame-0	0	0	-7079	-2500	0	2500	7079	5
fr-1	frame-1	700	0	-7079	-2500	0	2500	7079	5
fr-2	frame-2	1400	0	-7079	-2500	0	2500	7079	5
fr-3	bulkhead-3	2100	0	-7079	-2500	0	2500	7079	5
fr-4	frame-4	2800	0	-7079	-2500	0	2500	7079	5
fr-5	frame-5	3500	0	-7079	-2500	0	2500	7079	5
fr-6	frame-6	4200	0	-7079	-2500	0	2500	7079	5
fr-7	frame-7	4900	0	-7079	-2500	0	2500	7079	5
fr-8	frame-8	5600	0	-7079	-2500	0	2500	7079	5
fr-9	frame-9	6300	0	-7079	-2500	0	2500	7079	5
fr-10	frame-10	7000	0	-7079	-2500	0	2500	7079	5
fr-11	frame-11	7700	0	-7079	-2500	0	2500	7079	5
fr-12	bulkhead-12	8400	0	-10650	-6000	0	6000	10650	5
fr-13	frame-13	9100	0	-10650	-6000	0	6000	10650	4
fr-14	frame-14	9800	0	-10650	-6000	0	6000	10650	4
fr-15	frame-15	10500	0	-10650	-6000	0	6000	10650	4
fr-16	frame-16	11200	0	-10650	-6000	0	6000	10650	4
fr-17	frame-17	11900	0	-10650	-6000	0	6000	10650	4
fr-18	frame-18	12600	0	-10650	-6000	0	6000	10650	4
fr-19	frame-19	13300	0	-10650	-6000	0	6000	10650	4
fr-20	frame-20	14000	0	-10650	-6000	0	6000	10650	4
fr-21	frame-21	14700	0	-10650	-6000	0	6000	10650	4
fr-22	frame-22	15400	0	-10650	-6000	0	6000	10650	4
fr-23	frame-23	16100	0	-10650	-6000	0	6000	10650	4
fr-24	frame-24	16800	0	-10650	-6000	0	6000	10650	4

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr-25	frame-25	17500	0	-10650	-6000	0	6000	10650	4
fr-26	frame-26	18200	0	-10650	-6000	0	6000	10650	4
fr-27	frame-27	18900	0	-10650	-6000	0	6000	10650	4
fr-28	frame-28	19600	0	-10650	-6000	0	6000	10650	4
fr-29	frame-29	20300	0	-10650	-6000	0	6000	10650	4
fr-30	frame-30	21000	0	-10650	-6000	0	6000	10650	4
fr-31	frame-31	21700	0	-10650	-6000	0	6000	10650	4
fr-32	frame-32	22400	0	-10650	-6000	0	6000	10650	4
fr-33	frame-33	23100	0	-10650	-6000	0	6000	10650	4
fr-34	frame-34	23800	0	-10650	-7450	0	6000	10650	4
fr-35	bulkhead-35	24500	0	-10650	-7450	0	7450	10650	4
fr-36	frame-36	25200	0	-10650	-7450	0	7450	10650	4
fr-37	frame-37	25900	0	-10650	-7450	0	7450	10650	4
fr-38	frame-38	26600	0	-10650	-7450	0	7450	10650	4
fr-39	frame-39	27300	0	-10650	-7450	0	7450	10650	4
fr-40	frame-40	28000	0	-10650	-7450	0	7450	10650	4
fr-41	frame-41	28700	0	-10650	-7450	0	7450	10650	4
fr-42	frame-42	29400	0	-10650	-7450	0	7450	10650	4
fr-43	frame-43	30100	0	-10650	-7450	0	7450	10650	4
fr-44	frame-44	30800	0	-10650	-7450	0	7450	10650	4
fr-45	frame-45	31500	0	-10650	-7450	0	7450	10650	4
fr-46	frame-46	32200	0	-10650	-7450	0	7450	10650	4
fr-47	frame-47	32900	0	-10650	-7450	0	7450	10650	4
fr-48	frame-48	33600	0	-10650	-6771	0	6771	10650	4
fr-49	frame-49	34300	0	-10650	-6771	0	6771	10650	4
fr-50	frame-50	35000	0	-10650	-6771	0	6771	10650	4
fr-51	frame-51	35700	0	-10650	-6771	0	6771	10650	4
fr-52	frame-52	36400	0	-10650	-6771	0	6771	10650	4
fr-53	frame-53	37100	0	-10650	-6771	0	6771	10650	4
fr-54	frame-54	37800	0	-10650	-6771	0	6771	10650	4
fr-55	frame-55	38500	0	-10650	-6771	0	6771	10650	4
fr-56	frame-56	39200	0	-10650	-6771	0	6771	10650	4
fr-57	frame-57	39900	0	-10650	-6771	0	6771	10650	4
fr-58	frame-58	40600	0	-10650	-6771	0	6771	10650	4
fr-59	frame-59	41300	0	-10650	-6771	0	6771	10650	4
fr-60	frame-60	42000	0	-10650	-6771	0	6771	10650	4
fr-61	frame-61	42700	0	-10650	-6771	0	6771	10650	4
fr-62	frame-62	43400	0	-10650	-6771	0	6771	10650	4
fr-63	frame-63	44100	0	-10650	-6771	0	6771	10650	4
fr-64	frame-64	44800	0	-10650	-6771	0	6771	10650	4
fr-65	frame-65	45500	0	-10650	-6771	0	6771	10650	4
fr-66	frame-66	46200	0	-10650	-6771	0	6771	10650	4
fr-67	frame-67	46900	0	-10650	-6771	0	6771	10650	4
fr-68	frame-68	47600	0	-10650	-6771	0	6771	10650	4
fr-69	frame-69	48300	0	-10650	-6771	0	6771	10650	4
fr-70	frame-70	49000	0	-10650	-6771	0	6771	10650	4
fr-71	frame-71	49700	0	-10650	-6771	0	6771	10650	4
fr-72	frame-72	50400	0	-10650	-6771	0	6771	10650	4
fr-73	frame-73	51100	0	-10650	-6771	0	6771	10650	4
fr-74	frame-74	51800	0	-10650	-6771	0	6771	10650	4
fr-75	frame-75	52500	0	-10650	-6771	0	6771	10650	4
fr-76	frame-76	53200	0	-10650	-6771	0	6771	10650	4

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr-77	frame-77	53900	0	-10650	-6771	0	6771	10650	4
fr-78	frame-78	54600	0	-10650	-6771	0	6771	10650	4
fr-79	frame-79	55300	0	-10650	-6771	0	6771	10650	4
fr-80	frame-80	56000	0	-10650	-6771	0	6771	10650	4
fr-81	frame-81	56700	0	-10650	-6771	0	6771	10650	4
fr-82	frame-82	57400	0	-10650	-6771	0	6771	10650	4
fr-83	frame-83	58100	0	-10650	-6771	0	6771	10650	4
fr-84	frame-84	58800	0	-10650	-6771	0	6771	10650	4
fr-85	frame-85	59500	0	-10650	-6771	0	6771	10650	4
fr-86	frame-86	60200	0	-10650	-6771	0	6771	10650	4
fr-87	frame-87	60900	0	-10650	-6771	0	6771	10650	4
fr-88	frame-88	61600	0	-10650	-6771	0	6771	10650	4
fr-89	frame-89	62300	0	-10650	-6771	0	6771	10650	4
fr-90	frame-90	63000	0	-10650	-6771	0	6771	10650	4
fr-91	frame-91	63700	0	-10650	-6771	0	6771	10650	4
fr-92	frame-92	64400	0	-10650	-6771	0	6771	10650	4
fr-93	frame-93	65100	0	-10650	-6771	0	6771	10650	4
fr-94	frame-94	65800	0	-10650	-6771	0	6771	10650	4
fr-95	frame-95	66500	0	-10650	-6771	0	6771	10650	4
fr-96	frame-96	67200	0	-10650	-6771	0	6771	10650	4
fr-97	frame-97	67900	0	-10650	-6771	0	6771	10650	4
fr-98	frame-98	68600	0	-10650	-6771	0	6771	10650	4
fr-99	frame-99	69300	0	-10650	-6771	0	6771	10650	4
fr-100	frame-100	70000	0	-10650	-6771	0	6771	10650	4
fr-101	frame-101	70700	0	-10650	-6771	0	6771	10650	4
fr-102	frame-102	71400	0	-10650	-6771	0	6771	10650	4
fr-103	frame-103	72100	0	-10650	-6771	0	6771	10650	4
fr-104	frame-104	72800	0	-10650	-6771	0	6771	10650	4
fr-105	frame-105	73500	0	-10650	-6771	0	6771	10650	4
fr-106	frame-106	74200	0	-10650	-6771	0	6771	10650	4
fr-107	frame-107	74900	0	-10650	-6771	0	6771	10650	4
fr-108	frame-108	75600	0	-10650	-6771	0	6771	10650	4
fr-109	frame-109	76300	0	-10650	-6771	0	6771	10650	4
fr-110	bulkhead-110	77000	0	-10650	-6771	0	6771	10650	4
fr-111	frame-111	77700	0	-10650	-6771	0	6771	10650	4
fr-112	frame-112	78400	0	-10650	-6771	0	6771	10650	4
fr-113	frame-113	79100	0	-10650	-6771	0	6771	10650	4
fr-114	frame-114	79800	0	-10650	-6771	0	6771	10650	4
fr-115	frame-115	80500	0	-10650	-6771	0	6771	10650	4
fr-116	frame-116	81200	0	-10650	-6771	0	6771	10650	4
fr-117	frame-117	81900	0	-10650	-6771	0	6771	10650	4
fr-118	frame-118	82600	0	-10650	-6771	0	6771	10650	4
fr-119	frame-119	83300	0	-10650	-6771	0	6771	10650	4
fr-120	bulkhead-120	84000	0	-10650	-6771	0	6771	10650	4
fr-121	frame-121	84700	0	-10650	-6771	0	6771	10650	4
fr-122	frame-122	85400	0	-10650	-6771	0	6771	10650	4
fr-123	frame-123	86100	0	-10650	-6771	0	6771	10650	4
fr-124	frame-124	86800	0	-10650	-6771	0	6771	10650	4
fr-125	frame-125	87500	0	-10650	-6771	0	6771	10650	4
fr-126	frame-126	88200	0	-10650	-6771	0	6771	10650	4

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr-127	frame-127	88900	0	-10650	-6771	0	6771	10650	4
fr-128	frame-128	89600	0	-10650	-6771	0	6771	10650	4
fr-129	frame-129	90300	0	-10650	-6771	0	6771	10650	4
fr-130	bulkhead-130	91000	0	-10650	-6771	0	6771	10650	4
fr-131	frame-131	91700	0	-9967	-6771	0	6771	9967	4
fr-132	frame-132	92400	0	-9967	-6771	0	6771	9967	4
fr-133	frame-133	93100	0	-9967	-6771	0	6771	9967	4
fr-134	frame-134	93800	0	-9967	-6771	0	6771	9967	4
fr-135	frame-135	94500	0	-9967	-6771	0	6771	9967	4
fr-136	frame-136	95200	0	-9967	-6771	0	6771	9967	4
fr-137	frame-137	95900	0	-9967	-6771	0	6771	9967	4
fr-138	frame-138	96600	0	-9967	-6771	0	6771	9967	4
fr-139	frame-139	97300	0	-9967	-6771	0	6771	9967	4
fr-140	frame-140	98000	0	-9967	-6771	0	6771	9967	4
fr-141	frame-141	98700	0	-9967	-6771	0	6771	9967	4
fr-142	bulkhead-142	99400	0	-9967	-6771	0	6771	9967	5
fr-143	frame-143	100100	0	-7520	-6771	0	6771	7520	5
fr-144	frame-144	100800	0	-7520	-6771	0	6771	7520	5
fr-145	frame-145	101500	0	-7520	-6771	0	6771	7520	5
fr-146	frame-146	102200	0	-7520	-6771	0	6771	7520	5
fr-147	frame-147	102900	0	-7520	-6771	0	6771	7520	5
fr-148	frame-148	103600	0	-7520	-6771	0	6771	7520	5
fr-149	frame-149	104300	0	-7520	-6771	0	6771	7520	5
fr-150	frame-150	105000	0	-7520	-6771	0	6771	7520	5
fr-151	frame-151	105700	0	-7520	-6771	0	6771	7520	5
fr-152	frame-152	106400	0	-3015	0	0	0	3015	5
fr-153	frame-153	107100	0	-3015	0	0	0	3015	5
fr-154	frame-154	107800	0	-3015	0	0	0	3015	5
fr-155	frame-155	108500	0	-3015	0	0	0	3015	5
fr-156	frame-156	109200	0	-3015	0	0	0	3015	5
fr-157	frame-157	109900	0	-3015	0	0	0	3015	5
fr-158	frame-158	110600	0	-3015	0	0	0	3015	5

A.4.2. Tanktop Deck

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr–1	bulkhead–4	-2800	1120	-7079	-2500	0	2500	7079	0
fr–2	frame–3	-2100	1120	-7079	-2500	0	2500	7079	0
fr–3	frame–2	-1400	1120	-7079	-2500	0	2500	7079	0
fr–4	frame–1	-700	1120	-7079	-2500	0	2500	7079	0
fr-0	frame-0	0	1120	-7079	-2500	0	2500	7079	0
fr-1	frame-1	700	1120	-7079	-2500	0	2500	7079	0
fr-2	frame-2	1400	1120	-7079	-2500	0	2500	7079	0
fr-3	bulkhead-3	2100	1120	-7079	-2500	0	2500	7079	0
fr-4	frame-4	2800	1120	-7079	-2500	0	2500	7079	0
fr-5	frame-5	3500	1120	-7079	-2500	0	2500	7079	0
fr-6	frame-6	4200	1120	-7079	-2500	0	2500	7079	1
fr-7	frame-7	4900	1120	-7079	-2500	0	2500	7079	1
fr-8	frame-8	5600	1120	-7079	-2500	0	2500	7079	1
fr-9	frame-9	6300	1120	-7079	-2500	0	2500	7079	1

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr-10	frame-10	7000	1120	-7079	-2500	0	2500	7079	1
fr-11	frame-11	7700	1120	-7079	-2500	0	2500	7079	1
fr-12	bulkhead-12	8400	1120	-10650	-6000	0	6000	10650	1
fr-13	frame-13	9100	1120	-10650	-6000	0	6000	10650	1
fr-14	frame-14	9800	1120	-10650	-6000	0	6000	10650	1
fr-15	frame-15	10500	1120	-10650	-6000	0	6000	10650	1
fr-16	frame-16	11200	1120	-10650	-6000	0	6000	10650	1
fr-17	frame-17	11900	1120	-10650	-6000	0	6000	10650	1
fr-18	frame-18	12600	1120	-10650	-6000	0	6000	10650	1
fr-19	frame-19	13300	1120	-10650	-6000	0	6000	10650	1
fr-20	frame-20	14000	1120	-10650	-6000	0	6000	10650	1
fr-21	frame-21	14700	1120	-10650	-6000	0	6000	10650	1
fr-22	frame-22	15400	1120	-10650	-6000	0	6000	10650	1
fr-23	frame-23	16100	1120	-10650	-6000	0	6000	10650	1
fr-24	frame-24	16800	1120	-10650	-6000	0	6000	10650	1
fr-25	frame-25	17500	1120	-10650	-6000	0	6000	10650	1
fr-26	frame-26	18200	1120	-10650	-6000	0	6000	10650	1
fr-27	frame-27	18900	1120	-10650	-6000	0	6000	10650	1
fr-28	frame-28	19600	1120	-10650	-6000	0	6000	10650	1
fr-29	frame-29	20300	1120	-10650	-6000	0	6000	10650	1
fr-30	frame-30	21000	1120	-10650	-6000	0	6000	10650	1
fr-31	frame-31	21700	1120	-10650	-6000	0	6000	10650	1
fr-32	frame-32	22400	1120	-10650	-6000	0	6000	10650	1
fr-33	frame-33	23100	1120	-10650	-6000	0	6000	10650	1
fr-34	frame-34	23800	1120	-10650	-7450	0	6000	10650	1
fr-35	bulkhead-35	24500	1120	-10650	-7450	0	7450	10650	1
fr-36	frame-36	25200	1120	-10650	-7450	0	7450	10650	1
fr-37	frame-37	25900	1120	-10650	-7450	0	7450	10650	1
fr-38	frame-38	26600	1120	-10650	-7450	0	7450	10650	1
fr-39	frame-39	27300	1120	-10650	-7450	0	7450	10650	1
fr-40	frame-40	28000	1120	-10650	-7450	0	7450	10650	1
fr-41	frame-41	28700	1120	-10650	-7450	0	7450	10650	1
fr-42	frame-42	29400	1120	-10650	-7450	0	7450	10650	1
fr-43	frame-43	30100	1120	-10650	-7450	0	7450	10650	1
fr-44	frame-44	30800	1120	-10650	-7450	0	7450	10650	1
fr-45	frame-45	31500	1120	-10650	-7450	0	7450	10650	1
fr-46	frame-46	32200	1120	-10650	-7450	0	7450	10650	1
fr-47	bulkhead-47	32900	1120	-10650	-7450	0	7450	10650	1
fr-48	frame-48	33600	1120	-10650	-6771	0	6771	10650	1
fr-49	frame-49	34300	1120	-10650	-6771	0	6771	10650	1
fr-50	frame-50	35000	1120	-10650	-6771	0	6771	10650	1
fr-51	frame-51	35700	1120	-10650	-6771	0	6771	10650	1
fr-52	frame-52	36400	1120	-10650	-6771	0	6771	10650	1
fr-53	frame-53	37100	1120	-10650	-6771	0	6771	10650	1
fr-54	frame-54	37800	1120	-10650	-6771	0	6771	10650	1
fr-55	frame-55	38500	1120	-10650	-6771	0	6771	10650	1
fr-56	frame-56	39200	1120	-10650	-6771	0	6771	10650	1
fr-57	frame-57	39900	1120	-10650	-6771	0	6771	10650	1
fr-58	frame-58	40600	1120	-10650	-6771	0	6771	10650	1
fr-59	frame-59	41300	1120	-10650	-6771	0	6771	10650	1
fr-60	frame-60	42000	1120	-10650	-6771	0	6771	10650	1

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr-61	frame-61	42700	1120	-10650	-6771	0	6771	10650	1
fr-62	frame-62	43400	1120	-10650	-6771	0	6771	10650	1
fr-63	frame-63	44100	1120	-10650	-6771	0	6771	10650	1
fr-64	frame-64	44800	1120	-10650	-6771	0	6771	10650	1
fr-65	frame-65	45500	1120	-10650	-6771	0	6771	10650	1
fr-66	frame-66	46200	1120	-10650	-6771	0	6771	10650	1
fr-67	frame-67	46900	1120	-10650	-6771	0	6771	10650	1
fr-68	frame-68	47600	1120	-10650	-6771	0	6771	10650	1
fr-69	frame-69	48300	1120	-10650	-6771	0	6771	10650	1
fr-70	frame-70	49000	1120	-10650	-6771	0	6771	10650	1
fr-71	frame-71	49700	1120	-10650	-6771	0	6771	10650	1
fr-72	frame-72	50400	1120	-10650	-6771	0	6771	10650	1
fr-73	frame-73	51100	1120	-10650	-6771	0	6771	10650	1
fr-74	frame-74	51800	1120	-10650	-6771	0	6771	10650	1
fr-75	frame-75	52500	1120	-10650	-6771	0	6771	10650	1
fr-76	frame-76	53200	1120	-10650	-6771	0	6771	10650	1
fr-77	frame-77	53900	1120	-10650	-6771	0	6771	10650	1
fr-78	frame-78	54600	1120	-10650	-6771	0	6771	10650	1
fr-79	frame-79	55300	1120	-10650	-6771	0	6771	10650	1
fr-80	frame-80	56000	1120	-10650	-6771	0	6771	10650	1
fr-81	frame-81	56700	1120	-10650	-6771	0	6771	10650	1
fr-82	frame-82	57400	1120	-10650	-6771	0	6771	10650	1
fr-83	frame-83	58100	1120	-10650	-6771	0	6771	10650	1
fr-84	frame-84	58800	1120	-10650	-6771	0	6771	10650	1
fr-85	frame-85	59500	1120	-10650	-6771	0	6771	10650	1
fr-86	frame-86	60200	1120	-10650	-6771	0	6771	10650	1
fr-87	frame-87	60900	1120	-10650	-6771	0	6771	10650	1
fr-88	frame-88	61600	1120	-10650	-6771	0	6771	10650	1
fr-89	frame-89	62300	1120	-10650	-6771	0	6771	10650	1
fr-90	frame-90	63000	1120	-10650	-6771	0	6771	10650	1
fr-91	frame-91	63700	1120	-10650	-6771	0	6771	10650	1
fr-92	frame-92	64400	1120	-10650	-6771	0	6771	10650	1
fr-93	frame-93	65100	1120	-10650	-6771	0	6771	10650	1
fr-94	frame-94	65800	1120	-10650	-6771	0	6771	10650	1
fr-95	frame-95	66500	1120	-10650	-6771	0	6771	10650	1
fr-96	frame-96	67200	1120	-10650	-6771	0	6771	10650	1
fr-97	frame-97	67900	1120	-10650	-6771	0	6771	10650	1
fr-98	frame-98	68600	1120	-10650	-6771	0	6771	10650	1
fr-99	frame-99	69300	1120	-10650	-6771	0	6771	10650	1
fr-100	frame-100	70000	1120	-10650	-6771	0	6771	10650	1
fr-101	frame-101	70700	1120	-10650	-6771	0	6771	10650	1
fr-102	frame-102	71400	1120	-10650	-6771	0	6771	10650	1
fr-103	frame-103	72100	1120	-10650	-6771	0	6771	10650	1
fr-104	frame-104	72800	1120	-10650	-6771	0	6771	10650	1
fr-105	frame-105	73500	1120	-10650	-6771	0	6771	10650	1
fr-106	frame-106	74200	1120	-10650	-6771	0	6771	10650	1
fr-107	frame-107	74900	1120	-10650	-6771	0	6771	10650	1
fr-108	frame-108	75600	1120	-10650	-6771	0	6771	10650	1
fr-109	frame-109	76300	1120	-10650	-6771	0	6771	10650	1
fr-110	bulkhead-110	77000	1120	-10650	-6771	0	6771	10650	1
fr-111	frame-111	77700	1120	-10650	-6771	0	6771	10650	2
fr-112	frame-112	78400	1120	-10650	-6771	0	6771	10650	2
fr-113	frame-113	79100	1120	-10650	-6771	0	6771	10650	2

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr-114	frame-114	79800	1120	-10650	-6771	0	6771	10650	2
fr-115	frame-115	80500	1120	-10650	-6771	0	6771	10650	2
fr-116	frame-116	81200	1120	-10650	-6771	0	6771	10650	2
fr-117	frame-117	81900	1120	-10650	-6771	0	6771	10650	2
fr-118	frame-118	82600	1120	-10650	-6771	0	6771	10650	2
fr-119	frame-119	83300	1120	-10650	-6771	0	6771	10650	2
fr-120	bulkhead-120	84000	1120	-10650	-6771	0	6771	10650	2
fr-121	frame-121	84700	1120	-10650	-6771	0	6771	10650	2
fr-122	frame-122	85400	1120	-10650	-6771	0	6771	10650	2
fr-123	frame-123	86100	1120	-10650	-6771	0	6771	10650	2
fr-124	frame-124	86800	1120	-10650	-6771	0	6771	10650	2
fr-125	frame-125	87500	1120	-10650	-6771	0	6771	10650	2
fr-126	frame-126	88200	1120	-10650	-6771	0	6771	10650	2
fr-127	frame-127	88900	1120	-10650	-6771	0	6771	10650	2
fr-128	frame-128	89600	1120	-10650	-6771	0	6771	10650	2
fr-129	frame-129	90300	1120	-10650	-6771	0	6771	10650	2
fr-130	bulkhead-130	91000	2100	-10650	-6771	0	6771	10650	2
fr-131	frame-131	91700	2100	-9967	-6771	0	6771	9967	4
fr-132	frame-132	92400	2100	-9967	-6771	0	6771	9967	4
fr-133	frame-133	93100	2100	-9967	-6771	0	6771	9967	4
fr-134	frame-134	93800	2100	-9967	-6771	0	6771	9967	4
fr-135	frame-135	94500	2100	-9967	-6771	0	6771	9967	4
fr-136	frame-136	95200	2100	-9967	-6771	0	6771	9967	4
fr-137	frame-137	95900	2100	-9967	-6771	0	6771	9967	4
fr-138	frame-138	96600	2100	-9967	-6771	0	6771	9967	4
fr-139	frame-139	97300	2100	-9967	-6771	0	6771	9967	4
fr-140	frame-140	98000	2100	-9967	-6771	0	6771	9967	4
fr-141	frame-141	98700	2100	-9967	-6771	0	6771	9967	4
fr-142	bulkhead-142	99400	2100	-9967	-6771	0	6771	9967	4
fr-143	frame-143	100100	2100	-7520	-6771	0	6771	7520	5
fr-144	frame-144	100800	2100	-7520	-6771	0	6771	7520	5
fr-145	frame-145	101500	2100	-7520	-6771	0	6771	7520	5
fr-146	frame-146	102200	2100	-7520	-6771	0	6771	7520	5
fr-147	frame-147	102900	2100	-7520	-6771	0	6771	7520	5
fr-148	frame-148	103600	2100	-7520	-6771	0	6771	7520	5
fr-149	frame-149	104300	2100	-7520	-6771	0	6771	7520	5
fr-150	frame-150	105000	2100	-7520	-6771	0	6771	7520	5
fr-151	frame-151	105700	2100	-7520	-6771	0	6771	7520	5
fr-152	frame-152	106400	2100	-3015	0	0	0	3015	5
fr-153	frame-153	107100	2100	-3015	0	0	0	3015	5
fr-154	frame-154	107800	2100	-3015	0	0	0	3015	5
fr-155	frame-155	108500	2100	-3015	0	0	0	3015	5
fr-156	frame-156	109200	2100	-3015	0	0	0	3015	5
fr-157	frame-155	109900	2100	-3015	0	0	0	3015	5
fr-158	frame-156	110600	2100	-3015	0	0	0	3015	5

A.4.3. Tween Deck

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr–1	bulkhead–4	-2800	5100	-10650	-3500	0	3500	10650	1
fr–2	frame–3	-2100	5100	-10650	-3500	0	3500	10650	1
fr–3	frame–2	-1400	5100	-10650	-3500	0	3500	10650	1
fr–4	frame–1	-700	5100	-10650	-3500	0	3500	10650	1
fr-0	frame-0	0	5100	-10650	-3500	0	3500	10650	1
fr-1	frame-1	700	5100	-10650	-3500	0	3500	10650	1
fr-2	frame-2	1400	5100	-10650	-3500	0	3500	10650	1
fr-3	bulkhead-3	2100	5100	-10650	-3500	0	3500	10650	1
fr-4	frame-4	2800	5100	-10650	-3500	0	3500	10650	1
fr-5	frame-5	3500	5100	-10650	-3500	0	3500	10650	1
fr-6	frame-6	4200	5100	-10650	-3500	0	3500	10650	1
fr-7	frame-7	4900	5100	-10650	-3500	0	3500	10650	1
fr-8	frame-8	5600	5100	-10650	-3500	0	3500	10650	1
fr-9	frame-9	6300	5100	-10650	-3500	0	3500	10650	1
fr-10	frame-10	7000	5100	-10650	-3500	0	3500	10650	1
fr-11	frame-11	7700	5100	-10650	-3500	0	3500	10650	1
fr-12	bulkhead-12	8400	5100	-10650	-6000	0	6000	10650	1
fr-13	frame-13	9100	5100	-10650	-6000	0	6000	10650	1
fr-14	frame-14	9800	5100	-10650	-6000	0	6000	10650	1
fr-15	frame-15	10500	5100	-10650	-6000	0	6000	10650	1
fr-16	frame-16	11200	5100	-10650	-6000	0	6000	10650	1
fr-17	frame-17	11900	5100	-10650	-6000	0	6000	10650	1
fr-18	frame-18	12600	5100	-10650	-6000	0	6000	10650	1
fr-19	frame-19	13300	5100	-10650	-6000	0	6000	10650	1
fr-20	frame-20	14000	5100	-10650	-6000	0	6000	10650	1
fr-21	frame-21	14700	5100	-10650	-6000	0	6000	10650	1
fr-22	frame-22	15400	5100	-10650	-6000	0	6000	10650	1
fr-23	frame-23	16100	5100	-10650	-6000	0	6000	10650	1
fr-24	frame-24	16800	5100	-10650	-6000	0	6000	10650	1
fr-25	frame-25	17500	5100	-10650	-6000	0	6000	10650	1
fr-26	frame-26	18200	5100	-10650	-6000	0	6000	10650	1
fr-27	frame-27	18900	5100	-10650	-6000	0	6000	10650	1
fr-28	frame-28	19600	5100	-10650	-6000	0	6000	10650	1
fr-29	frame-29	20300	5100	-10650	-6000	0	6000	10650	1
fr-30	frame-30	21000	5100	-10650	-6000	0	6000	10650	1
fr-31	frame-31	21700	5100	-10650	-6000	0	6000	10650	1
fr-32	frame-32	22400	5100	-10650	-6000	0	6000	10650	1
fr-33	frame-33	23100	5100	-10650	-6000	0	6000	10650	1
fr-34	frame-34	23800	5100	-10650	-7450	0	6000	10650	1
fr-35	bulkhead-35	24500	5100	-10650	-7450	0	7450	10650	1
fr-36	frame-36	25200	5100	-10650	-7450	0	7450	10650	1
fr-37	frame-37	25900	5100	-10650	-7450	0	7450	10650	1
fr-38	frame-38	26600	5100	-10650	-7450	0	7450	10650	1
fr-39	frame-39	27300	5100	-10650	-7450	0	7450	10650	1
fr-40	frame-40	28000	5100	-10650	-7450	0	7450	10650	1
fr-41	frame-41	28700	5100	-10650	-7450	0	7450	10650	1
fr-42	frame-42	29400	5100	-10650	-7450	0	7450	10650	1
fr-43	frame-43	30100	5100	-10650	-7450	0	7450	10650	1
fr-44	frame-44	30800	5100	-10650	-7450	0	7450	10650	1
fr-45	frame-45	31500	5100	-10650	-7450	0	7450	10650	1

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr-46	frame-46	32200	5100	-10650	-7450	0	7450	10650	1
fr-47	bulkhead-47	32900	5100	-10650	-7450	0	7450	10650	1
fr-48	frame-48	33600	4200	-10650	-6771	0	6771	10650	1
fr-49	frame-49	34300	4200	-10650	-6771	0	6771	10650	1
fr-50	frame-50	35000	4200	-10650	-6771	0	6771	10650	1
fr-51	frame-51	35700	4200	-10650	-6771	0	6771	10650	1
fr-52	frame-52	36400	4200	-10650	-6771	0	6771	10650	1
fr-53	frame-53	37100	4200	-10650	-6771	0	6771	10650	1
fr-54	frame-54	37800	4200	-10650	-6771	0	6771	10650	1
fr-55	frame-55	38500	4200	-10650	-6771	0	6771	10650	1
fr-56	frame-56	39200	4200	-10650	-6771	0	6771	10650	1
fr-57	frame-57	39900	4200	-10650	-6771	0	6771	10650	1
fr-58	frame-58	40600	4200	-10650	-6771	0	6771	10650	1
fr-59	frame-59	41300	4200	-10650	-6771	0	6771	10650	1
fr-60	frame-60	42000	4200	-10650	-6771	0	6771	10650	1
fr-61	frame-61	42700	4200	-10650	-6771	0	6771	10650	1
fr-62	frame-62	43400	4200	-10650	-6771	0	6771	10650	1
fr-63	frame-63	44100	4200	-10650	-6771	0	6771	10650	1
fr-64	frame-64	44800	4200	-10650	-6771	0	6771	10650	1
fr-65	frame-65	45500	4200	-10650	-6771	0	6771	10650	1
fr-66	frame-66	46200	4200	-10650	-6771	0	6771	10650	1
fr-67	frame-67	46900	4200	-10650	-6771	0	6771	10650	1
fr-68	frame-68	47600	4200	-10650	-6771	0	6771	10650	1
fr-69	frame-69	48300	4200	-10650	-6771	0	6771	10650	1
fr-70	frame-70	49000	4200	-10650	-6771	0	6771	10650	1
fr-71	frame-71	49700	4200	-10650	-6771	0	6771	10650	1
fr-72	frame-72	50400	4200	-10650	-6771	0	6771	10650	1
fr-73	frame-73	51100	4200	-10650	-6771	0	6771	10650	1
fr-74	frame-74	51800	4200	-10650	-6771	0	6771	10650	1
fr-75	frame-75	52500	4200	-10650	-6771	0	6771	10650	1
fr-76	frame-76	53200	4200	-10650	-6771	0	6771	10650	1
fr-77	frame-77	53900	4200	-10650	-6771	0	6771	10650	1
fr-78	frame-78	54600	4200	-10650	-6771	0	6771	10650	1
fr-79	frame-79	55300	4200	-10650	-6771	0	6771	10650	1
fr-80	frame-80	56000	4200	-10650	-6771	0	6771	10650	1
fr-81	frame-81	56700	4200	-10650	-6771	0	6771	10650	1
fr-82	frame-82	57400	4200	-10650	-6771	0	6771	10650	1
fr-83	frame-83	58100	4200	-10650	-6771	0	6771	10650	1
fr-84	frame-84	58800	4200	-10650	-6771	0	6771	10650	1
fr-85	frame-85	59500	4200	-10650	-6771	0	6771	10650	1
fr-86	frame-86	60200	4200	-10650	-6771	0	6771	10650	1
fr-87	frame-87	60900	4200	-10650	-6771	0	6771	10650	1
fr-88	frame-88	61600	4200	-10650	-6771	0	6771	10650	1
fr-89	frame-89	62300	4200	-10650	-6771	0	6771	10650	1
fr-90	frame-90	63000	4200	-10650	-6771	0	6771	10650	1
fr-91	frame-91	63700	4200	-10650	-6771	0	6771	10650	1
fr-92	frame-92	64400	4200	-10650	-6771	0	6771	10650	1
fr-93	frame-93	65100	4200	-10650	-6771	0	6771	10650	1
fr-94	frame-94	65800	4200	-10650	-6771	0	6771	10650	1
fr-95	frame-95	66500	4200	-10650	-6771	0	6771	10650	1
fr-96	frame-96	67200	4200	-10650	-6771	0	6771	10650	1
fr-97	frame-97	67900	4200	-10650	-6771	0	6771	10650	1
fr-98	frame-98	68600	4200	-10650	-6771	0	6771	10650	1
fr-99	frame-99	69300	4200	-10650	-6771	0	6771	10650	1

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr-100	frame-100	70000	4200	-10650	-6771	0	6771	10650	1
fr-101	frame-101	70700	4200	-10650	-6771	0	6771	10650	1
fr-102	frame-102	71400	4200	-10650	-6771	0	6771	10650	1
fr-103	frame-103	72100	4200	-10650	-6771	0	6771	10650	1
fr-104	frame-104	72800	4200	-10650	-6771	0	6771	10650	1
fr-105	frame-105	73500	4200	-10650	-6771	0	6771	10650	1
fr-106	frame-106	74200	4200	-10650	-6771	0	6771	10650	1
fr-107	frame-107	74900	4200	-10650	-6771	0	6771	10650	1
fr-108	frame-108	75600	4200	-10650	-6771	0	6771	10650	1
fr-109	frame-109	76300	4200	-10650	-6771	0	6771	10650	1
fr-110	bulkhead-110	77000	4200	-10650	-6771	0	6771	10650	1
fr-111	frame-111	77700	4200	-10650	-6771	0	6771	10650	2
fr-112	frame-112	78400	4200	-10650	-6771	0	6771	10650	2
fr-113	frame-113	79100	4200	-10650	-6771	0	6771	10650	2
fr-114	frame-114	79800	4200	-10650	-6771	0	6771	10650	2
fr-115	frame-115	80500	4200	-10650	-6771	0	6771	10650	2
fr-116	frame-116	81200	4200	-10650	-6771	0	6771	10650	2
fr-117	frame-117	81900	4200	-10650	-6771	0	6771	10650	2
fr-118	frame-118	82600	4200	-10650	-6771	0	6771	10650	2
fr-119	frame-119	83300	4200	-10650	-6771	0	6771	10650	2
fr-120	bulkhead-120	84000	4200	-10650	-7100	0	7100	10650	2
fr-121	frame-121	84700	4200	-10650	-7100	0	7100	10650	2
fr-122	frame-122	85400	4200	-10650	-7100	0	7100	10650	2
fr-123	frame-123	86100	4200	-10650	-7100	0	7100	10650	2
fr-124	frame-124	86800	4200	-10650	-7100	0	7100	10650	2
fr-125	frame-125	87500	4200	-10650	-7100	0	7100	10650	2
fr-126	frame-126	88200	4200	-10650	-7100	0	7100	10650	2
fr-127	frame-127	88900	4200	-10650	-7100	0	7100	10650	2
fr-128	frame-128	89600	4200	-10650	-7100	0	7100	10650	2
fr-129	frame-129	90300	4200	-10650	-7100	0	7100	10650	2
fr-130	bulkhead-130	91000	4200	-10650	-7100	0	7100	10650	2
fr-131	frame-131	91700	4200	-9967	-6771	0	6771	9967	3
fr-132	frame-132	92400	4200	-9967	-6771	0	6771	9967	3
fr-133	frame-133	93100	4200	-9967	-6771	0	6771	9967	3
fr-134	frame-134	93800	4200	-9967	-6771	0	6771	9967	3
fr-135	frame-135	94500	4200	-9967	-6771	0	6771	9967	3
fr-136	frame-136	95200	4200	-9967	-6771	0	6771	9967	3
fr-137	frame-137	95900	4200	-9967	-6771	0	6771	9967	3
fr-138	frame-138	96600	4200	-9967	-6771	0	6771	9967	3
fr-139	frame-139	97300	4200	-9967	-6771	0	6771	9967	3
fr-140	frame-140	98000	4200	-9967	-6771	0	6771	9967	3
fr-141	frame-141	98700	4200	-9967	-6771	0	6771	9967	3
fr-142	bulkhead-142	99400	4200	-9967	-6771	0	6771	9967	3
fr-143	frame-143	100100	4200	-7520	-6771	0	6771	7520	5
fr-144	frame-144	100800	4200	-7520	-6771	0	6771	7520	5
fr-145	frame-145	101500	4200	-7520	-6771	0	6771	7520	5
fr-146	frame-146	102200	4200	-7520	-6771	0	6771	7520	5

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr-147	frame-147	102900	4200	-7520	-6771	0	6771	7520	5
fr-148	frame-148	103600	4200	-7520	-6771	0	6771	7520	5
fr-149	frame-149	104300	4200	-7520	-6771	0	6771	7520	5
fr-150	frame-150	105000	4200	-7520	-6771	0	6771	7520	5
fr-151	frame-151	105700	4200	-7520	-6771	0	6771	7520	5
fr-152	frame-152	106400	4200	-7520	-6771	0	6771	7520	5
fr-153	frame-153	107100	4200	-5725	0	0	0	5725	5
fr-154	frame-154	107800	4200	-5725	0	0	0	5725	5
fr-155	frame-155	108500	4200	-5725	0	0	0	5725	5
fr-156	frame-156	109200	4200	-5725	0	0	0	5725	5
fr-157	frame-157	109900	4200	0	0	0	0	0	0
fr-158	frame-158	110600	4200	0	0	0	0	0	0

A.4.4. Main Deck

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr–1	bulkhead–4	-2800	8400	-10650	-6000	0	6000	10650	1
fr–2	frame–3	-2100	8400	-10650	-6000	0	6000	10650	1
fr–3	frame–2	-1400	8400	-10650	-6000	0	6000	10650	1
fr–4	frame–1	-700	8400	-10650	-6000	0	6000	10650	1
fr-0	frame-0	0	8400	-10650	-6000	0	6000	10650	1
fr-1	frame-1	700	8400	-10650	-6000	0	6000	10650	1
fr-2	frame-2	1400	8400	-10650	-6000	0	6000	10650	1
fr-3	bulkhead-3	2100	8400	-10650	-6000	0	6000	10650	1
fr-4	frame-4	2800	8400	-10650	-6000	0	6000	10650	1
fr-5	frame-5	3500	8400	-10650	-6000	0	6000	10650	1
fr-6	frame-6	4200	8400	-10650	-6000	0	6000	10650	1
fr-7	frame-7	4900	8400	-10650	-6000	0	6000	10650	1
fr-8	frame-8	5600	8400	-10650	-6000	0	6000	10650	1
fr-9	frame-9	6300	8400	-10650	-6000	0	6000	10650	1
fr-10	frame-10	7000	8400	-10650	-6000	0	6000	10650	1
fr-11	frame-11	7700	8400	-10650	-6000	0	6000	10650	1
fr-12	bulkhead-12	8400	8400	-10650	-6000	0	6000	10650	1
fr-13	frame-13	9100	8400	-10650	-6000	0	6000	10650	1
fr-14	frame-14	9800	8400	-10650	-6000	0	6000	10650	1
fr-15	frame-15	10500	8400	-10650	-6000	0	6000	10650	1
fr-16	frame-16	11200	8400	-10650	-6000	0	6000	10650	1
fr-17	frame-17	11900	8400	-10650	-6000	0	6000	10650	1
fr-18	frame-18	12600	8400	-10650	-6000	0	6000	10650	1
fr-19	frame-19	13300	8400	-10650	-6000	0	6000	10650	1
fr-20	frame-20	14000	8400	-10650	-6000	0	6000	10650	1
fr-21	frame-21	14700	8400	-10650	-6000	0	6000	10650	1
fr-22	frame-22	15400	8400	-10650	-6000	0	6000	10650	1
fr-23	frame-23	16100	8400	-10650	-6000	0	6000	10650	1
fr-24	frame-24	16800	8400	-10650	-6000	0	6000	10650	1
fr-25	frame-25	17500	8400	-10650	-6000	0	6000	10650	1
fr-26	frame-26	18200	8400	-10650	-6000	0	6000	10650	1
fr-27	frame-27	18900	8400	-10650	-6000	0	6000	10650	1
fr-28	frame-28	19600	8400	-10650	-6000	0	6000	10650	1
fr-29	frame-29	20300	8400	-10650	-6000	0	6000	10650	1
fr-30	frame-30	21000	8400	-10650	-6000	0	6000	10650	1

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr-31	frame-31	21700	8400	-10650	-6000	0	6000	10650	1
fr-32	frame-32	22400	8400	-10650	-6000	0	6000	10650	1
fr-33	frame-33	23100	8400	-10650	-6000	0	6000	10650	1
fr-34	frame-34	23800	8400	-10650	-7450	0	6000	10650	1
fr-35	bulkhead-35	24500	8400	-10650	-7450	0	7450	10650	1
fr-36	frame-36	25200	8400	-10650	-7450	0	7450	10650	1
fr-37	frame-37	25900	8400	-10650	-7450	0	7450	10650	1
fr-38	frame-38	26600	8400	-10650	-7450	0	7450	10650	1
fr-39	frame-39	27300	8400	-10650	-7450	0	7450	10650	1
fr-40	frame-40	28000	8400	-10650	-7450	0	7450	10650	1
fr-41	frame-41	28700	8400	-10650	-7450	0	7450	10650	1
fr-42	frame-42	29400	8400	-10650	-7450	0	7450	10650	1
fr-43	frame-43	30100	8400	-10650	-7450	0	7450	10650	1
fr-44	frame-44	30800	8400	-10650	-7450	0	7450	10650	1
fr-45	frame-45	31500	8400	-10650	-7450	0	7450	10650	1
fr-46	frame-46	32200	8400	-10650	-7450	0	7450	10650	1
fr-47	bulkhead-47	32900	8400	-10650	-7450	0	7450	10650	1
fr-48	frame-48	33600	7500	-10650	-6771	0	6771	10650	1
fr-49	frame-49	34300	7500	-10650	-6771	0	6771	10650	1
fr-50	frame-50	35000	7500	-10650	-6771	0	6771	10650	1
fr-51	frame-51	35700	7500	-10650	-6771	0	6771	10650	1
fr-52	frame-52	36400	7500	-10650	-6771	0	6771	10650	1
fr-53	frame-53	37100	7500	-10650	-6771	0	6771	10650	1
fr-54	frame-54	37800	7500	-10650	-6771	0	6771	10650	1
fr-55	frame-55	38500	7500	-10650	-6771	0	6771	10650	1
fr-56	frame-56	39200	7500	-10650	-6771	0	6771	10650	1
fr-57	frame-57	39900	7500	-10650	-6771	0	6771	10650	1
fr-58	frame-58	40600	7500	-10650	-6771	0	6771	10650	1
fr-59	frame-59	41300	7500	-10650	-6771	0	6771	10650	1
fr-60	frame-60	42000	7500	-10650	-6771	0	6771	10650	1
fr-61	frame-61	42700	7500	-10650	-6771	0	6771	10650	1
fr-62	frame-62	43400	7500	-10650	-6771	0	6771	10650	1
fr-63	frame-63	44100	7500	-10650	-6771	0	6771	10650	1
fr-64	frame-64	44800	7500	-10650	-6771	0	6771	10650	1
fr-65	frame-65	45500	7500	-10650	-6771	0	6771	10650	1
fr-66	frame-66	46200	7500	-10650	-6771	0	6771	10650	1
fr-67	frame-67	46900	7500	-10650	-6771	0	6771	10650	1
fr-68	frame-68	47600	7500	-10650	-6771	0	6771	10650	1
fr-69	frame-69	48300	7500	-10650	-6771	0	6771	10650	1
fr-70	frame-70	49000	7500	-10650	-6771	0	6771	10650	1
fr-71	frame-71	49700	7500	-10650	-6771	0	6771	10650	1
fr-72	frame-72	50400	7500	-10650	-6771	0	6771	10650	1
fr-73	frame-73	51100	7500	-10650	-6771	0	6771	10650	1
fr-74	frame-74	51800	7500	-10650	-6771	0	6771	10650	1
fr-75	frame-75	52500	7500	-10650	-6771	0	6771	10650	1
fr-76	frame-76	53200	7500	-10650	-6771	0	6771	10650	1
fr-77	frame-77	53900	7500	-10650	-6771	0	6771	10650	1
fr-78	frame-78	54600	7500	-10650	-6771	0	6771	10650	1
fr-79	frame-79	55300	7500	-10650	-6771	0	6771	10650	1
fr-80	frame-80	56000	7500	-10650	-6771	0	6771	10650	1
fr-81	frame-81	56700	7500	-10650	-6771	0	6771	10650	1
fr-82	frame-82	57400	7500	-10650	-6771	0	6771	10650	1

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr-83	frame-83	58100	7500	-10650	-6771	0	6771	10650	1
fr-84	frame-84	58800	7500	-10650	-6771	0	6771	10650	1
fr-85	frame-85	59500	7500	-10650	-6771	0	6771	10650	1
fr-86	frame-86	60200	7500	-10650	-6771	0	6771	10650	1
fr-87	frame-87	60900	7500	-10650	-6771	0	6771	10650	1
fr-88	frame-88	61600	7500	-10650	-6771	0	6771	10650	1
fr-89	frame-89	62300	7500	-10650	-6771	0	6771	10650	1
fr-90	frame-90	63000	7500	-10650	-6771	0	6771	10650	1
fr-91	frame-91	63700	7500	-10650	-6771	0	6771	10650	1
fr-92	frame-92	64400	7500	-10650	-6771	0	6771	10650	1
fr-93	frame-93	65100	7500	-10650	-6771	0	6771	10650	1
fr-94	frame-94	65800	7500	-10650	-6771	0	6771	10650	1
fr-95	frame-95	66500	7500	-10650	-6771	0	6771	10650	1
fr-96	frame-96	67200	7500	-10650	-6771	0	6771	10650	1
fr-97	frame-97	67900	7500	-10650	-6771	0	6771	10650	1
fr-98	frame-98	68600	7500	-10650	-6771	0	6771	10650	1
fr-99	frame-99	69300	7500	-10650	-6771	0	6771	10650	1
fr-100	frame-100	70000	7500	-10650	-6771	0	6771	10650	1
fr-101	frame-101	70700	7500	-10650	-6771	0	6771	10650	1
fr-102	frame-102	71400	7500	-10650	-6771	0	6771	10650	1
fr-103	frame-103	72100	7500	-10650	-6771	0	6771	10650	1
fr-104	frame-104	72800	7500	-10650	-6771	0	6771	10650	1
fr-105	frame-105	73500	7500	-10650	-6771	0	6771	10650	1
fr-106	frame-106	74200	7500	-10650	-6771	0	6771	10650	1
fr-107	frame-107	74900	7500	-10650	-6771	0	6771	10650	1
fr-108	frame-108	75600	7500	-10650	-6771	0	6771	10650	1
fr-109	frame-109	76300	7500	-10650	-6771	0	6771	10650	1
fr-110	bulkhead-110	77000	7500	-10650	-7450	0	7450	10650	1
fr-111	frame-111	77700	7500	-10650	-7450	0	7450	10650	2
fr-112	frame-112	78400	7500	-10650	-7450	0	7450	10650	2
fr-113	frame-113	79100	7500	-10650	-7450	0	7450	10650	2
fr-114	frame-114	79800	7500	-10650	-7450	0	7450	10650	2
fr-115	frame-115	80500	7500	-10650	-7450	0	7450	10650	2
fr-116	frame-116	81200	7500	-10650	-7450	0	7450	10650	2
fr-117	frame-117	81900	7500	-10650	-7450	0	7450	10650	2
fr-118	frame-118	82600	7500	-10650	-7450	0	7450	10650	2
fr-119	frame-119	83300	7500	-10650	-7450	0	7450	10650	2
fr-120	bulkhead-120	84000	7500	-10650	-7450	0	7450	10650	2
fr-121	frame-121	84700	7500	-10650	-7450	0	7450	10650	2
fr-122	frame-122	85400	7500	-10650	-7450	0	7450	10650	2
fr-123	frame-123	86100	7500	-10650	-7450	0	7450	10650	2
fr-124	frame-124	86800	7500	-10650	-7450	0	7450	10650	2
fr-125	frame-125	87500	7500	-10650	-7450	0	7450	10650	2
fr-126	frame-126	88200	7500	-10650	-7450	0	7450	10650	2
fr-127	frame-127	88900	7500	-10650	-7450	0	7450	10650	2
fr-128	frame-128	89600	7500	-10650	-7450	0	7450	10650	2
fr-129	frame-129	90300	7500	-10650	-7450	0	7450	10650	2
fr-130	bulkhead-130	91000	7500	-10650	-7450	0	7450	10650	2
fr-131	frame-131	91700	7500	-9967	-7450	0	7450	9967	3
fr-132	frame-132	92400	7500	-9967	-7450	0	7450	9967	3
fr-133	frame-133	93100	7500	-9967	-7450	0	7450	9967	3
fr-134	frame-134	93800	7500	-9967	-7450	0	7450	9967	3
fr-135	frame-135	94500	7500	-9967	-7450	0	7450	9967	3
fr-136	frame-136	95200	7500	-9967	-7450	0	7450	9967	3
fr-137	frame-137	95900	7500	-9967	-7450	0	7450	9967	3

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr-138	frame-138	96600	7500	-9967	-7450	0	7450	9967	3
fr-139	frame-139	97300	7500	-9967	-7450	0	7450	9967	3
fr-140	frame-140	98000	7500	-9967	-7450	0	7450	9967	3
fr-141	frame-141	98700	7500	-9967	-7450	0	7450	9967	3
fr-142	bulkhead-142	99400	7500	-9967	-7450	0	7450	9967	3
fr-143	frame-143	100100	7500	-7520	-7450	0	7450	7520	4
fr-144	frame-144	100800	7500	-7520	-7450	0	7450	7520	4
fr-145	frame-145	101500	7500	-7520	-7450	0	7450	7520	4
fr-146	frame-146	102200	7500	-7520	-7450	0	7450	7520	4
fr-147	frame-147	102900	7500	-7520	-7450	0	7450	7520	4
fr-148	frame-148	103600	7500	-7520	-7450	0	7450	7520	4
fr-149	frame-149	104300	7500	-7520	-7450	0	7450	7520	4
fr-150	frame-150	105000	7500	-7520	-7450	0	7450	7520	4
fr-151	frame-151	105700	7500	-7520	-7450	0	7450	7520	4
fr-152	frame-152	106400	7500	-7520	-7450	0	7450	7520	4
fr-153	frame-153	107100	7500	-5725	0	0	0	5725	4
fr-154	frame-154	107800	7500	-5725	0	0	0	5725	4
fr-155	frame-155	108500	7500	-5725	0	0	0	5725	4
fr-156	frame-156	109200	7500	-5725	0	0	0	5725	4
fr-157	frame-157	109900	7500	-5725	0	0	0	5725	4
fr-158	frame-158	110600	7500	0	0	0	0	0	0

A.4.5. Coaming Deck

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr–1	bulkhead–4	-2800	11700	0	0	0	0	0	0
fr–2	frame–3	-2100	11700	0	0	0	0	0	0
fr–3	frame–2	-1400	11700	0	0	0	0	0	0
fr–4	frame–1	-700	11700	0	0	0	0	0	0
fr-0	frame-0	0	11700	0	0	0	0	0	0
fr-1	frame-1	700	11700	0	0	0	0	0	0
fr-2	frame-2	1400	11700	0	0	0	0	0	0
fr-3	bulkhead-3	2100	11700	0	0	0	0	0	0
fr-4	frame-4	2800	11700	0	0	0	0	0	0
fr-5	frame-5	3500	11700	0	0	0	0	0	0
fr-6	frame-6	4200	11700	0	0	0	0	0	0
fr-7	frame-7	4900	11700	0	0	0	0	0	0
fr-8	frame-8	5600	11700	0	0	0	0	0	0
fr-9	frame-9	6300	11700	0	0	0	0	0	0
fr-10	frame-10	7000	11700	0	0	0	0	0	0
fr-11	frame-11	7700	11700	0	0	0	0	0	0
fr-12	bulkhead-12	11700	11700	-6000	-6000	0	6000	6000	1
fr-13	frame-13	9100	11700	-6000	-6000	0	6000	6000	1
fr-14	frame-14	9800	11700	-6000	-6000	0	6000	6000	1
fr-15	frame-15	10500	11700	-6000	-6000	0	6000	6000	1
fr-16	frame-16	11200	11700	-6000	0	0	0	6000	1
fr-17	frame-17	11900	11700	-6000	0	0	0	6000	1
fr-18	frame-18	12600	11700	-6000	0	0	0	6000	1
fr-19	frame-19	13300	11700	-6000	0	0	0	6000	1
fr-20	frame-20	14000	11700	-6000	0	0	0	6000	1
fr-21	frame-21	14700	11700	-6000	0	0	0	6000	1
fr-22	frame-22	15400	11700	-6000	0	0	0	6000	1
fr-23	frame-23	16100	11700	-6000	0	0	0	6000	1

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr-24	frame-24	16800	11700	-6000	0	0	0	6000	1
fr-25	frame-25	17500	11700	-6000	0	0	0	6000	1
fr-26	frame-26	18200	11700	-6000	0	0	0	6000	1
fr-27	frame-27	18900	11700	-6000	0	0	0	6000	1
fr-28	frame-28	19600	11700	-6000	0	0	0	6000	1
fr-29	frame-29	20300	11700	-6000	0	0	0	6000	1
fr-30	frame-30	21000	11700	-6000	0	0	0	6000	1
fr-31	frame-31	21700	11700	-6000	0	0	0	6000	1
fr-32	frame-32	22400	11700	-6000	0	0	0	6000	1
fr-33	frame-33	23100	11700	-6000	0	0	0	6000	1
fr-34	frame-34	23800	11700	-6000	0	0	0	6000	1
fr-35	bulkhead-35	24500	11700	-7450	0	0	0	7450	1
fr-36	frame-36	25200	11700	-7450	0	0	0	7450	1
fr-37	frame-37	25900	11700	-7450	0	0	0	7450	1
fr-38	frame-38	26600	11700	-7450	0	0	0	7450	1
fr-39	frame-39	27300	11700	-7450	0	0	0	7450	1
fr-40	frame-40	28000	11700	-7450	0	0	0	7450	1
fr-41	frame-41	28700	11700	-7450	0	0	0	7450	1
fr-42	frame-42	29400	11700	-7450	0	0	0	7450	1
fr-43	frame-43	30100	11700	-7450	0	0	0	7450	1
fr-44	frame-44	30800	11700	-7450	0	0	0	7450	1
fr-45	frame-45	31500	11700	-7450	0	0	0	7450	1
fr-46	frame-46	32200	11700	-7450	0	0	0	7450	1
fr-47	bulkhead-47	32900	11700	-7450	0	0	0	7450	1
fr-48	frame-48	33600	10800	-7450	-3100	0	3100	7450	1
fr-49	frame-49	34300	10800	-7450	-3100	0	3100	7450	1
fr-50	frame-50	35000	10800	-7450	-3100	0	3100	7450	1
fr-51	frame-51	35700	10800	-7450	-3100	0	3100	7450	1
fr-52	frame-52	36400	10800	-7450	-3100	0	3100	7450	1
fr-53	frame-53	37100	10800	-7450	-3100	0	3100	7450	1
fr-54	frame-54	37800	10800	-7450	-3100	0	3100	7450	1
fr-55	frame-55	38500	10800	-7450	-3100	0	3100	7450	1
fr-56	frame-56	39200	10800	-7450	-3100	0	3100	7450	1
fr-57	frame-57	39900	10800	-7450	-3100	0	3100	7450	1
fr-58	frame-58	40600	10800	-7450	-3100	0	3100	7450	1
fr-59	frame-59	41300	10800	-7450	-3100	0	3100	7450	1
fr-60	frame-60	42000	10800	-7450	-3100	0	3100	7450	1
fr-61	frame-61	42700	10800	-7450	-3100	0	3100	7450	1
fr-62	frame-62	43400	10800	-7450	-3100	0	3100	7450	1
fr-63	frame-63	44100	10800	-7450	-3100	0	3100	7450	1
fr-64	frame-64	44800	10800	-7450	-3100	0	3100	7450	1
fr-65	frame-65	45500	10800	-7450	-3100	0	3100	7450	1
fr-66	frame-66	46200	10800	-7450	-3100	0	3100	7450	1
fr-67	frame-67	46900	10800	-7450	-3100	0	3100	7450	1
fr-68	frame-68	47600	10800	-7450	-3100	0	3100	7450	1
fr-69	frame-69	48300	10800	-7450	-3100	0	3100	7450	1
fr-70	frame-70	49000	10800	-7450	-3100	0	3100	7450	1
fr-71	frame-71	49700	10800	-7450	-3100	0	3100	7450	1
fr-72	frame-72	50400	10800	-7450	-3100	0	3100	7450	1
fr-73	frame-73	51100	10800	-7450	-3100	0	3100	7450	1
fr-74	frame-74	51800	10800	-7450	-3100	0	3100	7450	1
fr-75	frame-75	52500	10800	-7450	-3100	0	3100	7450	1

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr-76	frame-76	53200	10800	-7450	-3100	0	3100	7450	1
fr-77	frame-77	53900	10800	-7450	-3100	0	3100	7450	1
fr-78	frame-78	54600	10800	-7450	-3100	0	3100	7450	1
fr-79	frame-79	55300	10800	-7450	-3100	0	3100	7450	1
fr-80	frame-80	56000	10800	-7450	-3100	0	3100	7450	1
fr-81	frame-81	56700	10800	-7450	-3100	0	3100	7450	1
fr-82	frame-82	57400	10800	-7450	-3100	0	3100	7450	1
fr-83	frame-83	58100	10800	-7450	-3100	0	3100	7450	1
fr-84	frame-84	58800	10800	-7450	-3100	0	3100	7450	1
fr-85	frame-85	59500	10800	-7450	-3100	0	3100	7450	1
fr-86	frame-86	60200	10800	-7450	-3100	0	3100	7450	1
fr-87	frame-87	60900	10800	-7450	-3100	0	3100	7450	1
fr-88	frame-88	61600	10800	-7450	-3100	0	3100	7450	1
fr-89	frame-89	62300	10800	-7450	-3100	0	3100	7450	1
fr-90	frame-90	63000	10800	-7450	-3100	0	3100	7450	1
fr-91	frame-91	63700	10800	-7450	-3100	0	3100	7450	1
fr-92	frame-92	64400	10800	-7450	-3100	0	3100	7450	1
fr-93	frame-93	65100	10800	-7450	-3100	0	3100	7450	1
fr-94	frame-94	65800	10800	-7450	-3100	0	3100	7450	1
fr-95	frame-95	66500	10800	-7450	-3100	0	3100	7450	1
fr-96	frame-96	67200	10800	-7450	-3100	0	3100	7450	1
fr-97	frame-97	67900	10800	-7450	-3100	0	3100	7450	1
fr-98	frame-98	68600	10800	-7450	-3100	0	3100	7450	1
fr-99	frame-99	69300	10800	-7450	-3100	0	3100	7450	1
fr-100	frame-100	70000	10800	-7450	-3100	0	3100	7450	1
fr-101	frame-101	70700	10800	-7450	-3100	0	3100	7450	1
fr-102	frame-102	71400	10800	-7450	-3100	0	3100	7450	1
fr-103	frame-103	72100	10800	-7450	-3100	0	3100	7450	1
fr-104	frame-104	72800	10800	-7450	-3100	0	3100	7450	1
fr-105	frame-105	73500	10800	-7450	-3100	0	3100	7450	1
fr-106	frame-106	74200	10800	-7450	-3100	0	3100	7450	1
fr-107	frame-107	74900	10800	-7450	-3100	0	3100	7450	1
fr-108	frame-108	75600	10800	-7450	-3100	0	3100	7450	1
fr-109	frame-109	76300	10800	-7450	-3100	0	3100	7450	1
fr-110	bulkhead-110	77000	10800	-10650	0	0	0	10650	1
fr-111	frame-111	77700	10800	-10650	0	0	0	10650	2
fr-112	frame-112	78400	10800	-10650	0	0	0	10650	2
fr-113	frame-113	79100	10800	-10650	0	0	0	10650	2
fr-114	frame-114	79800	10800	-10650	0	0	0	10650	2
fr-115	frame-115	80500	10800	-10650	0	0	0	10650	2
fr-116	frame-116	81200	10800	-10650	0	0	0	10650	2
fr-117	frame-117	81900	10800	-10650	0	0	0	10650	2
fr-118	frame-118	82600	10800	-10650	0	0	0	10650	2
fr-119	frame-119	83300	10800	-10650	0	0	0	10650	2
fr-120	bulkhead-120	84000	10800	-10650	0	0	0	10650	2
fr-121	frame-121	84700	10800	-10650	0	0	0	10650	2
fr-122	frame-122	85400	10800	-10650	0	0	0	10650	2
fr-123	frame-123	86100	10800	-10650	0	0	0	10650	2
fr-124	frame-124	86800	10800	-10650	0	0	0	10650	2
fr-125	frame-125	87500	10800	-10650	0	0	0	10650	2
fr-126	frame-126	88200	10800	-10650	0	0	0	10650	2
fr-127	frame-127	88900	10800	-10650	0	0	0	10650	2
fr-128	frame-128	89600	10800	-10650	0	0	0	10650	2
fr-129	frame-129	90300	10800	-10650	0	0	0	10650	2

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps-center	CL-PS	curve
fr-130	bulkhead-130	91000	10800	-10650	0	0	0	10650	2
fr-131	frame-131	91700	10800	-9967	0	0	0	9967	3
fr-132	frame-132	92400	10800	-9967	0	0	0	9967	3
fr-133	frame-133	93100	10800	-9967	0	0	0	9967	3
fr-134	frame-134	93800	10800	-9967	0	0	0	9967	3
fr-135	frame-135	94500	10800	-9967	0	0	0	9967	3
fr-136	frame-136	95200	10800	-9967	0	0	0	9967	3
fr-137	frame-137	95900	10800	-9967	0	0	0	9967	3
fr-138	frame-138	96600	10800	-9967	0	0	0	9967	3
fr-139	frame-139	97300	10800	-9967	0	0	0	9967	3
fr-140	frame-140	98000	10800	-9967	0	0	0	9967	3
fr-141	frame-141	98700	10800	-9967	0	0	0	9967	3
fr-142	bulkhead-142	99400	10800	-9967	0	0	0	9967	3
fr-143	frame-143	100100	10800	-7520	0	0	0	7520	4
fr-144	frame-144	100800	10800	-7520	0	0	0	7520	4
fr-145	frame-145	101500	10800	-7520	0	0	0	7520	4
fr-146	frame-146	102200	10800	-7520	0	0	0	7520	4
fr-147	frame-147	102900	10800	-7520	0	0	0	7520	4
fr-148	frame-148	103600	10800	-7520	0	0	0	7520	4
fr-149	frame-149	104300	10800	-7520	0	0	0	7520	4
fr-150	frame-150	105000	10800	-7520	0	0	0	7520	4
fr-151	frame-151	105700	10800	-7520	0	0	0	7520	4
fr-152	frame-152	106400	10800	-7520	0	0	0	7520	4
fr-153	frame-153	107100	10800	-5725	0	0	0	5725	4
fr-154	frame-154	107800	10800	-5725	0	0	0	5725	4
fr-155	frame-155	108500	10800	-5725	0	0	0	5725	4
fr-156	frame-156	109200	10800	-5725	0	0	0	5725	4
fr-157	frame-157	109900	10800	-5725	0	0	0	5725	4
fr-158	frame-158	110600	10800	0	0	0	0	0	0

A.5. Equipment Table

Equipment ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	erect-x	erect-y	erect-z
eqp-001	bowthruster-pump-1	94500	-2100	2200	96600	100	5000	0	0	0
eqp-002	bowthruster-pump-2	96600	-100	2200	98700	2100	5000	0	0	0
eqp-201	conical-vale-1	72800	-6600	-75	76300	-3100	2250	0	0	1
eqp-202	conical-vale-tube	74200	-5200	2250	74900	-4300	10800	0	0	1
eqp-211	conical-vale-2	67900	-6600	-75	71400	-3100	2250	0	0	1
eqp-212	conical-vale-tube	69300	-5200	0	70000	-4300	10800	0	0	1
eqp-221	conical-vale-3	63000	-6600	-75	66500	-3100	2250	0	0	1
eqp-222	conical-vale-tube	64400	-5200	0	65100	-4300	10800	0	0	1
eqp-231	conical-vale-4	58100	-6600	-75	61600	-3100	2250	0	0	1
eqp-232	conical-vale-tube	59500	-5200	0	60200	-4300	10800	0	0	1
eqp-241	conical-vale-5	53200	-6600	-75	56700	-3100	2250	0	0	1
eqp-242	conical-vale-tube	54600	-5200	0	55300	-4300	10800	0	0	1
eqp-251	conical-vale-6	48300	-6600	-75	51800	-3100	2250	0	0	1
eqp-252	conical-vale-tube	49700	-5200	0	50400	-4300	10800	0	0	1
eqp-261	conical-vale-7	43400	-6600	-75	46900	-3100	2250	0	0	1

Equipment ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	erect-x	erect-y	erect-z
eqp-262	conical-vale-tube	44800	-5200	0	45500	-4300	10800	0	0	1
eqp-271	conical-vale-8	38500	-6600	-75	42000	-3100	2250	0	0	1
eqp-272	conical-vale-tube	39900	-5200	0	40600	-4300	10800	0	0	1
eqp-281	conical-vale-9	33600	-6600	-75	37100	-3100	2250	0	0	1
eqp-282	conical-vale-tube	35000	-5200	0	35700	-4300	10800	0	0	1
eqp-291	conical-vale-10	72800	6600	-75	76300	3100	2250	0	0	1
eqp-292	conical-vale-tube	74200	4300	0	74900	5200	10800	0	0	1
eqp-301	conical-vale-11	67900	6600	-75	71400	3100	2250	0	0	1
eqp-302	conical-vale-tube	69300	4300	0	70000	5200	10800	0	0	1

Equipment ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	erect-x	erect-y	erect-z
eqp-311	conical-vale-12	63000	6600	-75	66500	3100	2250	0	0	1
eqp-312	conical-vale-tube	64400	4300	0	65100	5200	10800	0	0	1
eqp-321	conical-vale-13	58100	6600	-75	61600	3100	2250	0	0	1
eqp-322	conical-vale-tube	59500	4300	0	60200	5200	10800	0	0	1
eqp-331	conical-vale-14	53200	6600	-75	56700	3100	2250	0	0	1
eqp-332	conical-vale-tube	54600	4300	0	55300	5200	10800	0	0	1
eqp-341	conical-vale-15	48300	6600	-75	51800	3100	2250	0	0	1
eqp-342	conical-vale-tube	49700	4300	0	50400	5200	10800	0	0	1
eqp-351	conical-vale-16	43400	6600	-75	46900	3100	2250	0	0	1
eqp-352	conical-vale-tube	44800	4300	0	45500	5200	10800	0	0	1
eqp-361	conical-vale-17	38500	6600	-75	42000	3100	2250	0	0	1
eqp-362	conical-vale-tube	39900	4300	0	40600	5200	10800	0	0	1
eqp-371	conical-vale-18	33600	6600	-75	37100	3100	2250	0	0	1
eqp-372	conical-vale-tube	35000	4300	0	35700	5200	10800	0	0	1
eqp-021	bow-pump	79800	-6770	1120	84000	-1000	4900	1	1	1
eqp-023	suctiontube-inlet-sb	28700	-10650	1120	32900	-9850	8400	0	0	0
eqp-024	suctiontube-inlet-ps	28700	10650	1120	32900	9850	8400	0	0	0
eqp-025	main-engine-sb	14000	-6020	1120	21700	-3220	5400	1	1	1
eqp-026	main-engine-ps	14000	6020	1120	21700	3220	5400	1	1	1
eqp-101	bow-thruster	94150	-9967	0	99050	9967	2100	2	2	2
eqp-111	skeg	2800	-300	0	8400	300	5100	2	2	2
eqp-112	skeg	8400	-300	0	17500	300	1120	0	0	1
eqp-113	skeg	-2700	-300	3600	2800	300	5100	2	2	2
eqp-104	dredgepump-tube	25000	-4500	1120	25700	-3800	11700	1	1	1
eqp-105	dredgepump-tube	25000	3800	1120	25700	4500	11700	1	1	1
eqp-901	coamingdeck-95-cd	66500	-10650	10699	74200	-6000	10700	2	2	2
eqp-902	coamingdeck-95-cd	66500	6000	10699	74200	10650	10700	2	2	2

A.6. Compartments Table

Compartment ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	Type
sys-1001	fresh-water-technical	85400	-6770	1120	91000	0	4200	watertank
sys-1002	fresh-water-SB	77000	-10650	1120	91000	-6771	4200	watertank
sys-1003	fresh-water-PS	77000	6771	1120	91000	10650	4200	watertank
sys-1004	ballast$_{b}ow1$	99400	-7520	2100	106400	7520	4200	watertank
sys-1005	ballast$_{b}ow2$	106400	-3015	2100	110600	3015	4200	watertank
sys-1006	ballast$_{b}ow3$	99400	-7520	4200	106400	7520	7500	watertank
sys-1007	ballast$_{b}ow4$	106400	-5725	4200	109200	5725	7500	watertank
sys-1008	ballast$_{b}ow5$	99400	-7520	7500	106400	7520	10800	watertank
sys-1009	ballast$_{b}ow6$	106400	-5725	7500	109900	5725	10800	watertank
sys-2001	bowthrusterroom1	91000	-9967	0	99400	9967	2100	techroom

Compartment ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	Type
sys-2002	bowthrusterroom2	91000	-9967	2100	99400	9967	4200	techroom
sys-3004	pumproom-bow-tween	77000	-10650	4200	84000	10650	7500	techroom
sys-3005	pumproom-bow-tt	77000	-6771	1120	85400	6771	4200	techroom
sys-3006	pumproom-bow-tt	85400	0	1120	91000	6771	4200	techroom
sys-3007	Fresh-water-tech-tt	85400	-6771	1120	91000	0	4200	watertank
sys-4001	boatswainstore-tween1	91000	-9967	4200	99400	9967	7500	workshop
sys-4005	boatswainstore-main	95200	-9967	7500	99400	9967	10800	workshop
sys-5001	laundryroom	84000	-7100	4200	91000	0	7500	accomodation
sys-5002	provisionstore	84000	0	4200	91000	8400	7500	accomodation
sys-5003	accomodation-main1	77000	-10650	7500	91000	10650	10800	accomodation
sys-5004	accomodation-main2	91000	-9967	7500	95200	9967	10800	accomodation
sys-1010	ballast$_{aft_sb}$	4200	-7079	1120	8400	-2500	4200	watertank
sys-1011	ballast$_{aft_ps}$	4200	7079	1120	8400	2500	4200	watertank
sys-3008	mdo$_{daily}$	8400	6000	5100	10500	10650	8400	oiltank
sys-3009	hfo$_{daily}$	21700	6000	5100	24500	10650	8400	oiltank
sys-3010	HFO	32900	-9650	1120	50050	-6771	4200	oiltank
sys-3011	HFO	50050	-9650	1120	64750	-6771	4200	oiltank
sys-3012	HFO	64750	-9650	1120	75600	-6771	4200	oiltank
sys-3013	HFO$_{settling}$	32900	6771	1120	37800	9650	4200	oiltank
sys-3014	HFO	37800	6771	1120	50050	9650	4200	oiltank
sys-3015	HFO	50050	6771	1120	64750	9650	4200	oiltank
sys-3016	HFO	64750	6771	1120	75600	9650	4200	oiltank
sys-4006	separator-room	10500	6000	5100	21700	10650	8400	techroom
sys-4007	electric-store	2100	6000	5100	8400	10650	8400	techroom
sys-4008	electric-repair-area	2100	3500	5100	8400	6000	8400	techroom
sys-4009	er-store	2100	-10650	5100	8400	-6000	8400	techroom
sys-4010	er-repair-area	2100	-6000	5100	8400	-3500	8400	techroom
sys-4011	switch-board$_{room}$	8400	-10650	5100	21700	-6000	8400	techroom
sys-4012	steering$_{room}$	-2800	-10650	5100	2100	10650	8400	navigation-room
sys-5005	tech-coaming1	8400	-6000	8400	24500	6000	11700	techroom
sys-5006	tech-coaming2	24500	-7450	8400	32900	7450	11700	techroom
sys-6001	engineroom-tt	8400	-10650	1120	24500	10650	5100	engine-room
sys-6002	engineroom-md	8400	-6000	5100	24500	6000	8400	engine-room
sys-6003	engineroom-md	2100	-3500	5100	8400	3500	8400	engine-room
sys-6004	pumproom-tt	24500	-10650	1120	32900	10650	5100	pump$_{room}$
sys-6005	pumproom-md	24500	-10650	5100	32900	10650	8400	pump$_{room}$
sys-7001	superstructure	79100	-7450	10800	95200	7450	13700	accomodation
sys-7002	superstructure	79100	-7450	13700	91000	7450	16600	accomodation
sys-7003	superstructure	79100	-7450	16600	91000	7450	19500	accomodation
sys-7004	superstructure	81200	-7450	19500	88900	7450	21400	accomodation
sys-7005	superstructure	81200	-7450	21400	88900	7450	24500	accomodation
sys-7006	chimnies	8400	-4000	11700	14000	4000	17500	accomodation

B

Top View Block Division Generator Results Verification

B.1. Verification Transverse Seams

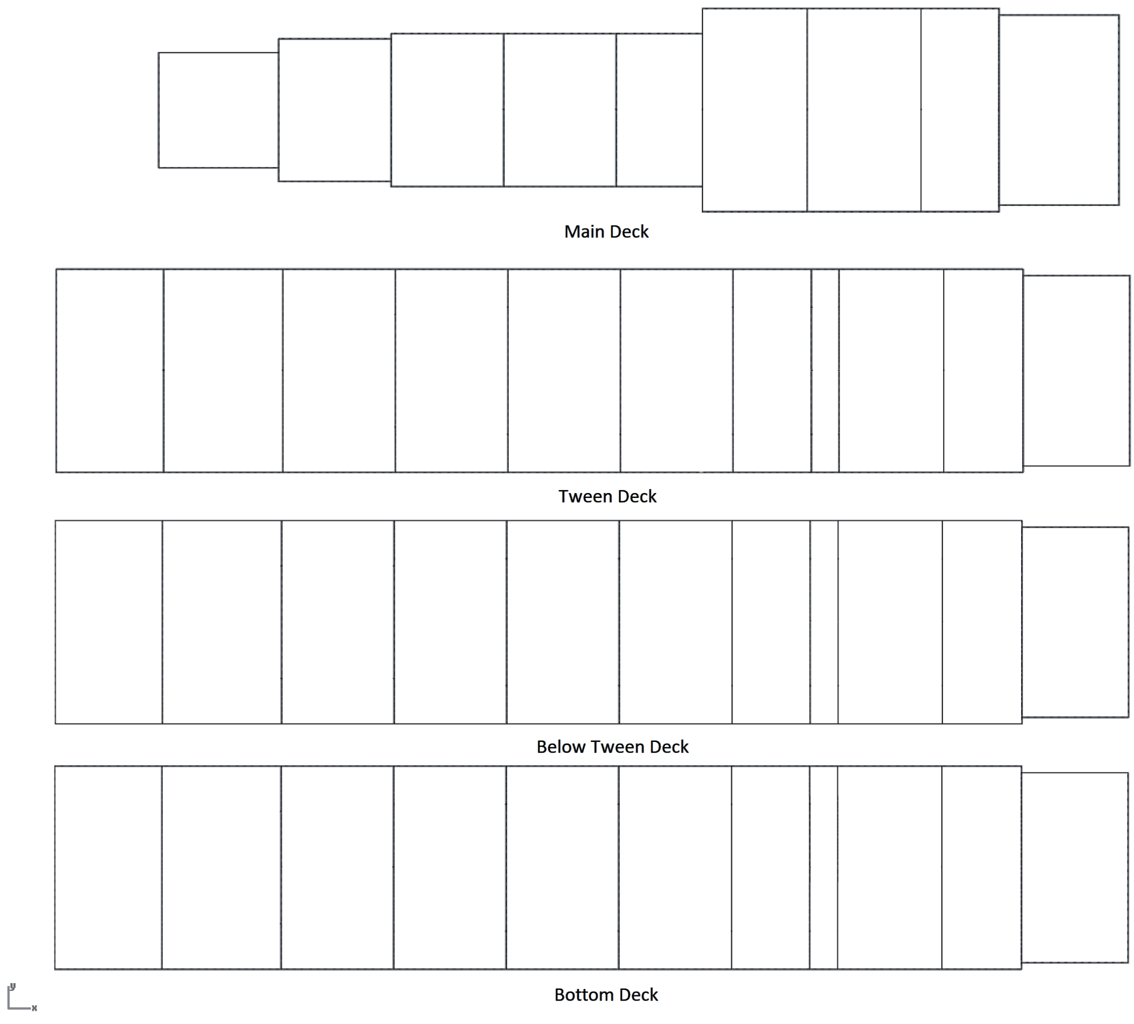


Figure B.1: Top view results of verification after transverse seam placing

B.2. Verification Longitudinal Seams

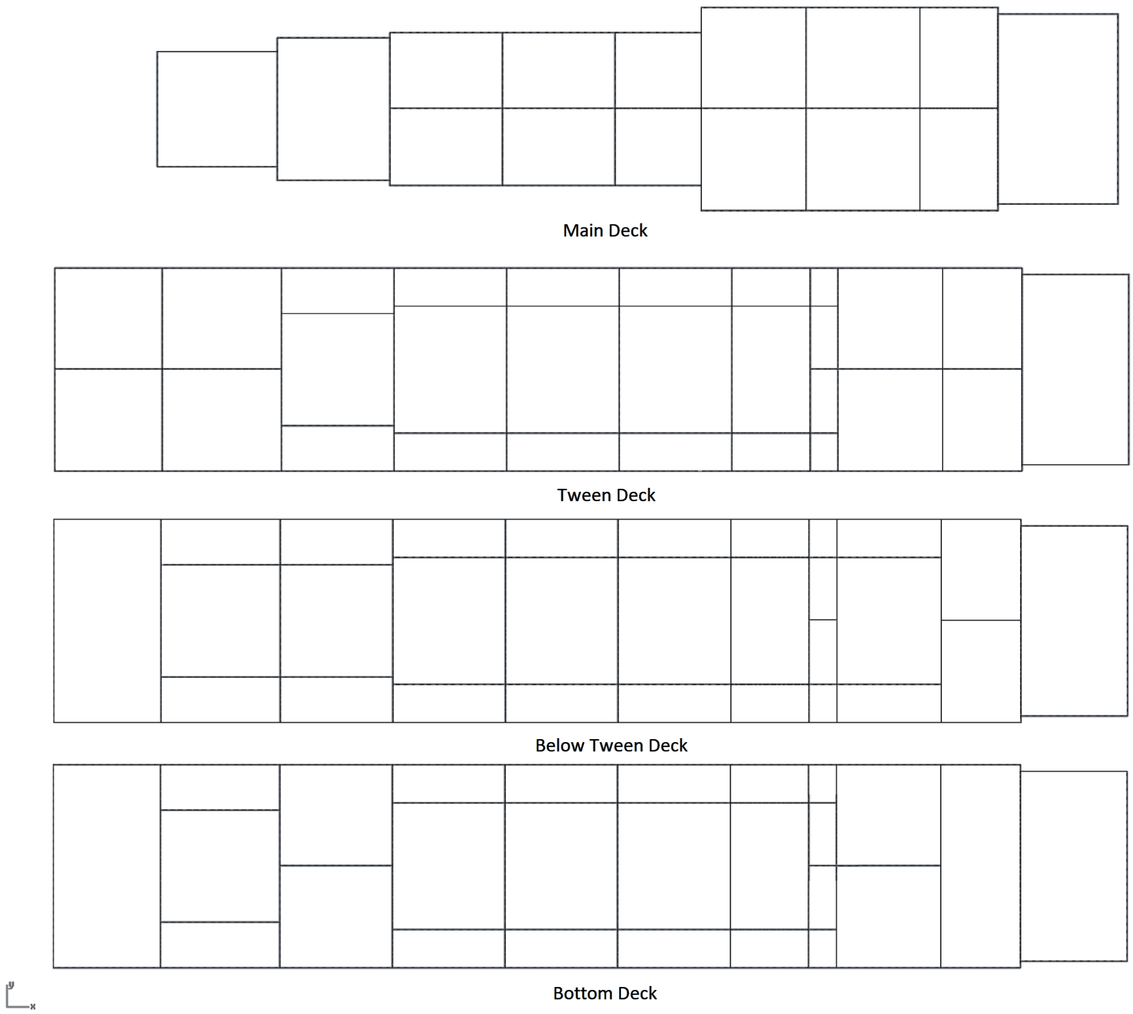


Figure B.2: Top view results of verification after longitudinal seam placing

B.3. Verification Grouping Results

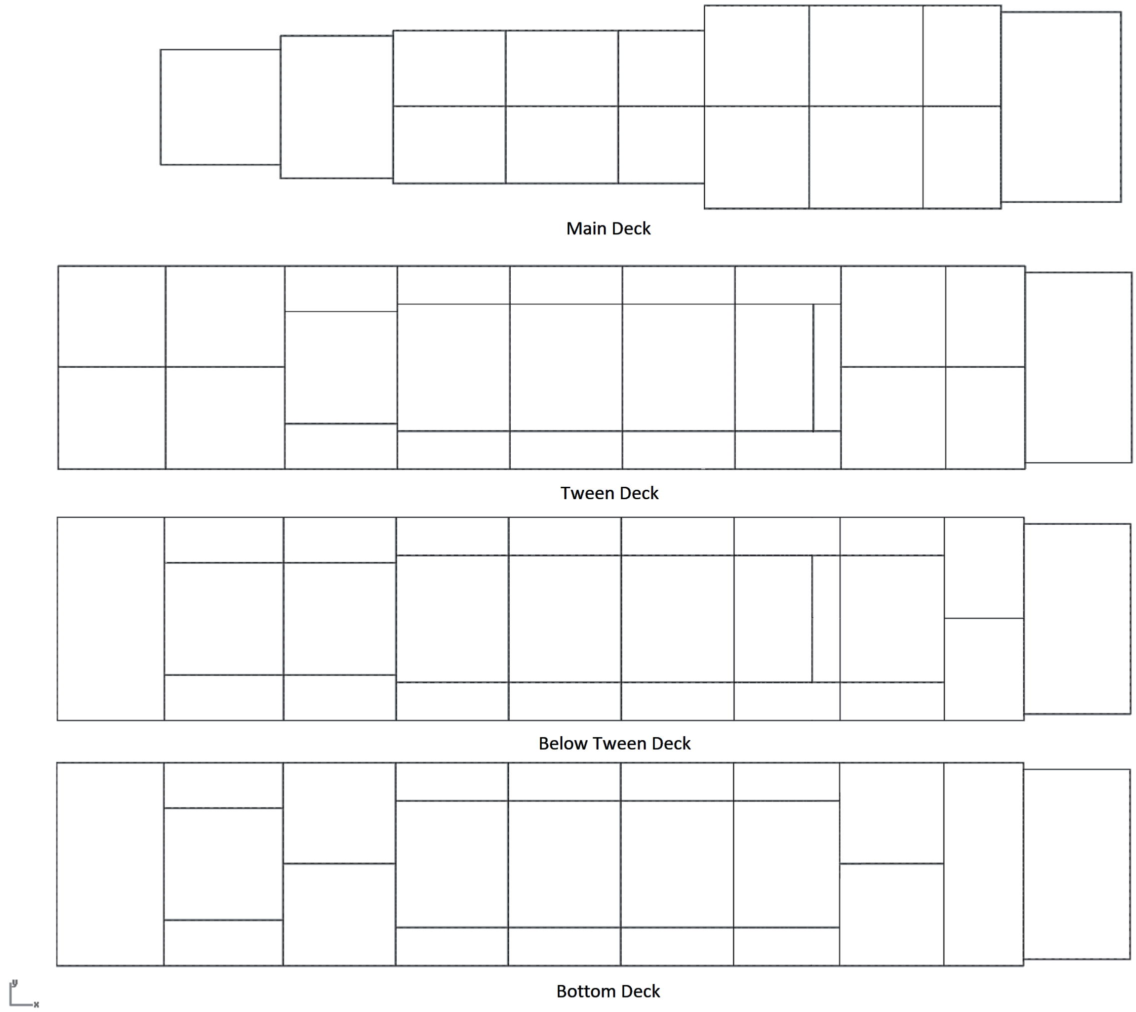


Figure B.3: Top view results of verification after Grouping

C

Longitudinal Seam Placing Arguments Verification

The references in column "Block" refer to Figure 6.9 in Sub Section 6.1.4

#	Deck	Block	No. of Blocks	Argument
1	Bottom	A	1	Integrated Skeg
2	Bottom	B	3	Engine Foundation
3	Bottom	C	2	Wider than B_{max}
4	Bottom	D	3	Hopper and Conical valve Equipment
5	Bottom	E	3	Hopper and Conical valve Equipment
6	Bottom	F	3	Hopper and Conical valve Equipment
7	Bottom	G	3	Hopper and Conical valve Equipment
8	Bottom	H	3	Shorter than L_{min}
9	Bottom	I	2	Wider than B_{max}
10	Bottom	J	1	Integrated Bow Thruster
11	Bottom	K	1	Sum of CL Compartments > Split Boundary
12	Below Tween	A	1	Integrated Skeg
13	Below Tween	B	3	Main Engines
14	Below Tween	C	3	Pump Equipment
15	Below Tween	D	3	Hopper and Conical valve Equipment
16	Below Tween	E	3	Hopper and Conical valve Equipment
17	Below Tween	F	3	Hopper and Conical valve Equipment
18	Below Tween	G	3	Hopper and Conical valve Equipment
19	Below Tween	H	3	Shorter than L_{min}
20	Below Tween	I	3	Bow Pump Equipment
21	Below Tween	J	2	Wider than B_{max}
22	Below Tween	K	1	Sum of CL Compartments > Split Boundary

#	Deck	Block	No. of Blocks	Argument
23	Tween	A	2	Wider than B_{max}
24	Tween	B	2	Wider than B_{max}
25	Tween	C	3	Pump Equipment
26	Tween	D	3	Hopper and Conical valve Equipment
27	Tween	E	3	Hopper and Conical valve Equipment
28	Tween	F	3	Hopper and Conical valve Equipment
29	Tween	G	3	Hopper and Conical valve Equipment
30	Tween	H	3	Shorter than L_{min}
31	Tween	I	2	Wider than B_{max}
32	Tween	J	2	Wider than B_{max}
33	Tween	K	1	Sum of CL Compartments > Split Boundary
34	Main	B	1	Smaller than B_{max}
35	Main	C	1	Smaller than B_{max}
36	Main	D	2	Wider than B_{max}
37	Main	E	2	Wider than B_{max}
38	Main	F	2	Wider than B_{max}
39	Main	G	2	Wider than B_{max}
41	Main	I	2	Wider than B_{max}
42	Main	J	2	Wider than B_{max}
43	Main	K	1	Sum of CL Compartments > Split Boundary

D

Weight Calculations Result Blocks Verification

x_1	y_1	z_1	x_2	y_2	z_2	w_b	Name	w_0	Deviation
-2875	-10725	-75	8475	10725	5175	133.96	1101	130	3 %
8475	-5925	-75	21075	5925	1195	88.04	1203	93	-5 %
8475	5925	-75	21075	10725	5175	35.31	1223	38	-7 %
8475	-10725	-75	21075	-5925	5175	35.26	1222	34	4 %
21075	75	-75	32975	10725	1195	58.43	1201	61	-4 %
21075	-10725	-75	32975	75	1195	61.07	1202	66	-7 %
32975	-6696	-75	44875	6696	1195	61.43	1401	62	-1 %
32975	6696	-75	44875	10725	7575	58.83	1421	58	1 %
32975	-10725	-75	44875	-6696	7575	57.74	1420	57	1 %
44875	-6696	-75	56775	6696	1195	62.21	1402	64	-3 %
44875	6696	-75	56775	10725	7575	61.80	1423	58	7 %
44875	-10725	-75	56775	-6696	7575	61.80	1422	58	7 %
56775	-6696	-75	68675	6696	1195	64.19	1403	66	-3 %
56775	6696	-75	68675	10725	7575	62.14	1425	60	4 %
56775	-10725	-75	68675	-6696	7575	62.14	1424	60	4 %
68675	-6696	-75	79875	6696	1195	65.84	1404	71	-7 %
68675	-10725	-75	79875	-6696	7575	59.75	1426	59	1 %
68675	6696	-75	79875	10725	7575	58.86	1427	60	-2 %
79875	75	-75	90925	10725	1195	39.69	1301	38	4 %
79875	-10725	-75	90925	75	1195	42.62	1302	45	-5 %
90925	-10725	-75	99325	10725	2175	75.80	1303	66	15 %
99325	-10042	-75	110600	10042	2175	72.63	1660	76	-4 %
8475	-5925	1195	21075	5925	5175	16.21	1251	12	35 %

x_1	y_1	z_1	x_2	y_2	z_2	w_b	Name	w_0	Deviation
21075	-5925	1195	32975	5925	5175	37.09	1250	39	-5 %
21075	5925	1195	32975	10725	8475	47.37	1221	44	8 %
21075	-10725	1195	32975	-5925	8475	47.33	1220	41	15 %
32975	-6696	1195	44875	6696	7575	15.21	1410	14	9 %
44875	-6696	1195	56775	6696	7575	15.21	1411	14	9 %
56775	-6696	1195	68675	6696	7575	15.21	1412	22	-31 %
68675	-6696	1195	76925	6696	7575	7.96	1413	7	14 %
76925	-6696	1195	79875	6696	7575	28.43	1431	31	-8 %
79875	-6696	1195	90925	6696	4275	20.77	1350	21	-1 %
79875	6696	1195	90925	10725	4275	18.01	1321	19	-5 %
79875	-10725	1195	90925	-6696	4275	19.45	1320	21	-7 %
90925	75	2175	99325	10725	4275	10.53	1323	14	-25 %
90925	-10725	2175	99325	75	4275	10.60	1322	15	-29 %
99325	-10042	2175	110600	10042	7575	80.07	1661	75	7 %
-2875	75	5175	8475	10725	8475	43.14	1161	45	-4 %
-2875	-10725	5175	8475	75	8475	43.56	1160	45	-3 %
8475	75	5175	21075	10725	8475	31.37	1261	32	-2 %
8475	-10725	5175	21075	75	8475	29.93	1262	32	-6 %
21075	-5925	5175	32975	5925	8475	42.21	1260	43	-2 %
79875	75	4275	90925	10725	7575	21.34	1361	23	-7 %
79875	-10725	4275	90925	75	7575	31.98	1360	34	-6 %
90925	75	4275	99325	10725	7575	16.26	1363	16	2 %
90925	-10725	4275	99325	75	7575	15.47	1362	16	-3 %
8400	-6075	8475	21075	6075	11775	53.87	1802	52	4 %
21075	-7525	8475	32975	7525	11775	63.93	1801	68	-6 %
32975	75	7575	44875	8075	10875	33.63	1441	35	-4 %
32975	-8075	7575	44875	75	10875	33.90	1440	35	-3 %
44875	75	7575	56775	8075	10875	28.17	1443	28	1 %
44875	-8075	7575	56775	75	10875	28.17	1442	28	1 %
56775	75	7575	65875	8075	10875	21.83	1445	35	-38 %
56775	-8075	7575	65875	75	10875	21.83	1444	33	-34 %
65875	75	7575	76925	10725	10875	46.82	1447	38	23 %
65875	-10725	7575	76925	75	10875	47.09	1446	38	24 %
76925	75	7575	88975	10725	10875	45.11	1371	43	5 %
76925	-10725	7575	88975	75	10875	45.69	1370	46	-1 %
88975	75	7575	97225	10725	10875	24.44	1373	25	-2 %
88975	-10725	7575	97225	75	10875	23.26	1372	24	-3 %
97225	-10042	7575	109900	10042	10875	65.69	1670	64	3 %
					Total	2627.95		2647	-0.72 %

E

Optional Seam Position Verification String

Table E.1 and E.2 show the by the BDG created Optional Seam Position strings, where in bold the Final Seam Position is indicated. Note that in both Table E.1 and E.2 column "1" and "14" indicate respectively five frames before and one frame after p_0, in the positive x direction, as elaborated upon in Sub Section 5.1.3.

Table E.1: Forward analyzing direction for chosen Optional Seam Position

#	pos p_0	Seams	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	13	12_{+75}	1	0	-1	-2	-3	-4	-5	-6	-7	**-100**	-9	-10	-11	-12
2	29	30_{+75}	108	108	108	108	108	108	108	108	108	-199	108	-200	108	**-202**
3	64	47_{+75}	-	-	-	-	-	-	-	-	-	-	900	**-100**	-	-
4	64	64_{+75}	1	0	-1	-2	-3	-4	-5	-6	-7	-8	-9	**-10**	-	-
5	81	81_{+75}	1	0	-1	-2	-3	-4	-5	-6	-7	-8	-9	**-10**	-	-
6	98	98_{+75}	1	0	-1	-2	-3	-4	-5	-6	-7	-8	-9	**-10**	-	-
7	-	110	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8	29	30_{+75}	1	0	-1	-2	-3	-4	-5	-6	-7	**-100**	-9	-10	-11	-12
9	-	47_{+75}	-	-	-	-	-	-	-	-	-	-	900	**-100**	-	-
10	64	64_{+75}	1	0	-1	-2	-3	-4	-5	-6	-7	-8	-9	**-10**	-	-
11	81	81_{+75}	1	0	-1	-2	-3	-4	-5	-6	-7	-8	-9	**-10**	-	-
12	98	94_{-75}	1	0	-1	**-2**	900	900	900	900	900	900	900	900	900	900
13	-	110_{-75}	-	-	-	-	-	-	-	-	-100	900	-	-	-	-

Table E.2: Backwards analyzing direction for chosen Optional Seam Position

#	pos p_0	Seams	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	113	114_{+75}	40	40	900	-100	40	40	40	40	-199	**-200**	900	-100	40	40
2	-	130_{-75}	**-100**	900	-	-	-	-	-	-	-	-	-	-	-	-
3	141	142_{-75}	44	44	44	44	44	44	44	44	44	**16**	900	900	900	900
4	122	127_{-75}	**1**	2	3	4	5	6	7	8	9	10	11	12	13	14
5	140	139_{-75}	16	16	16	16	16	16	44	44	44	44	44	44	4	**-199**

F

Erection Sequence Generator Input and Results

F.1. Case 0 - Verification

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection Date
1	1301	-4.11	-1.01	-75	12.11	1.01	5175	133.97	1		12/12/11
2	1302	12.11	-0.56	-75	30.11	0.56	1195	88.05	1		10/01/12
3	1303	12.11	0.56	-75	30.11	1.01	5175	35.31	1		10/01/12
4	1304	12.11	-1.01	-75	30.11	-0.56	5175	35.27	1		11/01/12
5	1305	30.11	0.01	-75	47.11	1.01	1195	58.44	1		24/01/12
6	1306	30.11	-1.01	-75	47.11	0.01	1195	61.07	1		1/02/12
7	1101	47.11	-0.63	-75	64.11	0.63	1195	61.44	1		31/01/12
8	1102	47.11	0.63	-75	64.11	1.01	7575	58.83	1		25/01/12
9	1103	47.11	-1.01	-75	64.11	-0.63	7575	57.74	1		7/02/12
10	1104	64.11	-0.63	-75	81.11	0.63	1195	62.22	1		14/02/12
11	1105	64.11	0.63	-75	81.11	1.01	7575	61.80	1		8/02/12
12	1106	64.11	-1.01	-75	81.11	-0.63	7575	61.80	1		28/02/12
13	1201	81.11	-0.63	-75	98.11	0.63	1195	64.20	1		15/02/12
14	1202	81.11	0.63	-75	98.11	1.01	7575	62.14	1		16/02/12
15	1203	81.11	-1.01	-75	98.11	-0.63	7575	62.14	1		17/02/12
16	1204	98.11	-0.63	-75	113.89	0.63	1195	63.65	1		22/02/12
17	1205	98.11	-1.01	-75	113.89	-0.63	7575	57.64	1		8/03/12
18	1206	98.11	0.63	-75	113.89	1.01	7575	56.80	1		24/02/12
19	1207	113.89	0.01	-75	129.89	1.01	1195	41.46	1		29/02/12
20	1208	113.89	-1.01	-75	129.89	0.01	1195	44.45	1		14/03/12
21	1209	129.89	-1.01	-75	141.89	1.01	2175	75.81	1		15/03/12
22	1210	141.89	-0.94	-75	158.00	0.94	2175	72.63	1		9/03/12
23	1307	12.11	-0.56	1195	30.11	0.56	5175	16.21	1	x	12/03/12
24	1308	30.11	-0.56	1195	47.11	0.56	5175	37.09	1	x	22/03/12
25	1309	30.11	0.56	1195	47.11	1.01	8475	47.38	1		23/03/12
26	1310	30.11	-1.01	1195	47.11	-0.56	8475	47.33	1		26/03/12
27	1107	47.11	-0.63	1195	64.11	0.63	7575	15.22	1		20/03/12
28	1108	64.11	-0.63	1195	81.11	0.63	7575	15.22	1		26/03/12
29	1211	81.11	-0.63	1195	98.11	0.63	7575	15.22	1		10/04/12

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection Date
30	1212	98.11	-0.63	1195	109.89	0.63	7575	7.96	1		11/04/12
31	1213	109.89	-0.63	1195	113.89	0.63	7575	28.06	1		29/03/12
32	1214	113.89	-0.63	1195	129.89	0.63	4275	20.93	1	x	5/04/12
33	1215	113.89	0.63	1195	129.89	1.01	4275	19.27	1		16/04/12
34	1216	113.89	-1.01	1195	129.89	-0.63	4275	20.73	1		19/04/12
35	1217	129.89	0.01	2175	141.89	1.01	4275	10.53	1		20/04/12
36	1218	129.89	-1.01	2175	141.89	0.01	4275	10.60	1		16/04/12
37	1219	141.89	-0.94	2175	158.00	0.94	7575	80.08	1		26/04/12
38	1311	-4.11	0.01	5175	12.11	1.01	8475	43.15	1		23/04/12
39	1312	-4.11	-1.01	5175	12.11	0.01	8475	43.56	1		24/04/12
40	1313	12.11	0.01	5175	30.11	1.01	8475	31.37	1		3/05/12
41	1314	12.11	-1.01	5175	30.11	0.01	8475	29.94	1		30/04/12
42	1315	30.11	-0.56	5175	47.11	0.56	8475	42.22	1	x	1/05/12
43	1220	113.89	0.01	4275	129.89	1.01	7575	21.58	1		3/05/12
44	1221	113.89	-1.01	4275	129.89	0.01	7575	32.24	1		14/05/12
45	1222	129.89	0.01	4275	141.89	1.01	7575	16.26	1		8/05/12
46	1223	129.89	-1.01	4275	141.89	0.01	7575	15.47	1		10/05/12
47	1316	12.00	-0.57	8475	30.11	0.57	11775	53.87	1		22/05/12
48	1317	30.11	-0.71	8475	47.11	0.71	11775	63.94	1		31/05/12
49	1109	47.11	0.01	7575	64.11	0.76	10875	33.63	1		7/06/12
50	1110	47.11	-0.76	7575	64.11	0.01	10875	33.90	1		25/05/12
51	1111	64.11	0.01	7575	81.11	0.76	10875	28.17	1		1/06/12
52	1112	64.11	-0.76	7575	81.11	0.01	10875	28.17	1		8/06/12
53	1224	81.11	0.01	7575	94.11	0.76	10875	21.83	1		18/06/12
54	1225	81.11	-0.76	7575	94.11	0.01	10875	21.83	1		18/06/12
55	1226	94.11	0.01	7575	109.89	1.01	10875	46.83	1		25/06/12
56	1227	94.11	-1.01	7575	109.89	0.01	10875	47.10	1		3/07/12
57	1228	109.89	0.01	7575	120.89	1.01	10875	34.61	1		16/07/12
58	1229	109.89	-1.01	7575	120.89	0.01	10875	31.21	1		10/07/12
59	1230	120.89	0.01	7575	138.89	1.01	10875	34.94	1		11/07/12
60	1231	120.89	-1.01	7575	138.89	0.01	10875	37.75	1		18/07/12
61	1232	138.89	-0.94	7575	157.00	0.94	10875	65.70	1		1/08/12

F.2. Case 1a - Equality Break

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection
1	1231	127.11	0.01	7,575.00	138.89	1.01	10,875.00	24.44	1		12/12/11
2	1301	-4.11	-1.01	-75.00	12.11	1.01	5,175.00	133.97	1		13/12/11
3	1302	12.11	-0.56	-75.00	30.11	0.56	1,195.00	88.05	1		20/12/11
4	1304	12.11	-1.01	-75.00	30.11	-0.56	5,175.00	35.27	1		27/12/11
5	1303	12.11	0.56	-75.00	30.11	1.01	5,175.00	35.31	1		28/12/11
6	1312	-4.11	-1.01	5,175.00	12.11	0.01	8,475.00	43.56	1		29/12/11
7	1306	30.11	-1.01	-75.00	47.11	0.01	1,195.00	61.07	1		3/01/12
8	1307	12.11	-0.56	1,195.00	30.11	0.56	5,175.00	16.21	1	x	4/01/12
9	1311	-4.11	0.01	5,175.00	12.11	1.01	8,475.00	43.15	1		5/01/12
10	1305	30.11	0.01	-75.00	47.11	1.01	1,195.00	58.44	1		10/01/12
11	1101	47.11	-0.63	-75.00	58.89	0.63	1,195.00	41.10	1		17/01/12
12	1314	12.11	-1.01	5,175.00	30.11	0.01	8,475.00	29.94	1		18/01/12
13	1104	58.89	-0.63	-75.00	70.89	0.63	1,195.00	45.27	1		24/01/12
14	1310	30.11	-1.01	1,195.00	47.11	-0.56	8,475.00	47.33	1		25/01/12
15	1313	12.11	0.01	5,175.00	30.11	1.01	8,475.00	31.37	1		26/01/12
16	1107	70.89	-0.63	-75.00	82.89	0.63	1,195.00	45.27	1		31/01/12

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection Date
17	1309	30.11	0.56	1,195.00	47.11	1.01	8,475.00	47.38	1		2/02/12
18	1201	82.89	-0.63	-75.00	94.89	0.63	1,195.00	42.51	1		7/02/12
19	1110	47.11	-0.63	1,195.00	58.89	0.63	7,575.00	10.55	1		9/02/12
20	1316	12.00	-0.57	8,475.00	23.89	0.57	11,775.00	40.06	1		10/02/12
21	1204	94.89	-0.63	-75.00	109.89	0.63	1,195.00	55.57	1		14/02/12
22	1103	47.11	-1.01	-75.00	58.89	-0.63	7,575.00	39.44	1		16/02/12
23	1102	47.11	0.63	-75.00	58.89	1.01	7,575.00	40.53	1		17/02/12
24	1111	58.89	-0.63	1,195.00	70.89	0.63	7,575.00	10.74	1		20/02/12
25	1207	109.89	-0.63	-75.00	113.89	0.63	1,195.00	21.79	1		22/02/12
26	1308	30.11	-0.56	1,195.00	47.11	0.56	5,175.00	37.09	1	x	24/02/12
27	1106	58.89	-1.01	-75.00	70.89	-0.63	7,575.00	41.42	1		27/02/12
28	1105	58.89	0.63	-75.00	70.89	1.01	7,575.00	41.42	1		28/02/12
29	1112	70.89	-0.63	1,195.00	82.89	0.63	7,575.00	10.74	1		1/03/12
30	1109	70.89	-1.01	-75.00	82.89	-0.63	7,575.00	44.99	1		8/03/12
31	1108	70.89	0.63	-75.00	82.89	1.01	7,575.00	44.99	1		9/03/12
32	1214	82.89	-0.63	1,195.00	94.89	0.63	7,575.00	10.74	1		12/03/12
33	1315	30.11	-0.56	5,175.00	47.11	0.56	8,475.00	42.22	1	x	13/03/12
34	1203	82.89	-1.01	-75.00	94.89	-0.63	7,575.00	44.16	1		19/03/12
35	1202	82.89	0.63	-75.00	94.89	1.01	7,575.00	44.16	1		20/03/12
36	1215	94.89	-0.63	1,195.00	109.89	0.63	7,575.00	10.84	1		21/03/12
37	1317	23.89	-0.71	8,475.00	42.11	0.71	11,775.00	55.34	1		27/03/12
38	1206	94.89	-1.01	-75.00	109.89	-0.63	7,575.00	52.19	1		28/03/12
39	1205	94.89	0.63	-75.00	109.89	1.01	7,575.00	52.19	1		29/03/12
40	1216	109.89	-0.63	1,195.00	113.89	0.63	7,575.00	28.06	1		30/03/12
41	1318	42.11	-0.71	8,475.00	47.11	0.71	11,775.00	22.41	1		4/04/12
42	1209	109.89	-1.01	-75.00	113.89	-0.63	7,575.00	17.12	1		6/04/12
43	1208	109.89	0.63	-75.00	113.89	1.01	7,575.00	16.28	1		9/04/12
44	1114	47.11	-0.76	7,575.00	58.89	0.01	10,875.00	25.03	1		11/04/12
45	1211	113.89	-1.01	-75.00	129.89	0.01	1,195.00	44.45	1		13/04/12
46	1116	58.89	-0.76	7,575.00	70.89	0.01	10,875.00	20.24	1		18/04/12
47	1113	47.11	0.01	7,575.00	58.89	0.76	10,875.00	24.76	1		19/04/12
48	1210	113.89	0.01	-75.00	129.89	1.01	1,195.00	41.46	1		20/04/12
49	1118	70.89	-0.76	7,575.00	82.89	0.01	10,875.00	20.24	1		25/04/12
50	1115	58.89	0.01	7,575.00	70.89	0.76	10,875.00	20.24	1		26/04/12
51	1219	113.89	-1.01	1,195.00	129.89	-0.63	4,275.00	20.73	1		27/04/12
52	1228	82.89	-1.01	7,575.00	109.89	0.01	10,875.00	65.49	1		2/05/12
53	1117	70.89	0.01	7,575.00	82.89	0.76	10,875.00	20.24	1		3/05/12
54	1218	113.89	0.63	1,195.00	129.89	1.01	4,275.00	19.27	1		4/05/12
55	1227	82.89	0.01	7,575.00	109.89	1.01	10,875.00	65.22	1		10/05/12
56	1212	129.89	-1.01	-75.00	141.89	1.01	2,175.00	75.81	1		11/05/12
57	1213	141.89	-0.94	-75.00	158.00	0.94	2,175.00	72.63	1		18/05/12
58	1217	113.89	-0.63	1,195.00	129.89	0.63	4,275.00	20.93	1	x	21/05/12
59	1221	129.89	-1.01	2,175.00	141.89	0.01	4,275.00	10.60	1		28/05/12
60	1220	129.89	0.01	2,175.00	141.89	1.01	4,275.00	10.53	1		4/06/12
61	1224	113.89	-1.01	4,275.00	129.89	0.01	7,575.00	32.24	1		5/06/12
62	1226	129.89	-1.01	4,275.00	141.89	0.01	7,575.00	15.47	1		12/06/12
63	1223	113.89	0.01	4,275.00	129.89	1.01	7,575.00	21.58	1		13/06/12
64	1230	109.89	-1.01	7,575.00	127.11	0.01	10,875.00	45.70	1		19/06/12
65	1225	129.89	0.01	4,275.00	141.89	1.01	7,575.00	16.26	1		20/06/12
66	1232	127.11	-1.01	7,575.00	138.89	0.01	10,875.00	23.27	1		26/06/12
67	1222	141.89	-0.94	2,175.00	158.00	0.94	7,575.00	80.08	1		27/06/12
68	1229	109.89	0.01	7,575.00	127.11	1.01	10,875.00	45.11	1		28/06/12
69	1233	138.89	-0.94	7,575.00	157.00	0.94	10,875.00	65.70	1		11/07/12

F.3. Case 1b - No Bulkhead Preference

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection
#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection
1	1301	-4.11	-1.01	-75.00	14.11	1.01	1,195.00	25.51	1		12/12/11
2	1302	14.11	-0.56	-75.00	31.89	0.56	1,195.00	87.94	1		13/12/11
3	1307	-4.11	-1.01	1,195.00	14.11	1.01	5,175.00	125.58	1		14/12/11
4	1304	14.11	-1.01	-75.00	31.89	-0.56	5,175.00	34.38	1		21/12/11
5	1303	14.11	0.56	-75.00	31.89	1.01	5,175.00	34.42	1		22/12/11
6	1306	31.89	-1.01	-75.00	47.11	0.01	1,195.00	55.52	1		28/12/11
7	1313	-4.11	-1.01	5,175.00	14.11	0.01	8,475.00	46.88	1		29/12/11
8	1308	14.11	-0.56	1,195.00	31.89	0.56	5,175.00	16.02	1	x	30/12/11
9	1305	31.89	0.01	-75.00	47.11	1.01	1,195.00	53.16	1		4/01/12
10	1312	-4.11	0.01	5,175.00	14.11	1.01	8,475.00	46.44	1		5/01/12
11	1101	47.11	-0.63	-75.00	64.11	0.63	1,195.00	61.44	1		11/01/12
12	1315	14.11	-1.01	5,175.00	31.89	0.01	8,475.00	31.47	1		13/01/12
13	1104	64.11	-0.63	-75.00	81.11	0.63	1,195.00	62.22	1		18/01/12
14	1311	31.89	-1.01	1,195.00	47.11	-0.56	8,475.00	42.33	1		20/01/12
15	1314	14.11	0.01	5,175.00	31.89	1.01	8,475.00	32.89	1		23/01/12
16	1201	81.11	-0.63	-75.00	98.11	0.63	1,195.00	64.20	1		25/01/12
17	1310	31.89	0.56	1,195.00	47.11	1.01	8,475.00	42.38	1		30/01/12
18	1204	98.11	-0.63	-75.00	113.89	0.63	1,195.00	63.65	1		1/02/12
19	1107	47.11	-0.63	1,195.00	64.11	0.63	7,575.00	15.22	1		6/02/12
20	1317	12.00	-0.57	8,475.00	30.11	0.57	11,775.00	53.87	1		7/02/12
21	1103	47.11	-1.01	-75.00	64.11	-0.63	7,575.00	57.74	1		13/02/12
22	1102	47.11	0.63	-75.00	64.11	1.01	7,575.00	58.83	1		14/02/12
23	1108	64.11	-0.63	1,195.00	81.11	0.63	7,575.00	15.22	1		15/02/12
24	1309	31.89	-0.56	1,195.00	47.11	0.56	5,175.00	35.49	1	x	16/02/12
25	1106	64.11	-1.01	-75.00	81.11	-0.63	7,575.00	61.80	1		22/02/12
26	1105	64.11	0.63	-75.00	81.11	1.01	7,575.00	61.80	1		23/02/12
27	1211	81.11	-0.63	1,195.00	98.11	0.63	7,575.00	15.22	1		24/02/12
28	1316	31.89	-0.56	5,175.00	47.11	0.56	8,475.00	39.95	1	x	1/03/12
29	1203	81.11	-1.01	-75.00	98.11	-0.63	7,575.00	62.14	1		2/03/12
30	1202	81.11	0.63	-75.00	98.11	1.01	7,575.00	62.14	1		5/03/12
31	1212	98.11	-0.63	1,195.00	109.89	0.63	7,575.00	7.96	1		6/03/12
32	1213	109.89	-0.63	1,195.00	113.89	0.63	7,575.00	28.06	1		13/03/12
33	1318	30.11	-0.71	8,475.00	47.11	0.71	11,775.00	63.94	1		15/03/12
34	1205	98.11	-1.01	-75.00	113.89	-0.63	7,575.00	57.64	1		20/03/12
35	1206	98.11	0.63	-75.00	113.89	1.01	7,575.00	56.80	1		21/03/12
36	1110	47.11	-0.76	7,575.00	64.11	0.01	10,875.00	33.90	1		22/03/12
37	1208	113.89	-1.01	-75.00	129.89	0.01	1,195.00	44.45	1		27/03/12
38	1112	64.11	-0.76	7,575.00	81.11	0.01	10,875.00	28.17	1		29/03/12
39	1109	47.11	0.01	7,575.00	64.11	0.76	10,875.00	33.63	1		30/03/12
40	1207	113.89	0.01	-75.00	129.89	1.01	1,195.00	41.46	1		3/04/12
41	1225	81.11	-0.76	7,575.00	94.11	0.01	10,875.00	21.83	1		5/04/12
42	1111	64.11	0.01	7,575.00	81.11	0.76	10,875.00	28.17	1		6/04/12
43	1216	113.89	-1.01	1,195.00	129.89	-0.63	4,275.00	20.73	1		10/04/12
44	1227	94.11	-1.01	7,575.00	109.89	0.01	10,875.00	47.10	1		12/04/12
45	1224	81.11	0.01	7,575.00	94.11	0.76	10,875.00	21.83	1		13/04/12
46	1215	113.89	0.63	1,195.00	129.89	1.01	4,275.00	19.27	1		17/04/12
47	1226	94.11	0.01	7,575.00	109.89	1.01	10,875.00	46.83	1		20/04/12
48	1209	129.89	-1.01	-75.00	141.89	1.01	2,175.00	75.81	1		24/04/12
49	1210	141.89	-0.94	-75.00	158.00	0.94	2,175.00	72.63	1		1/05/12

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection Date
50	1214	113.89	-0.63	1,195.00	129.89	0.63	4,275.00	20.93	1	x	2/05/12
51	1218	129.89	-1.01	2,175.00	141.89	0.01	4,275.00	10.60	1		9/05/12
52	1217	129.89	0.01	2,175.00	141.89	1.01	4,275.00	10.53	1		16/05/12
53	1221	113.89	-1.01	4,275.00	129.89	0.01	7,575.00	32.24	1		17/05/12
54	1223	129.89	-1.01	4,275.00	141.89	0.01	7,575.00	15.47	1		24/05/12
55	1220	113.89	0.01	4,275.00	129.89	1.01	7,575.00	21.58	1		25/05/12
56	1229	109.89	-1.01	7,575.00	120.89	0.01	10,875.00	31.21	1		31/05/12
57	1222	129.89	0.01	4,275.00	141.89	1.01	7,575.00	16.26	1		1/06/12
58	1231	120.89	-1.01	7,575.00	138.89	0.01	10,875.00	37.75	1		7/06/12
59	1219	141.89	-0.94	2,175.00	158.00	0.94	7,575.00	80.08	1		8/06/12
60	1228	109.89	0.01	7,575.00	120.89	1.01	10,875.00	34.61	1		11/06/12
61	1230	120.89	0.01	7,575.00	138.89	1.01	10,875.00	34.94	1		18/06/12
62	1232	138.89	-0.94	7,575.00	157.00	0.94	10,875.00	65.70	1		25/06/12

F.4. Case 1c - No Transit Preference

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection
#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection
1	1233	123.89	0.01	7,575.00	141.89	1.01	10,875.00	33.90	1		12/12/11
2	1301	-4.11	-1.01	-75.00	12.11	1.01	5,175.00	133.97	1		13/12/11
3	1302	12.11	-0.56	-75.00	30.11	0.56	1,195.00	88.05	1		20/12/11
4	1304	12.11	-1.01	-75.00	30.11	-0.56	5,175.00	35.27	1		27/12/11
5	1303	12.11	0.56	-75.00	30.11	1.01	5,175.00	35.31	1		28/12/11
6	1312	-4.11	-1.01	5,175.00	12.11	0.01	8,475.00	43.56	1		29/12/11
7	1306	30.11	-1.01	-75.00	47.11	0.01	1,195.00	61.07	1		3/01/12
8	1307	12.11	-0.56	1,195.00	30.11	0.56	5,175.00	16.21	1	x	4/01/12
9	1311	-4.11	0.01	5,175.00	12.11	1.01	8,475.00	43.15	1		5/01/12
10	1305	30.11	0.01	-75.00	47.11	1.01	1,195.00	58.44	1		10/01/12
11	1101	47.11	-0.63	-75.00	64.11	0.63	1,195.00	61.44	1		17/01/12
12	1314	12.11	-1.01	5,175.00	30.11	0.01	8,475.00	29.94	1		18/01/12
13	1104	64.11	-0.63	-75.00	81.11	0.63	1,195.00	62.22	1		24/01/12
14	1310	30.11	-1.01	1,195.00	47.11	-0.56	8,475.00	47.33	1		25/01/12
15	1313	12.11	0.01	5,175.00	30.11	1.01	8,475.00	31.37	1		26/01/12
16	1201	81.11	-0.63	-75.00	98.11	0.63	1,195.00	64.20	1		31/01/12
17	1309	30.11	0.56	1,195.00	47.11	1.01	8,475.00	47.38	1		2/02/12
18	1204	98.11	-0.63	-75.00	109.89	0.63	1,195.00	41.86	1		7/02/12
19	1107	47.11	-0.63	1,195.00	64.11	0.63	7,575.00	15.22	1		9/02/12
20	1207	109.89	-0.63	-75.00	118.11	0.63	1,195.00	36.82	1		14/02/12
21	1103	47.11	-1.01	-75.00	64.11	-0.63	7,575.00	57.74	1		16/02/12
22	1102	47.11	0.63	-75.00	64.11	1.01	7,575.00	58.83	1		17/02/12
23	1108	64.11	-0.63	1,195.00	81.11	0.63	7,575.00	15.22	1		20/02/12
24	1308	30.11	-0.56	1,195.00	47.11	0.56	5,175.00	37.09	1	x	22/02/12
25	1316	12.00	-0.57	8,475.00	30.11	0.57	11,775.00	53.87	1		24/02/12
26	1106	64.11	-1.01	-75.00	81.11	-0.63	7,575.00	61.80	1		27/02/12
27	1105	64.11	0.63	-75.00	81.11	1.01	7,575.00	61.80	1		28/02/12
28	1214	81.11	-0.63	1,195.00	98.11	0.63	7,575.00	15.22	1		1/03/12
29	1315	30.11	-0.56	5,175.00	47.11	0.56	8,475.00	42.22	1	x	7/03/12
30	1203	81.11	-1.01	-75.00	98.11	-0.63	7,575.00	62.14	1		8/03/12
31	1202	81.11	0.63	-75.00	98.11	1.01	7,575.00	62.14	1		9/03/12
32	1215	98.11	-0.63	1,195.00	109.89	0.63	7,575.00	7.96	1		12/03/12
33	1206	98.11	-1.01	-75.00	109.89	-0.63	7,575.00	40.52	1		19/03/12

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection Date
34	1205	98.11	0.63	-75.00	109.89	1.01	7,575.00	40.52	1		20/03/12
35	1216	109.89	-0.63	1,195.00	118.11	0.63	7,575.00	34.06	1		21/03/12
36	1317	30.11	-0.71	8,475.00	47.11	0.71	11,775.00	63.94	1		22/03/12
37	1209	109.89	-1.01	-75.00	118.11	-0.63	7,575.00	31.02	1		28/03/12
38	1208	109.89	0.63	-75.00	118.11	1.01	7,575.00	29.29	1		29/03/12
39	1110	47.11	-0.76	7,575.00	64.11	0.01	10,875.00	33.90	1		30/03/12
40	1211	118.11	-1.01	-75.00	129.89	0.01	1,195.00	31.66	1		4/04/12
41	1112	64.11	-0.76	7,575.00	81.11	0.01	10,875.00	28.17	1		6/04/12
42	1109	47.11	0.01	7,575.00	64.11	0.76	10,875.00	33.63	1		9/04/12
43	1210	118.11	0.01	-75.00	129.89	1.01	1,195.00	29.42	1		11/04/12
44	1228	81.11	-0.76	7,575.00	94.11	0.01	10,875.00	21.83	1		13/04/12
45	1111	64.11	0.01	7,575.00	81.11	0.76	10,875.00	28.17	1		16/04/12
46	1219	118.11	-1.01	1,195.00	129.89	-0.63	4,275.00	14.65	1		18/04/12
47	1230	94.11	-1.01	7,575.00	109.89	0.01	10,875.00	47.10	1		20/04/12
48	1227	81.11	0.01	7,575.00	94.11	0.76	10,875.00	21.83	1		23/04/12
49	1218	118.11	0.63	1,195.00	129.89	1.01	4,275.00	13.54	1		25/04/12
50	1229	94.11	0.01	7,575.00	109.89	1.01	10,875.00	46.83	1		30/04/12
51	1212	129.89	-1.01	-75.00	141.89	1.01	2,175.00	75.81	1		2/05/12
52	1213	141.89	-0.94	-75.00	158.00	0.94	2,175.00	72.63	1		9/05/12
53	1217	118.11	-0.63	1,195.00	129.89	0.63	4,275.00	19.38	1	x	10/05/12
54	1221	129.89	-1.01	2,175.00	141.89	0.01	4,275.00	10.60	1		17/05/12
55	1220	129.89	0.01	2,175.00	141.89	1.01	4,275.00	10.53	1		24/05/12
56	1224	118.11	-1.01	4,275.00	129.89	0.01	7,575.00	27.16	1		25/05/12
57	1223	118.11	0.01	4,275.00	129.89	1.01	7,575.00	16.89	1		1/06/12
58	1226	129.89	-1.01	4,275.00	141.89	0.01	7,575.00	15.47	1		4/06/12
59	1232	109.89	-1.01	7,575.00	123.89	0.01	10,875.00	37.31	1		8/06/12
60	1225	129.89	0.01	4,275.00	141.89	1.01	7,575.00	16.26	1		11/06/12
61	1231	109.89	0.01	7,575.00	123.89	1.01	10,875.00	39.49	1		15/06/12
62	1222	141.89	-0.94	2,175.00	158.00	0.94	7,575.00	80.08	1		18/06/12
63	1234	123.89	-1.01	7,575.00	141.89	0.01	10,875.00	35.47	1		19/06/12
64	1235	141.89	-0.94	7,575.00	157.00	0.94	10,875.00	58.04	1		2/07/12

F.5. Case 1d - Separability Weight Hierarchy

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection
#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection
1	1301	-4.11	-1.01	-75.00	12.11	1.01	5,175.00	133.97	1		12/12/11
2	1302	12.11	-0.56	-75.00	30.11	0.56	1,195.00	88.05	1		13/12/11
3	1312	-4.11	-1.01	5,175.00	12.11	0.01	8,475.00	43.56	1		14/12/11
4	1304	12.11	-1.01	-75.00	30.11	-0.56	5,175.00	35.27	1		20/12/11
5	1303	12.11	0.56	-75.00	30.11	1.01	5,175.00	35.31	1		21/12/11
6	1311	-4.11	0.01	5,175.00	12.11	1.01	8,475.00	43.15	1		22/12/11
7	1306	30.11	-1.01	-75.00	47.11	0.01	1,195.00	61.07	1		27/12/11
8	1307	12.11	-0.56	1,195.00	30.11	0.56	5,175.00	16.21	1	x	28/12/11
9	1305	30.11	0.01	-75.00	47.11	1.01	1,195.00	58.44	1		3/01/12
10	1101	47.11	-0.63	-75.00	64.11	0.63	1,195.00	61.44	1		10/01/12
11	1314	12.11	-1.01	5,175.00	30.11	0.01	8,475.00	29.94	1		11/01/12
12	1104	64.11	-0.63	-75.00	81.11	0.63	1,195.00	62.22	1		17/01/12
13	1310	30.11	-1.01	1,195.00	47.11	-0.56	8,475.00	47.33	1		18/01/12
14	1313	12.11	0.01	5,175.00	30.11	1.01	8,475.00	31.37	1		19/01/12
15	1201	81.11	-0.63	-75.00	98.11	0.63	1,195.00	64.20	1		24/01/12

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection Date
16	1309	30.11	0.56	1,195.00	47.11	1.01	8,475.00	47.38	1		26/01/12
17	1204	98.11	-0.63	-75.00	113.89	0.63	1,195.00	63.65	1		31/01/12
18	1107	47.11	-0.63	1,195.00	64.11	0.63	7,575.00	15.22	1		2/02/12
19	1103	47.11	-1.01	-75.00	64.11	-0.63	7,575.00	57.74	1		9/02/12
20	1102	47.11	0.63	-75.00	64.11	1.01	7,575.00	58.83	1		10/02/12
21	1108	64.11	-0.63	1,195.00	81.11	0.63	7,575.00	15.22	1		13/02/12
22	1308	30.11	-0.56	1,195.00	47.11	0.56	5,175.00	37.09	1	x	14/02/12
23	1316	12.00	-0.57	8,475.00	30.11	0.57	11,775.00	53.87	1		17/02/12
24	1106	64.11	-1.01	-75.00	81.11	-0.63	7,575.00	61.80	1		20/02/12
25	1105	64.11	0.63	-75.00	81.11	1.01	7,575.00	61.80	1		21/02/12
26	1211	81.11	-0.63	1,195.00	98.11	0.63	7,575.00	15.22	1		22/02/12
27	1315	30.11	-0.56	5,175.00	47.11	0.56	8,475.00	42.22	1	x	28/02/12
28	1203	81.11	-1.01	-75.00	98.11	-0.63	7,575.00	62.14	1		29/02/12
29	1202	81.11	0.63	-75.00	98.11	1.01	7,575.00	62.14	1		1/03/12
30	1212	98.11	-0.63	1,195.00	109.89	0.63	7,575.00	7.96	1		2/03/12
31	1213	109.89	-0.63	1,195.00	113.89	0.63	7,575.00	28.06	1		9/03/12
32	1317	30.11	-0.71	8,475.00	47.11	0.71	11,775.00	63.94	1		13/03/12
33	1205	98.11	-1.01	-75.00	113.89	-0.63	7,575.00	57.64	1		16/03/12
34	1206	98.11	0.63	-75.00	113.89	1.01	7,575.00	56.80	1		19/03/12
35	1110	47.11	-0.76	7,575.00	64.11	0.01	10,875.00	33.90	1		20/03/12
36	1208	113.89	-1.01	-75.00	129.89	0.01	1,195.00	44.45	1		23/03/12
37	1112	64.11	-0.76	7,575.00	81.11	0.01	10,875.00	28.17	1		27/03/12
38	1109	47.11	0.01	7,575.00	64.11	0.76	10,875.00	33.63	1		28/03/12
39	1207	113.89	0.01	-75.00	129.89	1.01	1,195.00	41.46	1		30/03/12
40	1221	81.11	-0.76	7,575.00	94.11	0.01	10,875.00	21.83	1		3/04/12
41	1111	64.11	0.01	7,575.00	81.11	0.76	10,875.00	28.17	1		4/04/12
42	1216	113.89	-1.01	1,195.00	129.89	-0.63	4,275.00	20.73	1		6/04/12
43	1223	94.11	-1.01	7,575.00	109.89	0.01	10,875.00	47.10	1		10/04/12
44	1220	81.11	0.01	7,575.00	94.11	0.76	10,875.00	21.83	1		11/04/12
45	1215	113.89	0.63	1,195.00	129.89	1.01	4,275.00	19.27	1		13/04/12
46	1222	94.11	0.01	7,575.00	109.89	1.01	10,875.00	46.83	1		18/04/12
47	1209	129.89	-1.01	-75.00	141.89	1.01	2,175.00	75.81	1		20/04/12
48	1210	141.89	-0.94	-75.00	158.00	0.94	2,175.00	72.63	1		27/04/12
49	1214	113.89	-0.63	1,195.00	129.89	0.63	4,275.00	20.93	1	x	30/04/12
50	1219	113.89	-1.01	4,275.00	129.89	1.01	7,575.00	53.82	1		14/05/12
51	1217	129.89	-1.01	2,175.00	141.89	1.01	7,575.00	52.87	1		21/05/12
52	1218	141.89	-0.94	2,175.00	158.00	0.94	7,575.00	80.08	1		28/05/12
53	1224	109.89	-1.01	7,575.00	120.89	1.01	10,875.00	65.82	1		29/05/12
54	1225	120.89	-1.01	7,575.00	138.89	1.01	10,875.00	72.69	1		5/06/12
55	1226	138.89	-0.94	7,575.00	157.00	0.94	10,875.00	65.70	1		12/06/12

F.6. Case 1e - Minimum Split Boundary

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection
#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection
1	1301	-4.11	-1.01	-75.00	12.11	1.01	5,175.00	133.97	1		12/12/11
2	1302	12.11	-0.56	-75.00	30.11	0.56	1,195.00	88.05	1		13/12/11
3	1310	-4.11	-1.01	5,175.00	12.11	1.01	8,475.00	86.71	1		14/12/11
4	1304	12.11	-1.01	-75.00	30.11	-0.56	5,175.00	35.27	1		20/12/11
5	1303	12.11	0.56	-75.00	30.11	1.01	5,175.00	35.31	1		21/12/11
6	1305	30.11	-1.01	-75.00	47.11	1.01	1,195.00	119.51	1		28/12/11
7	1306	12.11	-0.56	1,195.00	30.11	0.56	5,175.00	16.21	1	x	29/12/11
8	1101	47.11	-0.63	-75.00	64.11	0.63	1,195.00	61.44	1		4/01/12

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection Date
9	1104	64.11	-0.63	-75.00	81.11	0.63	1,195.00	62.22	1		11/01/12
10	1311	12.11	-1.01	5,175.00	30.11	1.01	8,475.00	61.31	1		12/01/12
11	1201	81.11	-0.63	-75.00	98.11	0.63	1,195.00	64.20	1		18/01/12
12	1309	30.11	-1.01	1,195.00	47.11	-0.56	8,475.00	47.33	1		19/01/12
13	1308	30.11	0.56	1,195.00	47.11	1.01	8,475.00	47.38	1		20/01/12
14	1204	98.11	-0.63	-75.00	113.89	0.63	1,195.00	63.65	1		25/01/12
15	1107	47.11	-0.63	1,195.00	64.11	0.63	7,575.00	15.22	1		27/01/12
16	1103	47.11	-1.01	-75.00	64.11	-0.63	7,575.00	57.74	1		3/02/12
17	1102	47.11	0.63	-75.00	64.11	1.01	7,575.00	58.83	1		6/02/12
18	1108	64.11	-0.63	1,195.00	81.11	0.63	7,575.00	15.22	1		7/02/12
19	1307	30.11	-0.56	1,195.00	47.11	0.56	5,175.00	37.09	1	x	8/02/12
20	1313	12.00	-0.57	8,475.00	30.11	0.57	11,775.00	53.87	1		13/02/12
21	1106	64.11	-1.01	-75.00	81.11	-0.63	7,575.00	61.80	1		14/02/12
22	1105	64.11	0.63	-75.00	81.11	1.01	7,575.00	61.80	1		15/02/12
23	1210	81.11	-0.63	1,195.00	98.11	0.63	7,575.00	15.22	1		16/02/12
24	1312	30.11	-0.56	5,175.00	47.11	0.56	8,475.00	42.22	1	x	22/02/12
25	1203	81.11	-1.01	-75.00	98.11	-0.63	7,575.00	62.14	1		23/02/12
26	1202	81.11	0.63	-75.00	98.11	1.01	7,575.00	62.14	1		24/02/12
27	1211	98.11	-0.63	1,195.00	109.89	0.63	7,575.00	7.96	1		27/02/12
28	1212	109.89	-0.63	1,195.00	113.89	0.63	7,575.00	28.06	1		5/03/12
29	1314	30.11	-0.71	8,475.00	47.11	0.71	11,775.00	63.94	1		7/03/12
30	1205	98.11	-1.01	-75.00	113.89	-0.63	7,575.00	57.64	1		12/03/12
31	1206	98.11	0.63	-75.00	113.89	1.01	7,575.00	56.80	1		13/03/12
32	1109	47.11	-0.76	7,575.00	64.11	0.76	10,875.00	67.54	1		14/03/12
33	1207	113.89	-1.01	-75.00	129.89	1.01	1,195.00	85.91	1		20/03/12
34	1110	64.11	-0.76	7,575.00	81.11	0.76	10,875.00	56.35	1		21/03/12
35	1219	81.11	-0.76	7,575.00	94.11	0.76	10,875.00	43.66	1		28/03/12
36	1215	113.89	-1.01	1,195.00	129.89	-0.63	4,275.00	20.73	1		3/04/12
37	1214	113.89	0.63	1,195.00	129.89	1.01	4,275.00	19.27	1		4/04/12
38	1220	94.11	-1.01	7,575.00	109.89	1.01	10,875.00	93.92	1		5/04/12
39	1208	129.89	-1.01	-75.00	141.89	1.01	2,175.00	75.81	1		11/04/12
40	1209	141.89	-0.94	-75.00	158.00	0.94	2,175.00	72.63	1		18/04/12
41	1213	113.89	-0.63	1,195.00	129.89	0.63	4,275.00	20.93	1	x	19/04/12
42	1218	113.89	-1.01	4,275.00	129.89	1.01	7,575.00	53.82	1		3/05/12
43	1216	129.89	-1.01	2,175.00	141.89	1.01	7,575.00	52.87	1		10/05/12
44	1217	141.89	-0.94	2,175.00	158.00	0.94	7,575.00	80.08	1		17/05/12
45	1221	109.89	-1.01	7,575.00	120.89	1.01	10,875.00	65.82	1		18/05/12
46	1222	120.89	-1.01	7,575.00	138.89	1.01	10,875.00	72.69	1		25/05/12
47	1223	138.89	-0.94	7,575.00	157.00	0.94	10,875.00	65.70	1		1/06/12

F.7. Case 1f - Maximum Split Boundary

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection Date
1	1102	47.11	0.63	-75.00	64.11	1.01	7,575.00	58.83	1		12/12/11
2	1302	12.11	-0.56	-75.00	30.11	0.56	1,195.00	88.05	1		13/12/11
3	1304	12.11	-1.01	-75.00	30.11	-0.56	5,175.00	35.27	1		20/12/11
4	1303	12.11	0.56	-75.00	30.11	1.01	5,175.00	35.31	1		21/12/11
5	1306	30.11	-1.01	-75.00	47.11	0.01	1,195.00	61.07	1		27/12/11
6	1301	-4.11	-1.01	-75.00	12.11	1.01	5,175.00	133.97	1		28/12/11
7	1305	30.11	0.01	-75.00	47.11	1.01	1,195.00	58.44	1		3/01/12
8	1307	12.11	-0.56	1,195.00	30.11	0.56	5,175.00	16.21	1	x	4/01/12
9	1101	47.11	-0.63	-75.00	64.11	0.63	1,195.00	61.44	1		10/01/12
10	1104	64.11	-0.63	-75.00	81.11	0.63	1,195.00	62.22	1		17/01/12

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection Date
11	1314	12.11	-1.01	5,175.00	30.11	0.01	8,475.00	29.94	1		18/01/12
12	1201	81.11	-0.63	-75.00	98.11	0.63	1,195.00	64.20	1		24/01/12
13	1313	12.11	0.01	5,175.00	30.11	1.01	8,475.00	31.37	1		25/01/12
14	1312	-4.11	-1.01	5,175.00	12.11	0.01	8,475.00	43.56	1		26/01/12
15	1310	30.11	-1.01	1,195.00	47.11	-0.56	8,475.00	47.33	1		27/01/12
16	1309	30.11	0.56	1,195.00	47.11	1.01	8,475.00	47.38	1		1/02/12
17	1204	98.11	-0.63	-75.00	113.89	0.63	1,195.00	63.65	1		2/02/12
18	1311	-4.11	0.01	5,175.00	12.11	1.01	8,475.00	43.15	1		3/02/12
19	1107	47.11	-0.63	1,195.00	64.11	0.63	7,575.00	15.22	1		8/02/12
20	1103	47.11	-1.01	-75.00	64.11	-0.63	7,575.00	57.74	1		15/02/12
21	1108	64.11	-0.63	1,195.00	81.11	0.63	7,575.00	15.22	1		16/02/12
22	1308	30.11	-0.56	1,195.00	47.11	0.56	5,175.00	37.09	1	x	17/02/12
23	1316	12.00	-0.57	8,475.00	30.11	0.57	11,775.00	53.87	1		20/02/12
24	1106	64.11	-1.01	-75.00	81.11	-0.63	7,575.00	61.80	1		23/02/12
25	1105	64.11	0.63	-75.00	81.11	1.01	7,575.00	61.80	1		24/02/12
26	1211	81.11	-0.63	1,195.00	98.11	0.63	7,575.00	15.22	1		27/02/12
27	1315	30.11	-0.56	5,175.00	47.11	0.56	8,475.00	42.22	1	x	2/03/12
28	1203	81.11	-1.01	-75.00	98.11	-0.63	7,575.00	62.14	1		5/03/12
29	1202	81.11	0.63	-75.00	98.11	1.01	7,575.00	62.14	1		6/03/12
30	1212	98.11	-0.63	1,195.00	109.89	0.63	7,575.00	7.96	1		7/03/12
31	1213	109.89	-0.63	1,195.00	113.89	0.63	7,575.00	28.06	1		14/03/12
32	1317	30.11	-0.71	8,475.00	47.11	0.71	11,775.00	63.94	1		16/03/12
33	1205	98.11	-1.01	-75.00	113.89	-0.63	7,575.00	57.64	1		21/03/12
34	1206	98.11	0.63	-75.00	113.89	1.01	7,575.00	56.80	1		22/03/12
35	1110	47.11	-0.76	7,575.00	64.11	0.01	10,875.00	33.90	1		23/03/12
36	1208	113.89	-1.01	-75.00	129.89	0.01	1,195.00	44.45	1		28/03/12
37	1112	64.11	-0.76	7,575.00	81.11	0.01	10,875.00	28.17	1		30/03/12
38	1109	47.11	0.01	7,575.00	64.11	0.76	10,875.00	33.63	1		2/04/12
39	1207	113.89	0.01	-75.00	129.89	1.01	1,195.00	41.46	1		4/04/12
40	1225	81.11	-0.76	7,575.00	94.11	0.01	10,875.00	21.83	1		6/04/12
41	1111	64.11	0.01	7,575.00	81.11	0.76	10,875.00	28.17	1		9/04/12
42	1216	113.89	-1.01	1,195.00	129.89	-0.63	4,275.00	20.73	1		11/04/12
43	1227	94.11	-1.01	7,575.00	109.89	0.01	10,875.00	47.10	1		13/04/12
44	1224	81.11	0.01	7,575.00	94.11	0.76	10,875.00	21.83	1		16/04/12
45	1215	113.89	0.63	1,195.00	129.89	1.01	4,275.00	19.27	1		18/04/12
46	1226	94.11	0.01	7,575.00	109.89	1.01	10,875.00	46.83	1		23/04/12
47	1209	129.89	-1.01	-75.00	141.89	1.01	2,175.00	75.81	1		25/04/12
48	1210	141.89	-0.94	-75.00	158.00	0.94	2,175.00	72.63	1		2/05/12
49	1214	113.89	-0.63	1,195.00	129.89	0.63	4,275.00	20.93	1	x	3/05/12
50	1218	129.89	-1.01	2,175.00	141.89	0.01	4,275.00	10.60	1		10/05/12
51	1217	129.89	0.01	2,175.00	141.89	1.01	4,275.00	10.53	1		17/05/12
52	1221	113.89	-1.01	4,275.00	129.89	0.01	7,575.00	32.24	1		18/05/12
53	1223	129.89	-1.01	4,275.00	141.89	0.01	7,575.00	15.47	1		25/05/12
54	1220	113.89	0.01	4,275.00	129.89	1.01	7,575.00	21.58	1		28/05/12
55	1229	109.89	-1.01	7,575.00	120.89	0.01	10,875.00	31.21	1		1/06/12
56	1222	129.89	0.01	4,275.00	141.89	1.01	7,575.00	16.26	1		4/06/12
57	1231	120.89	-1.01	7,575.00	138.89	0.01	10,875.00	37.75	1		8/06/12
58	1219	141.89	-0.94	2,175.00	158.00	0.94	7,575.00	80.08	1		11/06/12
59	1228	109.89	0.01	7,575.00	120.89	1.01	10,875.00	34.61	1		12/06/12
60	1230	120.89	0.01	7,575.00	138.89	1.01	10,875.00	34.94	1		19/06/12
61	1233	138.89	-0.94	7,575.00	157.00	0.01	10,875.00	32.93	1		25/06/12
62	1232	138.89	0.01	7,575.00	157.00	0.94	10,875.00	32.77	1		2/07/12

F.8. Case 1g - Default Center Line Side

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection Date
#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection
1	1303	12.11	0.56	-75.00	30.11	1.01	5,175.00	35.31	1		12/12/11
2	1302	12.11	-0.56	-75.00	30.11	0.56	1,195.00	88.05	1		13/12/11
3	1305	30.11	-0.01	-75.00	47.11	1.01	1,195.00	61.07	1		20/12/11
4	1304	12.11	-1.01	-75.00	30.11	-0.56	5,175.00	35.27	1		21/12/11
5	1301	-4.11	-1.01	-75.00	12.11	1.01	5,175.00	133.97	1		28/12/11
6	1306	30.11	-1.01	-75.00	47.11	-0.01	1,195.00	58.44	1		29/12/11
7	1307	12.11	-0.56	1,195.00	30.11	0.56	5,175.00	16.21	1	x	4/01/12
8	1101	47.11	-0.63	-75.00	64.11	0.63	1,195.00	61.44	1		5/01/12
9	1104	64.11	-0.63	-75.00	81.11	0.63	1,195.00	62.22	1		12/01/12
10	1313	12.11	-0.01	5,175.00	30.11	1.01	8,475.00	31.71	1		18/01/12
11	1201	81.11	-0.63	-75.00	98.11	0.63	1,195.00	64.20	1		19/01/12
12	1311	-4.11	-0.01	5,175.00	12.11	1.01	8,475.00	43.56	1		25/01/12
13	1204	98.11	-0.63	-75.00	113.89	0.63	1,195.00	63.65	1		26/01/12
14	1314	12.11	-1.01	5,175.00	30.11	-0.01	8,475.00	29.60	1		27/01/12
15	1312	-4.11	-1.01	5,175.00	12.11	-0.01	8,475.00	43.15	1		3/02/12
16	1310	30.11	-1.01	1,195.00	47.11	-0.56	8,475.00	47.33	1		6/02/12
17	1309	30.11	0.56	1,195.00	47.11	1.01	8,475.00	47.38	1		7/02/12
18	1107	47.11	-0.63	1,195.00	64.11	0.63	7,575.00	15.22	1		14/02/12
19	1103	47.11	-1.01	-75.00	64.11	-0.63	7,575.00	57.74	1		21/02/12
20	1102	47.11	0.63	-75.00	64.11	1.01	7,575.00	58.83	1		22/02/12
21	1108	64.11	-0.63	1,195.00	81.11	0.63	7,575.00	15.22	1		23/02/12
22	1308	30.11	-0.56	1,195.00	47.11	0.56	5,175.00	37.09	1	x	24/02/12
23	1316	12.00	-0.57	8,475.00	30.11	0.57	11,775.00	53.87	1		29/02/12
24	1106	64.11	-1.01	-75.00	81.11	-0.63	7,575.00	61.80	1		1/03/12
25	1105	64.11	0.63	-75.00	81.11	1.01	7,575.00	61.80	1		2/03/12
26	1211	81.11	-0.63	1,195.00	98.11	0.63	7,575.00	15.22	1		5/03/12
27	1315	30.11	-0.56	5,175.00	47.11	0.56	8,475.00	42.22	1	x	9/03/12
28	1203	81.11	-1.01	-75.00	98.11	-0.63	7,575.00	62.14	1		12/03/12
29	1202	81.11	0.63	-75.00	98.11	1.01	7,575.00	62.14	1		13/03/12
30	1212	98.11	-0.63	1,195.00	109.89	0.63	7,575.00	7.96	1		14/03/12
31	1213	109.89	-0.63	1,195.00	113.89	0.63	7,575.00	28.06	1		21/03/12
32	1317	30.11	-0.71	8,475.00	47.11	0.71	11,775.00	63.94	1		23/03/12
33	1205	98.11	-1.01	-75.00	113.89	-0.63	7,575.00	57.64	1		28/03/12
34	1206	98.11	0.63	-75.00	113.89	1.01	7,575.00	56.80	1		29/03/12
35	1109	47.11	-0.01	7,575.00	64.11	0.76	10,875.00	33.90	1		30/03/12
36	1207	113.89	-0.01	-75.00	129.89	1.01	1,195.00	43.75	1		5/04/12
37	1111	64.11	-0.01	7,575.00	81.11	0.76	10,875.00	28.17	1		6/04/12
38	1110	47.11	-0.76	7,575.00	64.11	-0.01	10,875.00	33.63	1		9/04/12
39	1208	113.89	-1.01	-75.00	129.89	-0.01	1,195.00	42.16	1		12/04/12
40	1224	81.11	-0.01	7,575.00	94.11	0.76	10,875.00	21.83	1		13/04/12
41	1112	64.11	-0.76	7,575.00	81.11	-0.01	10,875.00	28.17	1		16/04/12
42	1226	94.11	-0.01	7,575.00	109.89	1.01	10,875.00	47.10	1		20/04/12
43	1225	81.11	-0.76	7,575.00	94.11	-0.01	10,875.00	21.83	1		23/04/12
44	1216	113.89	-1.01	1,195.00	129.89	-0.63	4,275.00	20.73	1		26/04/12
45	1215	113.89	0.63	1,195.00	129.89	1.01	4,275.00	19.27	1		27/04/12
46	1227	94.11	-1.01	7,575.00	109.89	-0.01	10,875.00	46.83	1		30/04/12
47	1209	129.89	-1.01	-75.00	141.89	1.01	2,175.00	75.81	1		4/05/12
48	1210	141.89	-0.94	-75.00	158.00	0.94	2,175.00	72.63	1		11/05/12
49	1214	113.89	-0.63	1,195.00	129.89	0.63	4,275.00	20.93	1	x	14/05/12
50	1217	129.89	-0.01	2,175.00	141.89	1.01	4,275.00	10.59	1		21/05/12
51	1218	129.89	-1.01	2,175.00	141.89	-0.01	4,275.00	10.54	1		28/05/12
52	1220	113.89	-0.01	4,275.00	129.89	1.01	7,575.00	24.86	1		29/05/12
53	1221	113.89	-1.01	4,275.00	129.89	-0.01	7,575.00	28.96	1		5/06/12

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection Date
54	1222	129.89	-0.01	4,275.00	141.89	1.01	7,575.00	16.41	1		6/06/12
55	1228	109.89	-0.01	7,575.00	120.89	1.01	10,875.00	35.31	1		12/06/12
56	1223	129.89	-1.01	4,275.00	141.89	-0.01	7,575.00	15.32	1		13/06/12
57	1229	109.89	-1.01	7,575.00	120.89	-0.01	10,875.00	30.52	1		19/06/12
58	1219	141.89	-0.94	2,175.00	158.00	0.94	7,575.00	80.08	1		20/06/12
59	1230	120.89	-0.01	7,575.00	138.89	1.01	10,875.00	37.99	1		21/06/12
60	1231	120.89	-1.01	7,575.00	138.89	-0.01	10,875.00	34.70	1		28/06/12
61	1232	138.89	-0.94	7,575.00	157.00	0.94	10,875.00	65.70	1		5/07/12

F.9. Case 2 - Ring-Mega-Block division Approach

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection Date
1	1243	109.89	0.01	7,575.00	119.11	1.01	10,875.00	29.74	1		12/12/11
2	1211	109.89	-1.01	-75.00	119.89	0.01	1,195.00	32.55	1		13/12/11
3	1210	109.89	0.01	-75.00	119.89	1.01	1,195.00	30.70	1		20/12/11
4	1213	119.89	-1.01	-75.00	129.89	0.01	1,195.00	27.98	1		21/12/11
5	1207	99.89	-0.63	-75.00	109.89	0.63	1,195.00	35.86	1		27/12/11
6	1212	119.89	0.01	-75.00	129.89	1.01	1,195.00	26.04	1		28/12/11
7	1222	109.89	-1.01	1,195.00	119.89	-0.63	4,275.00	14.26	1		29/12/11
8	1204	92.11	-0.63	-75.00	99.89	0.63	1,195.00	28.63	1		3/01/12
9	1221	109.89	0.63	1,195.00	119.89	1.01	4,275.00	13.41	1		4/01/12
10	1225	119.89	-1.01	1,195.00	129.89	-0.63	4,275.00	12.99	1		5/01/12
11	1201	81.11	-0.63	-75.00	92.11	0.63	1,195.00	41.56	1		10/01/12
12	1220	109.89	-0.63	1,195.00	119.89	0.63	4,275.00	15.95	1	x	11/01/12
13	1224	119.89	0.63	1,195.00	129.89	1.01	4,275.00	12.03	1		12/01/12
14	1107	72.11	-0.63	-75.00	81.11	0.63	1,195.00	32.96	1		17/01/12
15	1214	129.89	-1.01	-75.00	141.89	1.01	2,175.00	75.81	1		19/01/12
16	1104	59.11	-0.63	-75.00	72.11	0.63	1,195.00	48.19	1		24/01/12
17	1232	109.89	-1.01	4,275.00	119.89	0.01	7,575.00	20.16	1		25/01/12
18	1215	141.89	-0.94	-75.00	150.11	0.94	2,175.00	46.00	1		26/01/12
19	1223	119.89	-0.63	1,195.00	129.89	0.63	4,275.00	18.76	1	x	27/01/12
20	1231	109.89	0.01	4,275.00	119.89	1.01	7,575.00	19.12	1		1/02/12
21	1101	47.11	-0.63	-75.00	59.11	0.63	1,195.00	42.51	1		2/02/12
22	1227	129.89	-1.01	2,175.00	141.89	0.01	4,275.00	10.60	1		3/02/12
23	1216	150.11	-0.71	-75.00	158.00	0.71	2,175.00	26.63	1		6/02/12
24	1219	99.89	-0.63	1,195.00	109.89	0.63	7,575.00	6.36	1		9/02/12
25	1244	109.89	-1.01	7,575.00	119.11	0.01	10,875.00	26.36	1		10/02/12
26	1234	119.89	-1.01	4,275.00	129.89	0.01	7,575.00	25.03	1		13/02/12
27	1226	129.89	0.01	2,175.00	141.89	1.01	4,275.00	10.53	1		14/02/12
28	1209	99.89	-1.01	-75.00	109.89	-0.63	7,575.00	34.55	1		17/02/12
29	1208	99.89	0.63	-75.00	109.89	1.01	7,575.00	34.55	1		20/02/12
30	1218	92.11	-0.63	1,195.00	99.89	0.63	7,575.00	6.97	1		21/02/12
31	1233	119.89	0.01	4,275.00	129.89	1.01	7,575.00	14.92	1		22/02/12
32	1246	119.11	-1.01	7,575.00	126.89	0.01	10,875.00	17.05	1		27/02/12
33	1206	92.11	-1.01	-75.00	99.89	-0.63	7,575.00	30.25	1		28/02/12
34	1205	92.11	0.63	-75.00	99.89	1.01	7,575.00	30.25	1		29/02/12
35	1217	81.11	-0.63	1,195.00	92.11	0.63	7,575.00	9.85	1		1/03/12
36	1236	129.89	-1.01	4,275.00	141.89	0.01	7,575.00	15.47	1		6/03/12
37	1245	119.11	0.01	7,575.00	126.89	1.01	10,875.00	14.62	1		7/03/12
38	1203	81.11	-1.01	-75.00	92.11	-0.63	7,575.00	37.86	1		8/03/12
39	1202	81.11	0.63	-75.00	92.11	1.01	7,575.00	37.86	1		9/03/12
40	1242	92.11	-1.01	7,575.00	109.89	0.01	10,875.00	50.27	1		14/03/12
41	1112	72.11	-0.63	1,195.00	81.11	0.63	7,575.00	8.06	1		15/03/12
42	1235	129.89	0.01	4,275.00	141.89	1.01	7,575.00	16.26	1		16/03/12
43	1229	141.89	-0.94	2,175.00	150.11	0.01	4,275.00	10.19	1		19/03/12

#	Name	x_1	y_1	z_1	x_2	y_2	z_2	w	Type	c-deck	Erection Date
44	1240	81.11	-0.76	7,575.00	92.11	0.01	10,875.00	18.66	1		22/03/12
45	1241	92.11	0.01	7,575.00	109.89	1.01	10,875.00	50.00	1		23/03/12
46	1109	72.11	-1.01	-75.00	81.11	-0.63	7,575.00	30.89	1		26/03/12
47	1108	72.11	0.63	-75.00	81.11	1.01	7,575.00	30.89	1		27/03/12
48	1239	81.11	0.01	7,575.00	92.11	0.76	10,875.00	18.66	1		30/03/12
49	1111	59.11	-0.63	1,195.00	72.11	0.63	7,575.00	11.64	1		2/04/12
50	1248	126.89	-1.01	7,575.00	141.11	0.01	10,875.00	28.35	1		3/04/12
51	1228	141.89	0.01	2,175.00	150.11	0.94	4,275.00	10.02	1		4/04/12
52	1106	59.11	-1.01	-75.00	72.11	-0.63	7,575.00	48.06	1		9/04/12
53	1105	59.11	0.63	-75.00	72.11	1.01	7,575.00	48.06	1		10/04/12
54	1110	47.11	-0.63	1,195.00	59.11	0.63	7,575.00	10.74	1		11/04/12
55	1247	126.89	0.01	7,575.00	141.11	1.01	10,875.00	28.02	1		12/04/12
56	1118	72.11	-0.76	7,575.00	81.11	0.01	10,875.00	14.88	1		17/04/12
57	1103	47.11	-1.01	-75.00	59.11	-0.63	7,575.00	40.59	1		18/04/12
58	1102	47.11	0.63	-75.00	59.11	1.01	7,575.00	41.68	1		19/04/12
59	1238	141.89	-0.94	4,275.00	150.11	0.01	7,575.00	13.34	1		20/04/12
60	1117	72.11	0.01	7,575.00	81.11	0.76	10,875.00	14.88	1		25/04/12
61	1116	59.11	-0.76	7,575.00	72.11	0.01	10,875.00	21.83	1		26/04/12
62	1309	37.11	-1.01	-75.00	47.11	0.01	1,195.00	35.01	1		27/04/12
63	1237	141.89	0.01	4,275.00	150.11	0.94	7,575.00	13.13	1		30/04/12
64	1114	47.11	-0.76	7,575.00	59.11	0.01	10,875.00	25.37	1		3/05/12
65	1115	59.11	0.01	7,575.00	72.11	0.76	10,875.00	21.83	1		4/05/12
66	1308	37.11	0.01	-75.00	47.11	1.01	1,195.00	33.48	1		7/05/12
67	1307	29.11	-1.01	-75.00	37.11	0.01	1,195.00	30.99	1		8/05/12
68	1113	47.11	0.01	7,575.00	59.11	0.76	10,875.00	25.10	1		11/05/12
69	1317	37.11	-1.01	1,195.00	47.11	0.01	5,175.00	21.56	1		14/05/12
70	1306	29.11	0.01	-75.00	37.11	1.01	1,195.00	29.69	1		15/05/12
71	1250	141.11	-0.94	7,575.00	149.11	0.01	10,875.00	15.40	1		16/05/12
72	1316	37.11	0.01	1,195.00	47.11	1.01	5,175.00	21.30	1		21/05/12
73	1303	19.11	-0.56	-75.00	29.11	0.56	1,195.00	55.92	1		22/05/12
74	1249	141.11	0.01	7,575.00	149.11	0.94	10,875.00	15.17	1		23/05/12
75	1230	150.11	-0.71	2,175.00	158.00	0.71	7,575.00	33.39	1		24/05/12
76	1326	37.11	-1.01	5,175.00	47.11	0.01	8,475.00	25.89	1		29/05/12
77	1325	37.11	0.01	5,175.00	47.11	1.01	8,475.00	26.67	1		5/06/12
78	1315	29.11	-1.01	1,195.00	37.11	-0.56	8,475.00	23.71	1		6/06/12
79	1252	149.11	-0.71	7,575.00	157.00	0.01	10,875.00	14.73	1		7/06/12
80	1314	29.11	0.56	1,195.00	37.11	1.01	8,475.00	23.71	1		12/06/12
81	1305	19.11	-1.01	-75.00	29.11	-0.56	5,175.00	19.65	1		13/06/12
82	1251	149.11	0.01	7,575.00	157.00	0.71	10,875.00	14.77	1		14/06/12
83	1304	19.11	0.56	-75.00	29.11	1.01	5,175.00	19.65	1		19/06/12
84	1313	29.11	-0.56	1,195.00	37.11	0.56	5,175.00	18.05	1	x	20/06/12
85	1302	10.11	-1.01	-75.00	19.11	1.01	1,195.00	48.41	1		26/06/12
86	1312	19.11	-0.56	1,195.00	29.11	0.56	5,175.00	9.01	1	x	27/06/12
87	1301	-4.11	-0.67	-75.00	10.11	0.67	1,195.00	6.99	1		3/07/12
88	1324	29.11	-0.56	5,175.00	37.11	0.56	8,475.00	18.74	1	x	4/07/12
89	1311	10.11	-1.01	1,195.00	19.11	1.01	5,175.00	40.23	1		10/07/12
90	1323	19.11	-1.01	5,175.00	29.11	0.01	8,475.00	16.66	1		11/07/12
91	1310	-4.11	-1.01	1,195.00	10.11	1.01	5,175.00	96.98	1		17/07/12
92	1322	19.11	0.01	5,175.00	29.11	1.01	8,475.00	16.39	1		18/07/12
93	1331	35.11	-0.71	8,475.00	47.11	0.01	11,775.00	17.45	1		19/07/12
94	1321	10.11	-1.01	5,175.00	19.11	0.01	8,475.00	18.13	1		24/07/12
95	1330	35.11	0.01	8,475.00	47.11	0.71	11,775.00	21.82	1		26/07/12
96	1329	26.11	-0.71	8,475.00	35.11	0.01	11,775.00	18.28	1		27/07/12
97	1320	10.11	0.01	5,175.00	19.11	1.01	8,475.00	19.83	1		31/07/12
98	1319	-4.11	-1.01	5,175.00	10.11	0.01	8,475.00	15.33	1		1/08/12
99	1328	26.11	0.01	8,475.00	35.11	0.71	11,775.00	15.28	1		3/08/12
100	1318	-4.11	0.01	5,175.00	10.11	1.01	8,475.00	15.12	1		8/08/12
101	1327	12.00	-0.57	8,475.00	26.11	0.57	11,775.00	44.98	1		14/08/12

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Interviews

G.1. Royal IHC - Block division Engineer

Itemized summary of the interview with Arie Runge – Royal IHC, conducted at 20 June 2017
Attendees: Arie Runge, Gerrit Alblas and Dirk de Bruijn
Location: Royal IHC, Kinderdijk

Required information for Block division
General Arrangement

- Frames
- Rooms
- Fuel and ballast/water tanks
- Midship section
- Position and dimensions of major equipment

Weight estimation

- Fore ship
- Mid sip
- Aft ship
- Superstructure including funnels

Block division plans of reference ships

- Experience with building this Block division

Material dimensions commonly used

- Steel plate lengths: 6 – 8 – 10 – 12 meter
- Steel plate width: 2 – 2.5 – 3 meter

Extra available information not required for Block division

- Stability calculations
  - Centre of gravity of ship
  - Weight major equipment
- Overall plate thicknesses of mid section

General systematic approach to choosing Block seams

- Divide everything higher than coaming deck of the hull
  - Superstructure
    - ◇ Will be erected in one piece when finished

        - Too many different disciplines to be working simultaneously on the slipway
    - Coaming
    - Verticale seam to split core functionality where mid section is equal
    - For a Hopper dredger this is the hopper
    - For a passenger ship this will be all cabins
    - For a Cutter dregder this will be where the cutter is hang
- Hopper Module will be split in bottom and side Blocks

Fixed constraints

- Outsourcing Block building
    - Doors and cranes of shipyard and outsource partners
    - Skills outsource partners, not all capable of building each Block type

Constraints that can be overruled

- Compartments
    - Exceptional areas
        - Bow thruster
        - Engine room
            - Engine Foundation
        - (Extremely) curved shell
        - Suction pipe sliders and fittings
        - Long lead time items
    - Systems
        - Steel system
            - Preferably the least curved connections, straight panel mounts are better
        - Propulsion system
            - Incl main engine
        - Fuel system
            - Tanks
            - Pipes and pumps
        - Mooring system
            - Anchors
            - Winches
        - Mission system
            - Suction pipes
            - Hopper
            - Bottom conical valves
    - Aim: least splitting of compartments in order to maximize pre-outfitting, aligning, carrying in components, skilled workers. can be overruled but extra costs will be incured
- Producibility
    - Redundant planning
        - Closing decks for long lead time items
    - Maximizing pre-outfitting
        - Damper of exhaust always within Block
        - Pull up a frame partly to intall more pre-outfitting
    - Mountability / welding
    - No minimization of seams
    - Goals: reduction of costs, decrease throughput time
- Plate dimensions
    - Block 12m x 12m x 12m is maximum (starting point)

  - If everything fits in one plate less waste is produced and less meters are welded
  - Combine seam/weld for material with Block seam
  - Goal: less weldlenth in production, secondary to other objectives
- Weight estimation
  - Based on gut feel and experience
  - Design and proposal uses panel method
  - Check total weight of Blocks with stated weight of modules
  - Combination of complexity and size to estimate weight
  - Maximization of weight and size towards crane capacity
  - Goal: Cost savings by using available facilities, but bigger equipment can be hired if necessary

General

- Many constraints can be overruled but result in, for example, high risks (planning, damage during production), so a situation will be assumed to override these constraints as little as possible, but it will be carefully chosen where this will be overruled for a greater importance than the constraint
  - Shipard condtitions can influence block division by high exception
- There is more information available that is not used for Block division
- In theory multiple Block divisions are possible, but if a solution is found satisfying all constraints it is chosing as final
  - Sometimes in a later stage seams can be changed, but only marginally
- Building beds are a production utility
- Block division dictates the detailed structural design
- Structural integrity is not taken into consideration because it can easily be solved with temporary stiffeners
- Making a Block division takes around a day including weight estimations
- It takes three days to make the preliminary production plan
  - Iterative process using support tools
- Block types
  - Curved Blocks are most expensive
  - Straigth Blocks least
  - Block types are not a way of creating a Block division, merely a categorization

Itemized summary of the interview with Arie Runge – Royal IHC, conducted at 11 July 2017
Attendees: Arie Runge, Gerrit Alblas and Dirk de Bruijn
Location: Royal IHC, Kinderdijk

Erection redundancy

- Side Blocks are a type of closing Block
- Lead time of Blocks remains important in case of outsourcing
  - Krimpen does all conservation of outsourced Blocks
  - Capacity outsourcepartners
    - Royal IHC is not their only customer
    - Important to know how many people per week are available for which price

Critical Long lead time items to take into consideration

- Main engines
- Dregdge pumps
- Bow pump
- Bow thruster (system)
- Everything non-standard
  - Not “off the shelve” items, but custom made for example
    - Spare part is more complicated
    - Lead times are longer

        - For example Hopper suction pipe inlet

Detailed planning long lead time items (not important for Block division)

- Douche cabines
    - Unable to place after closing decks
        - Standard item whith reliable lead time
        - Is taken into account while erecting the superstructure
- Everything that does not fit through a door
    - Has to be taken into account in the sequence and planning of components
- In the detailed planning extra closing decks/Blocks can be added
    - If something does not work with delivery times and original planning, change some things. For the biggest things you have already taken into account flexibility (see list above)
    - Extra closing blocks can be created that can be delivered separately or mounted lightly

Non critical long lead time items:

- box cooler can always be mounted afterwards via hatches
    - Place box and conserve like watertanks or shell
    - In contact with sea water
- Conical valves
    - Are deployed on the slipway and erected upwards
        - In case they are late they can be slid under the bottom from the side

Block division constraints:

- Crane Kinderdijk capacity 140 ton
- Crane Krimpen capaity 240 ton
- Structural integrity of Block is not taken into consideration
    - 90% of Blocks is structurally stirdy on its own
    - Other Blocks are reinforced with temporary stiffeners
- Blocks that are never different because that always results in problems
    - Aft ship Module is sometimes difficult, but with temporary support and sleds by extra weight larger section to solve. You prefer not to split due to curvature and no underlying Block
        - Eventually this will decrease throughput time
        - Should show in erectino sequence planning

Block division plan and erection sequence

- Choose an erection strategy
    - Start with a mid block keeps options open
    - Sometimes a new ship starts on the slipway while another is not yet finished
        - You can start with most labour intensive Block
            - For a hopper dredger that would be the engine room
    - Erection sequence constraints are taken into account for the Block division
    - For production reasons sometimes other erection sequences are preferred
        - For example in case of delays at Block building or procured equipment
    - Sometimes fore ship will be starting point when slipway is not completely available
        - In case of hopper dredger is that not so labour intensive so not optimal
        - In case of a subsea ship this would make more sensse due to present diving support equipment in the fore ship
    - General erection sequence planners use a single block division to create the optimal production plan
        - Block division can depend on the chosen erection sequence

        - ◇ Erection sequence also depends on block division
        - ◇ 95% of the time the block division is independent of shipyard conditions
            - · In theory there are scenarios where this would not be the case
    - Out of scope
        - ◇ Assume Block division independent of shipyard conditions
        - ◇ Block division is not constantly changed in early stage, also not in case of change in lead times
            - · Due to many changes this is done at the time final conditions are more certain
    - Detailed planning will solve upcoming problems in production
        - ◇ For example by creating extra closing Blocks

Block seam position compared to frame positions

- Seams are placed on side of plates where no stiffeners are found
    - Not for every frame or plate this is known
        - ◇ Many stiffeners are part of detailed design following at a later stage
            - · Structural requirements for stiffeners outweigh the initially chosen seam position
    - Block seam position can simply be changed to other side of the frame without many consequences
    - There is a weight change due to extra steel included in a Block
        - ◇ Weight difference of a single frame will be around 1.5 ton so no significant change in total weight of Blocks
        - ◇ Seam position around frames is not influenced by outfitting components
    - Seam can change around PS and SB side of CL over length
    - Always choose Blocks in a way that most of the welds can be welded under hands
    - Block seam can be off a frame more than 75mm in case of other structural parts, this will be added to the Block division at a later stage than during the initial creation of the Block division plan
    - Transits will be split by seams for aligning of transit

Block number names

- Standard number strategy by Royal IHC in work description
    - Not consistantly put into practise
    - International numbering standard exists
- Always in the range of 1000
    - SFI system code for steel

Engine room block example ship

- Engine room Block is mainly chosen like this for material lengths
- Aft is most curved compared to the two so the aft Block will be maximum length

All frames will be stiffened

- Depending on type of frame the stiffeners can be thicker or smaller
- Engine room frame
    - Stiffeners standard on inside of engine room
        - ◇ In case of space requirements this can be turned around
            - · Block seam will in that case also change side
- Stiffeners for that matter can also be inside watertanks but not preferably
    - Conservation of such tanks gets increasingly complex and expensive

Seams always above decks

- Creating work area
- All mounting welds are underhands
- Stiffeners are always on the lowerside of decks

Watertanks:

- In example ship watertanks are often split
  - Sometimes impossible to avoid this
    - Final conservation has to take place on board
  - Size is constraint at outsource partners
    - Building beds are around 12 meters
  - Offshore ship contains more watertanks and than this is more important
  - Rather split one Tank two times than two tanks one time

Superstructure Block

- is not split but exceeds 12 meter
  - Is build in two pieces but combined before erection
  - Superstructure Blocks are generally light weight and high finish so preferably not split

General Block division considerations

- Rather split too large and heavy Blocks to create two smaller Blocks than to arrange extra equipent
  - Bow thruster
  - Aft ship with many alinged pieces and curves
- Maximizing Blocks wieght only when there is capacity available at outsourcepartners
  - Optimizing to create as large as possible Blocks within maximium weight

Itemized summary of the interview with Arie Runge – Royal IHC, conducted at 29 September 2017
Attendees: Arie Runge and Dirk de Bruijn
Location: Royal IHC, Kinderdijk

Shipyard facilities dictate Block Division Approach – general starting point is to minimize erection actions by maximizing blocks weight and size

- Royal IHC maximizes single Blocks weight and size
  - Simply no space at shipyard to construct Mega Blocks in combination with engineered to order product and shipyard's organization

Block division:

- Closing decks vs closing Blocks
  - Closing decks create extra Block vs two symmetrical closing Blocks
  - At Schelde they erect equipment from the side and use symmetrical closing Blocks that always include a bulkhea
- Lower decks
  - De crosswise seams are placed vertically above each other in order to minimize erectino constraints
  - Closing deck at bow thruster is not chosen as such due to fitting thruster engines through transit
  - Proposed hierarchy of Compartments is confirmed

- Whether I have to erect it next to the slipway as a mega block, or on the slipway, does not matter (from that your engineering is not finished and lead times etc)
  - Probably more hoisting pints have to be created
  - Maybe increased temporary stiffeners
  - Organization work structure not fit for Mega Blocks
- Why do you think they work in modules / Ring Blocks at Damen Schelde and Meyer Werff?
  - They have a lot more space, their entire yard is set up there, much more "mass production"
  - All difficult Blocks are outsourced at Meijer
  - At Schelde they have also closed a slope to create a new panel street to build in this way

- Do you think Royal IHC should also build in Ring-Mega-Blocks?
  - Not sure if that works for Royal IHC
  - In everything you make bigger (Mega Blocks), you have to run the whole organization equal
  - When everything is smaller you can release earlier
  - With Mega Blocks everything has to be on time, everything has to wait until everything is finished Depends on order types, in case of serie production it can be convenient
  - Depends on delivery and turnaround times
- At IHC they make in case of 35 frames two large Blocks, and Schelde makes three small ones based on bulkheads. engineering:
  - Block building for one block takes around 8 weeks
  - Mega Block building takes around 20 weeks
  - IHC does more engineer-to-order
  - Schelde some more (small) series
  - There will be made small improvements in series. But if you have an order, you will come up with a route, engineering
- Why create closing decks and not symmetrical closing Blocks
  - Erecting a closing Block within two other Blocks is complicated due to shrinkage. The space where it goes changes shape and the chance arises that the closing Block will not fit anymore
  - How thicker the to be welded plates are, how more shrinkage occurs
  - We use much thicker plates than Damen Schelde and then this effect is also greater, because you have to put more heat into it
  - If the outside deck has been completed, then it can also be launched much more easily if a motor is delivered shortly before
- Main deck saems not always equal to lower deck transverse seams
  - You want to create the ful length of the ship as soon as possible
    - ◇ Work area
    - ◇ Fore ship and aft ship contain most work Enables outfitting to be continues
    - ◇ Pulling cables
  - Main deck – closing decks can always be placed on top of the hull
- Symmetrical bottom Block
  - Can be used to align the seams, up to 10mm seam is accepted by BV legislation
  - Pump room of test case ship provides both possibilities
    - ◇ Skeg is good to keep within a Block, but otherwise the correction in aligning is an advantage in production, it is a choice

G.2. Royal IHC - Design and Proposal

Itemized summary of the interview with Peter van der Poel – Royal IHC, conducted at 26 June 2017
Attendees: Peter van der Poel, Gerrit Alblas and Dirk de Bruijn
Location: Royal IHC, Kinderdijk

Estimated Steel weight Blocks

1. Rough Block estimation technique

- Comparable reference ships
  - Major dimensions
    - ◇ Length
    - ◇ Breadth
    - ◇ Frame spacing
  - Function
    - ◇ For example trailing suction hopper dredger
  - System type
    - ◇ Conical valves
    - ◇ Trailing draghead / cutter

- Available actual information data of comparable reference ships
    - General Arrangement
        - ◇ Bulkheads
        - ◇ Decks
        - ◇ Centre of gravity: longitudinal, transverse and depth
        - ◇ Weight distribution
    - Detailed hull structural design
    - Weight
        - ◇ Per block
        - ◇ Including centre of gravity
        - ◇ Cubic weight
    - Cost
- Estimate weight of new Blocks
    - Cubic weight per compartments based on available information
    - New Block weight can be calculated using this cubic weight and corrected for deviations
        - ◇ Block length for example is equal
            - · Block weight including sensible correction factor
            - · Forepeak for ship of 30m wide similar as for a ship of 32m wide
    - Compare to midschip weight, foreship weight and aft ship weight
    - Check centre of gravity

2. More detailed estimation techniques

- Panel method
    - Based on weight of panels
        - ◇ Recalculation
        - ◇ Detailed hull structural design
    - Block weights
        - ◇ Compare to built Blocks
        - ◇ Find comparable Blocks
            - · Major dimensions
            - · Function
            - · Type
            - · Location
        - ◇ Compare and correct
            - · Different dimensions (extrapolate)
            - · Length is imporant factor
            - · Exceptions
            - · For example foundations
            - · New regulation
            - · Intelligent adding variables
        - ◇ Calculate panel weights
            - · Bulkheads
            - · Decks
            - · Profiles
            - · Add 20-25% for lack of detailed structural design
        - ◇ Outfitting is fixed % of light weight equally for whole ship
            - · Every ship has manholes
            - · Everywhere in the ship are staircases

2. Corrected Steel weight of Blocks

- CAD calculation based on detailed hull structural design

3. Final steel weight

- Actual weight based on built Blocks

4. General (erection) planning

  - Two months with four FTE for contract designGeneral Arrangement Find comparable Blocks
    - ◇ Centre of gravity
    - ◇ Literature states certain % of depth
    - ◇ Make minor corrections to correct centre of gravity
  - Hydostatical model
  - Load conditions
  - Three weeks to determine Block weight
  - Two weeks to do other weight calculations
  - Rough estimation of ship weight / 1000 = of months erection building and ship on slipway
    - ◇ Add 11-12 months to the start of the planning
      - · Depending on complexity based on the General Arrangement
    - ◇ Add 8 months to the end of the planning
    - ◇ Longer/shorter correct depending on ship dimensions
    - ◇ How high is superstructure, can it be placed in one piece
      - · Can all cables be installed at once from the navigation room to the engine room
    - ◇ If possible, six weeks after launch engines can be started Erection is usually started with a centre Block
      - · Provides platform to erect Blocks on either side
      - · Minimize erection time on slipway

Offshore ship:

- Engineering is a planning challenge due to complexity
- Engine room is generally in the fore ship
- Many pipe routing or moon pools for example
- Engine room must be finished shortly after hopper or moon pool
  - High engineering labour intensive
- Coop with by agreeing upon decision with ship owner
  - Choose engine
  - Choose supplier
- All to make there can be started with HVAC etc

Dredging ship:

- Engine room is generally in the aft
- Most import decision for planning is dredging system
  - Hopper cage must be started with due to special materials
    - ◇ Includes jet-water pipes to empty hopper
    - ◇ Also pipes to be able to spray "rainbow"
    - ◇ All pipes deteriorate very fast so special materials must be chosen
  - Drop load through hopper floors by conical valves
- Sequence of constructing a hopper
  - 1. Bottom Blocks
  - 2. Hopper floors including hopper cage - requires engineering

        - ◇ Parts must be delivered in month number eight
        - ◇ Must be used in Block building in month 9

5. Block division

- Where steel system interacts with compartments is generally a seam
- Isolate watertanks
    - Water (ballast + fresh water etc) prefer not to split due to conservation
        - ◇ Legislation can influence Block seam positions
    - Fuel tank does not require conservation
- Closing decks
- Routing of outfitting goes around closing decks so information is required early
- Frame or bulkhead can also be closing Block
    - For Example: Hopper end bulkhead
        - ◇ Generator set can be installed at late stage in case of long lead time due to this bulkhead
            - · When engineering is behind schedule
            - · User list are delayed
            - · Load balance is delayed
            - · Definitive required power is delayed
            - · Equipment is ordered too late and planning can not be completed
        - ◇ Bulkheads are important in the Block division
    - Seam placing next to frames or decks determine structural integrity fo Block
- Shipyard and supply facilities constraint
    - Material size constraint
    - Weight constraints
    - Convenient to handle Blocks

G.3. Royal IHC - Naval Architect

Itemized summary of the interview with Bram Scherf – Royal IHC, conducted at 9 September 2017
Attendees: Bram Scherf and Dirk de Bruijn
Location: Royal IHC, Kinderdijk

- Take existing blocks when it looks very similar
- For bulb, or whole bow
- Or whole aft ship
- or bottom aft ship
- I look at detail section drawing, to panels and stiffeners etc
- I compare with total section weight, this is always higher because you do not take all small parts in opp of all those plates.
- That difference is a factor, and I then multiply it over the panels and then I arrive at the total section weight
- You can also use large truss for weight per linear meter of, for example, midship
    - I grab a web frame, I see all the plates in the big span and then I divide that by the running meters, then you have a meter weight
    - Then factor of, for example, 5% for small parts
- There is not a standard method, I always look per section how I can get it done as accurately as possible as quickly as possible
- Which panels do you always take with you?

  - Head long-term
  - Bulkheads
  - Decks
  - Shell
  - Primary + secondary stiffeners
    - ◇ Are not yet known for new ship, suit reference ships
  - Double soil is actually always weight per m2, not per soil and per tanktop + frames or similar (I want to do this this way)
  - For side Blocks it is difficult to count the web frames on panels, so grab it from 1 web frame,
- Old method: Carstens, for carriers and container ships
- It is very important for IHC to make very accurate weight estimation because the weight of the steel determines for a large part how expensive the ship will be
  - You can not be too high because then you are not competitive
  - And also not too low because then you do not get your deadweight and you do not go through inspection etc
- Plate thicknesses differ greatly across the entire ship
  - Midship very thick (decks) for bending moment
  - Skin bow thick for eg impact
  - Foundations thicker of course
  - Also thickness is likely in the width
- You will have to estimate panel thicknesses because I make this weight classification in the initial phase of concept design
- I base myself on everything that is drawn on the general plan
- The panel method is used for determining weight of Blocks for new ships
- I only look at panel fields
- Bow thruster pipe can be seen as a circular panel

G.4. DAMEN Schelde Naval - Project Department

Itemized summary of the interview with Arjen Poortvliet – DAMEN Schelde Naval 25 september 2017
Attendees: Arjen Poortvliet and Dirk de Bruijn
Location: DAMEN Schelde Naval Shipyard, Kinderdijk

- We also keep engine room Block open as long as possible, but do not work with closing decks
- For example even sometimes we keep it open longer and did the same for other later construction numbers
- We take very much arguments into account in the Block division plan, with the help of the Block division plan we make construction strategy, or actually the other way around
- We do take into account rudder king, but we often add it later. So then that seam can be there, then it is no problem
- In NUPAS it is already very detailed structural plan, from which follow the Block seams
- The work planners then determine the seams, and take particular take into account the erection of equipment. The erection schedule has also been developed according to the erection direction of equipment, always from the side (green arrows left, right etc)
- You do not create a new Block division plan if you already have an existing ship, because then you have to redo all your drawings + work preparation + production so you will not do that
- We always keep one bulkhead in the block, for structural integrity requirement and so that equipment can be erected from the other side
- Are the stiffeners first and then comes the section seam that follows or vice versa? The construction is really determined by the engineer. The construction is therefore never adjusted because the Block division has to be chosen in a certain way
- How long are you working on a detailed structural plan, do not you want to make your Block division earlier? You get a GA plan very quickly, you know a lot about that. With a built-to-order, it is all the

information you have. With our own designs, the Blocks are always about 7200mm long. Size of the construction beds of the yard where it is built are leading for the dimensions of the Blocks
- Building beds are at the order of 7-12 meters in size
- Do you work differently at one-off than in series construction? Yes, then you do it differently, then you only look at GA and not detailed detail design at NUPAS. So you do not know how thick the steel is going to be everywhere. Sometimes corrections have to be made to the Block division later in construction, or extra splits, because the crane capacity may not be sufficient. You develop your drawing in NUPAS more and more and occasionally you count how heavy the individual Blocks get. If the weight is too high you have to split the Block
- We have a rudder-king, that is often a separate block, is put in as a whole. Also bow thrusters are installed later in order to prevent all kinds of discussions, same goes for propeller kings
- Basically what you have developed looks like reality, but your starting points are just different. We look much more at the yard and then make the Block division based on what the yard could do in terms of erection strategy
- At IHC, ofcourse, they only look at IHC shipyards. At Schelde we look at different yards, we choose the Block division so that it is supportive to the building strategy, and the building strategy depends on the yard facilities
- Restriction of the yard in Vlissingen is height of the conservation hall, and they prefer to make as large rings as possible so you can conserve as much as 1x because it takes a long time with an eye on drying etc, mutual purpose of maximizing outfitting in Block construction and Mega Block / Ring Mega Block assembly
- If you can enter the max weight and height etc you can still end up with your logic
  - Constraint height does not exist directly in BDG
  - Starting point in that sense is equal that they both aim for maximum weight, only at Schelde to maximize weight Ring Mega Blocks are constructed and at IHC indiviudal Blocks are maximized
  - The developed methodology better fits engineered to order ships rather than series
- In series construction they first develop the ship in more detail before the production plan is made, with built-to-order it makes more sense
- Starting point is also rather smaller Blocks so you can handle it more flexibly, read other Mega Blocks configurations, with larger Blocks you have less possibilities for Ring Mega Block combinations
- The BDG can also be applied when a new ship will be available to order, the BDG can than be used to come up with the ideal Block division plan so as many yards as possible are able to build the ship effectively
- For the redevelopment of a Block division plan for an existing ship, it makes no sense as mentioned earlier
- Look carefully at optimization objective where a shipyard earns its money, popping hulls does not earn you anything, you have to earn it on total turnaround time of the entire ship including everything. The hull is 10-20% of cost, at bit sophisticated "complex ship" this will probably be the case
- There is a lot more money involved in the engineering and ordering of resources, and in preparing the ship, it is about total construction time, not only the hulls crash into each other as quickly as possible, it's all about everything
- Preference on bulkheads is indirect choice to support outfitting maximization
- For now it seems too much work and in advance so different assumptions that it makes no sense to apply the BDG already on naval ships with the erection strategy DAMEN Schelde is using
- I think that different Block division engineers make different choices? I do not believe that someone would make a completely different plan, it should always be in consultation with production, you can not say: this is it, good luck with it
- It is very strange that they keep the bow thruster in its entirety and divide the Blocks above in two
- At Schelde, they make split bow thruster Block and insert tubes later, different in strategy, you draw in 3D and tube in and go. In terms of construction, it is not logical to apply different rules to Blocks, by keeping that one very broad, you should actually keep your starting points the same
- Do you take meters of welding work into account? Not directly, but you take into account sheet material distance, so then you make sure that you weld the seams that you have to weld then immediately make a seam section
- Your apply conservation coatings to water tank only after construction and after grinding and burning

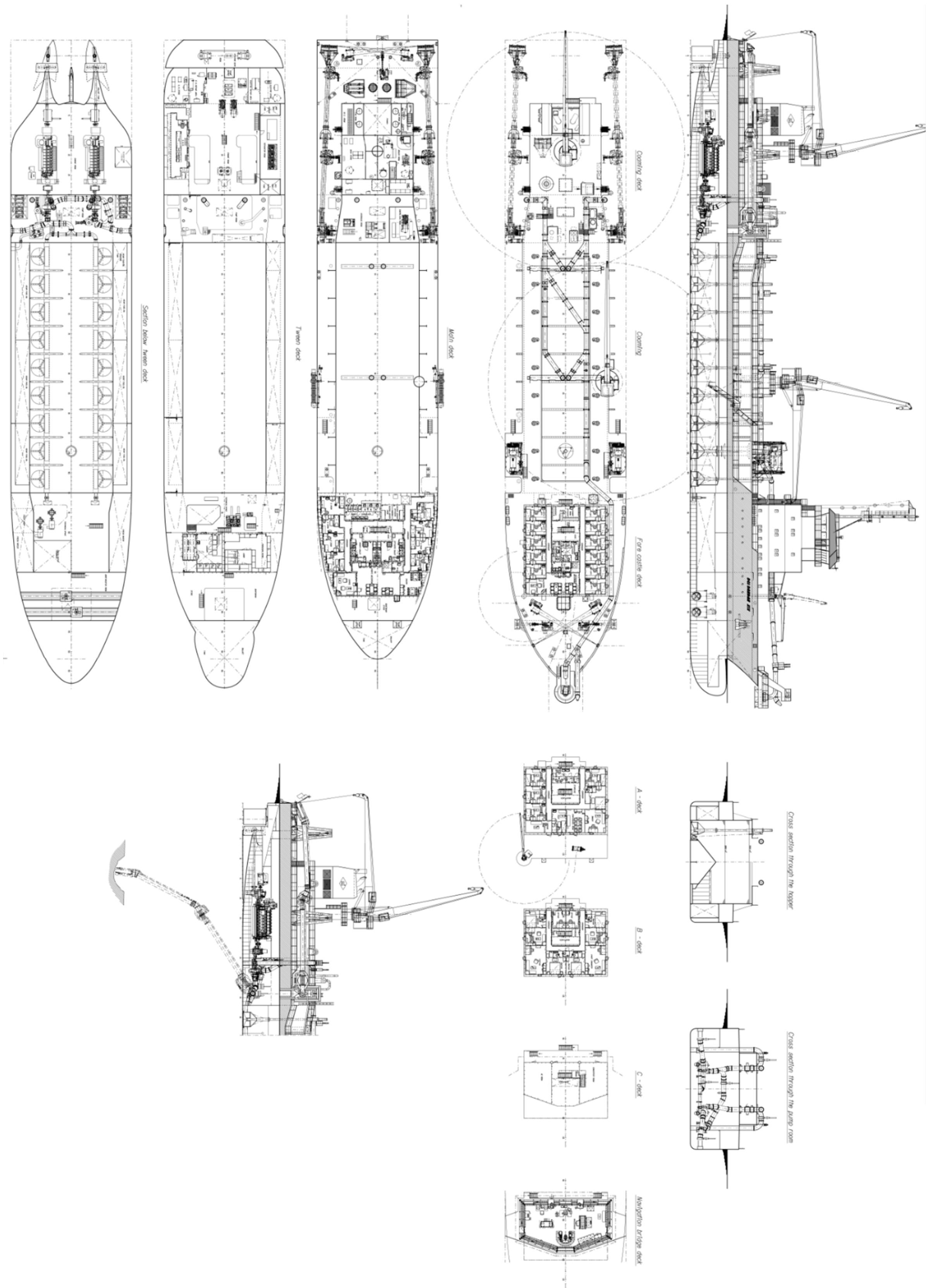
etc because the chance is too great that you can damage it, keep it as late as possible but in time for the launch. There is already primer but not a final coating

- At midship we also look at how well something can be hoisted, then we put in time I-beam between it to stiffen something etc
- In the single Block erection strategy two large Blocks are preferred, in the Mega Block erection strategy three smaller Blocks are preferred in order to create Ring Mega Blocks, other construction strategy with same objective but different required facilities
  - IHC optimizes to maximum Blocks because of lead times and engineered to order processes
  - Schelde optimized to max ring Mega Blocks and then choose smaller Blocks with which you can use more flexible to create Mega Blocks
- Theory of constraints, at our conservation hall in Vlissingen, but your construction constraints determine the building strategy
  - Max height hall
  - Max height conservation hall
  - Max capacity crane
  - Max size of building beds
- Open question: does every yard with the same facilities apply the same building strategy
  - Would Schelde choose the same plan as IHC to build at Krimpen
  - IHC would choose the same plan as Schelde
    - ◇ Probably this will not differ that much
    - ◇ It can also be the earnings model that you strive for, if you do your hull construction as quickly as possible, you may choose different things than if you were starting to use the entire ship as quickly as possible
    - ◇ You have to take account of logistics at your yard, you have to be able to transport materials ans assemblies
- I think that the starting point of maximizing Blocks is the same with IHC and Schelde, only that they at IHC apply that on the Block itself and at Schelde applies this to Mega Blocks and thus start with smaller individual Blocks
- Open question: you have a Block division that is not useful, and you could calculate how much you saved to take the extra work for granted and do it again / improve, then you can say: look, we can better do it once instead over instead of 20x making doing it the hard way, because now you can not demonstrate that
- Starting point: construction strategy depends on site facilities, that is not fully implemented in the BDG

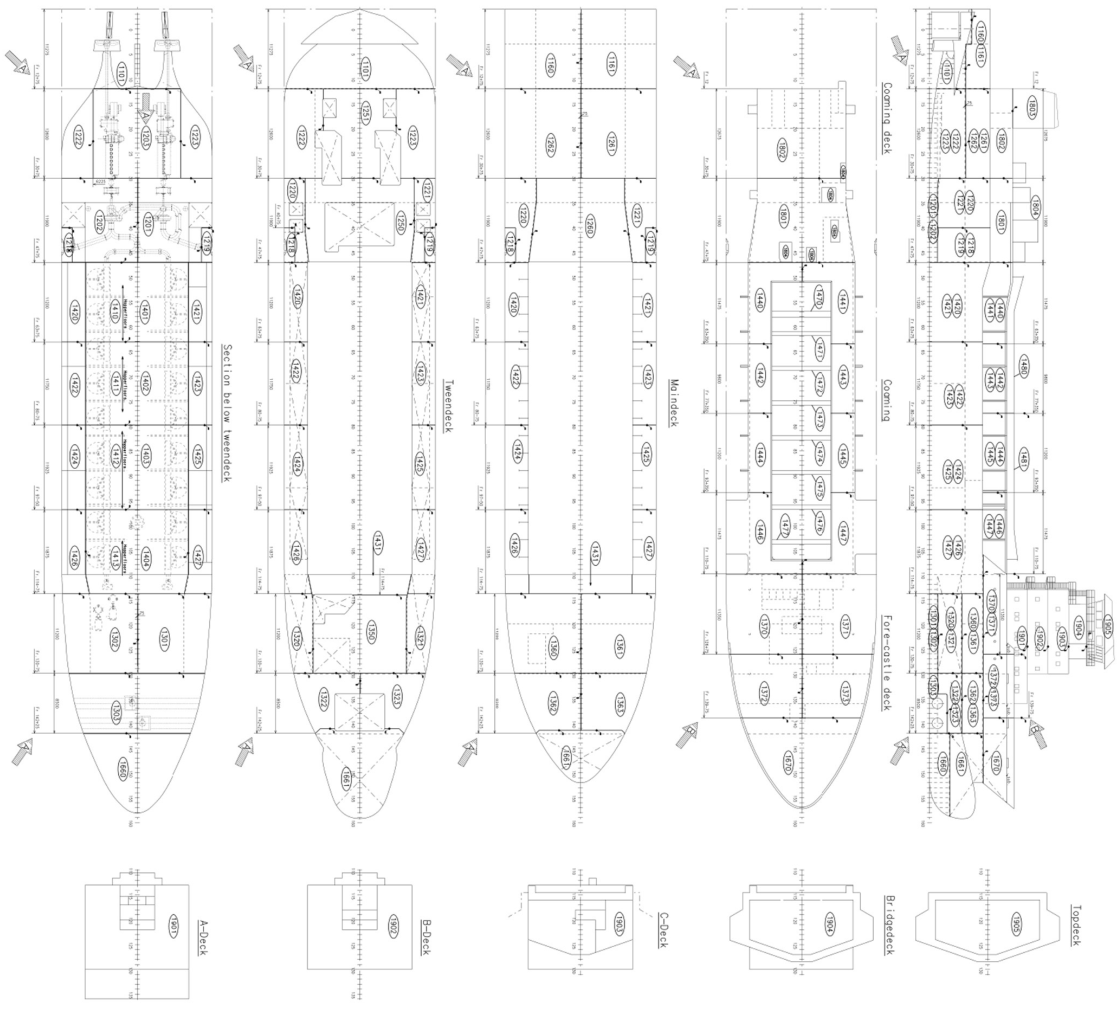
H

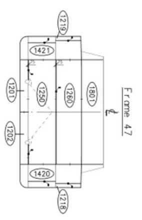
Design Information Test Case Ships

H.1. General Arrangement Test case ship 1 - Trailing Suction Hopper Dredger



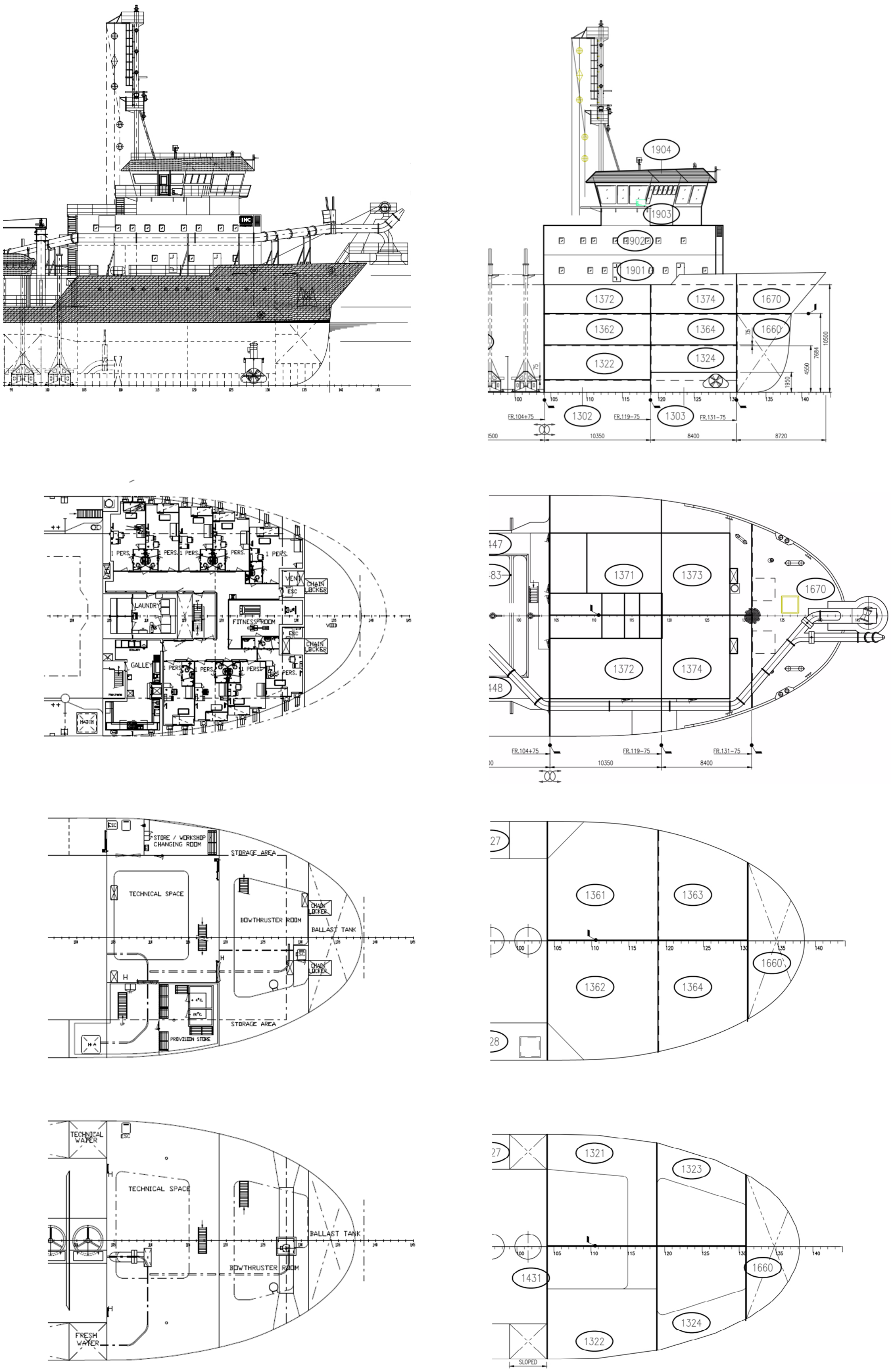
H.2. Original Block division Solution Test case ship 2 - Trailing Suction Hopper Dredger



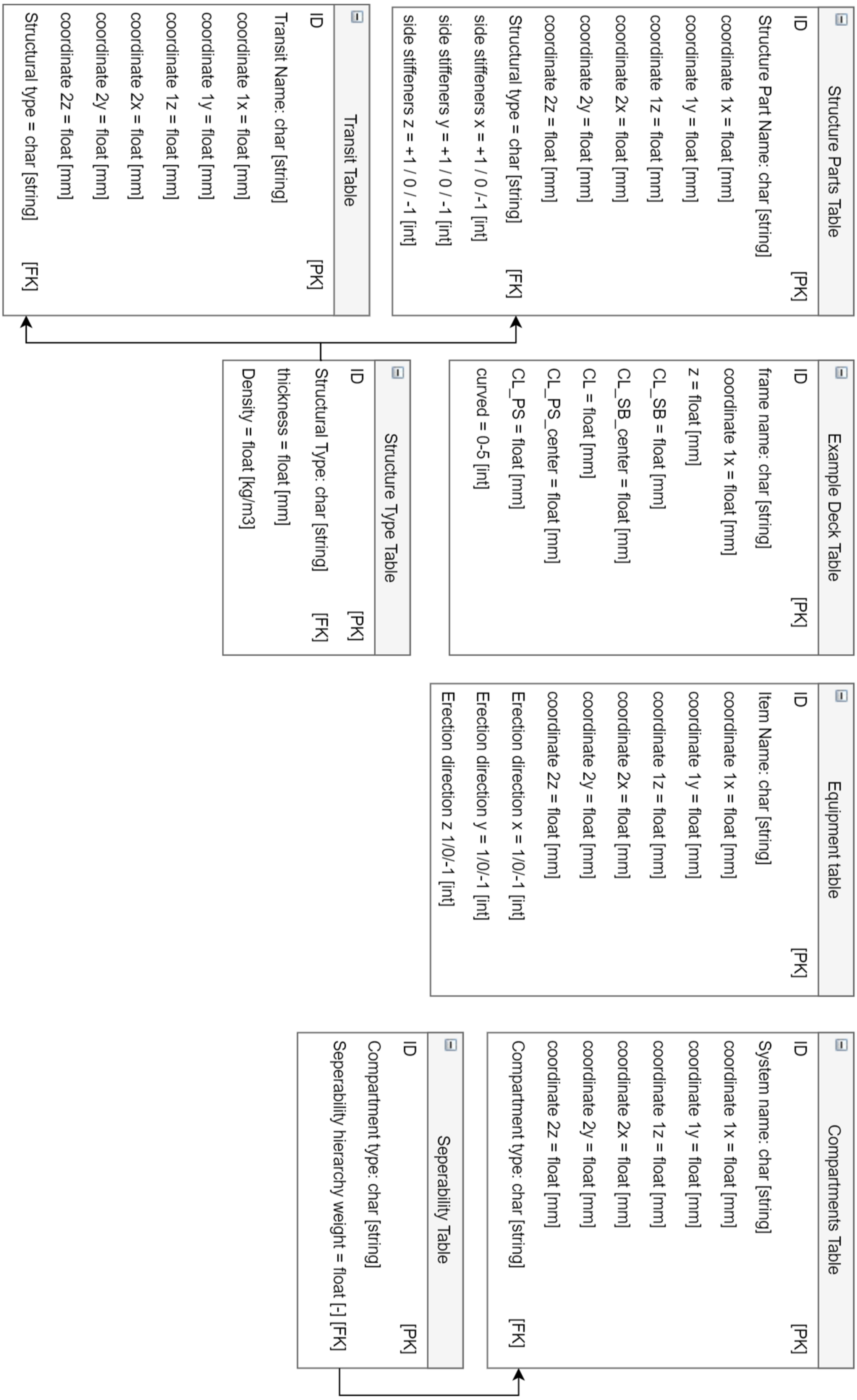


Block number IHC	Section nr.	Section Name	Side	Position	Estimated Steel Weight (tons)	Corrected Steel Weight (tons)	Final Steel Weight (tons)	Remarks
11.00	1101	Construction Aftship below Tweendeck	C.L.	Fr.-4 -12	100	131	130	excl. nozzles etc
	1160	Construction Maindeck Aftship	S.B.	Fr.-4 -12	81	43	45	
	1161	Construction Maindeck Aftship	P.S.	Fr.-4 -12	21	42	45	
				Block 11.00=	202	216	220	= 3 sections
12.00	1201	Double Bottom Pumproom	P.S	Fr.30-47	60	60	61	
	1202	Double Bottom Pumproom	S.B.	Fr.30-47	60	62	66	
	1203	Double Bottom Engineroom	C.L.	Fr.12-30	167	93	93	
	1218	Suctiontube inlet section	S.B.	Fr.40-47	17	17	18	
	1219	Suctiontube inlet section	P.S.	Fr.40-47	17	17	18	
	1220	Side Shell Pumproom	S.B.	Fr.30-47	22	29	41	
	1221	Side Shell Pumproom	P.S	Fr.30-47	22	30	44	
	1222	Side Shell Engineroom	S.B.	Fr.12-30	33	33	34	
	1223	Side Shell Engineroom	P.S	Fr.12-30	33	36	38	
	1250	Tweendeck Pumproom with bulkh. Fr.35/47	C.L.	Fr.30-47	17	44	39	
	1251	Tweendeck Engineroom	C.L.	Fr.12-30	6	12	12	
	1260	Maindeck Pumproom with bulkh. Fr. 35/47	S.B.	Fr.30-47	16	38	43	
	1261	Maindeck Engineroom	P.S	Fr.12-30	13	31	32	
	1262	Maindeck Engineroom	S.B.	Fr.12-30	12	30	32	
				Block 12.00=	495	532	571	= 14 sections
13.00	1301	Double Bottom Technical Space	P.S.	Fr.114-130	49	43	38	
	1302	Double Bottom Technical Space	S.B.	Fr.114-130	49	47	45	
	1303	Double Bottom Bowthrusterroom	C.L.	Fr.130-142	82	55	66	
	1320	Side Shell Technical Space	S.B.	Fr.114-130	17	18	21	
	1321	Side Shell Technical Space	P.S.	Fr.114-130	17	19	19	
	1322	Side Shell Bowthrusterroom	S.B.	Fr.130-142	15	15	15	
	1323	Side Shell Bowthrusterroom	P.S	Fr.130-142	15	14	14	
	1350	Tweendeck	S.B.	Fr.114-130	42	21	21	
	1360	Maindeck with shell	S.B.	Fr.114-130	29	27	34	
	1361	Maindeck with shell	P.S	Fr.114-130	29	24	23	
	1362	Maindeck with shell	S.B.	Fr.130-142	12	13	16	
	1363	Maindeck with shell	P.S	Fr.130-142	16	14	16	
	1370	Forecastledeck with Shell	S.B.	Fr.110-126	34	47	46	
	1371	Forecastledeck with Shell	P.S	Fr.110-126	34	41	43	
	1372	Forecastledeck with Shell	S.B.	Fr.126-142	21	24	24	
	1373	Forecastledeck with Shell	P.S	Fr.126-142	21	24	25	
				Block 13.00=	482	446	465	= 16 sections
14.00	1401	Centre box girder	C.L.	Fr.47-63	65	65	62	
	1402	Centre box girder	C.L.	Fr.63-80	66	66	64	
	1403	Centre box girder	C.L.	Fr.80-97	71	71	66	
	1404	Centre box girder with doublebottom	C.L.	Fr.97-114	69	69	71	
	1410	Hopperfloors at section 1401	C.L.	Fr.54 61	15	15	14	
	1411	Hopperfloors at section 1402	C.L.	Fr. 68 75	15	15	14	
	1412	Hopperfloors at section 1403	C.L.	Fr. 82 89 96	22	22	22	
	1413	Hopperfloors at section 1404	C.L.	Fr. 103	7	7	7	
	1420	Buoyancy Compartment	S.B.	Fr.47-63	56	56	57	
	1421	Buoyancy Compartment	P.S.	Fr.47-63	56	56	58	
	1422	Buoyancy Compartment	S.B.	Fr.63-80	58	58	58	
	1423	Buoyancy Compartment	P.S.	Fr.63-80	58	58	58	
	1424	Buoyancy Compartment	S.B.	Fr.80-97	60	60	60	
	1425	Buoyancy Compartment	P.S.	Fr.80-97	60	60	60	
	1426	Buoyancy Compartment	S.B.	Fr.97-114	58	58	59	
	1427	Buoyancy Compartment	S.B.	Fr.97-114	58	58	60	
	1431	Hopperend Bulkhead section fore	C.L.	Fr.110	31	31	31	
	1440	Hopper Coaming	S.B.	Fr.47-63.5	37	34	35	
	1441	Hopper Coaming	P.S.	Fr.47-63.5	37	34	35	
	1442	Hopper Coaming	S.B.	Fr.63.5-77.5	32	27	28	
	1443	Hopper Coaming	P.S.	Fr.63.5-77.5	32	27	28	
	1444	Hopper Coaming	S.B.	Fr.77.5-93.5	37	36	33	
	1445	Hopper Coaming	P.S.	Fr.77.5-93.5	41	32	35	
	1446	Hopper Coaming	S.B.	Fr.93.5-110	36	34	38	
	1447	Hopper Coaming	P.S.	Fr.93.5-110	36	34	38	
	1470	Hopperbeam	C.L.	Fr. 57	3	3	3	
	1471	Hopperbeam	C.L.	Fr. 61	2	2	3	
	1472	Hopperbeam	C.L.	Fr. 68	2	2	2	
	1473	Hopperbeam	C.L.	Fr. 75	2	2	5	
	1474	Hopperbeam	C.L.	Fr. 82	3	3	3	
	1475	Hopperbeam	C.L.	Fr. 89	2	2	2	
	1476	Hopperbeam	C.L.	Fr. 96	2	2	3	
	1477	Hopperbeam	C.L.	Fr. 103	2	2	2	
	1480	Hopper Splash Screen aft	C.L.	Fr.50-77.5	6	6	6	
	1481	Hopper Splash Screen fore	C.L.	Fr.77.5-106	6	6	6	
				Block 14.00=	1143	1113	1124	= 35 sections
16.00	1660	Fore Peak double bottom	C.L.	Fr.142-FORE	94	73	76	
	1661	Fore Peak below Maindeck	C.L.	Fr.142-FORE	77	70	75	
	1670	Fore Peak below Fore Castle Deck	C.L.	Fr.142-FORE	48	63	64	
				Block 16.00=	219	206	215	= 3 sections
18.00	1801	Coamingdeck aft	C.L.	Fr.30-47	69	53	68	
	1802	Coamingdeck aft	C.L.	Fr.12-30	42	53	52	
	1803	Funnel	C.L.	Fr.12-20	30	25	29	
	1804	Ventilation Deckhouses Aftship	C.L.	Fr. 27-47	-	10	7	
				Block 18.00=	141	141	156	= 4 sections
19.00	1901	Deckhouse A-deck with walls	C.L.	Fr.113-136	41	45	47	
	1902	Deckhouse B-deck with walls	C.L.	Fr.113-130	28	29	29	
	1903	Deckhouse C-deck with walls	C.L.	Fr.113-130	27	33	31	
	1904	Bridgedeck	C.L.	Fr.114-129	16	27	27	
	1905	Wheelhouse	C.L.	Fr.114-129	35	25	29	
				Block 19.00=	148	159	164	= 5 section
		Total weight steel casco =			2830	2811	2914	= 80 sections

H.3. GA and Block division Test case ship 2 - Trailing Suction Hopper Dredger



System Diagram Relational Database


Structure Parts Table
ID [PK]
Structure Part Name: char [string]
coordinate 1x = float [mm]
coordinate 1y = float [mm]
coordinate 1z = float [mm]
coordinate 2x = float [mm]
coordinate 2y = float [mm]
coordinate 2z = float [mm]
Structural type = char [string] [FK]
side stiffeners x = +1 / 0 /-1 [int]
side stiffeners y = +1 / 0 / -1 [int]
side stiffeners z = +1 / 0 / -1 [int]
Transit Table
ID [PK]
Transit Name: char [string]
coordinate 1x = float [mm]
coordinate 1y = float [mm]
coordinate 1z = float [mm]
coordinate 2x = float [mm]
coordinate 2y = float [mm]
coordinate 2z = float [mm]
Structural type = char [string] [FK]
Example Deck Table
ID [PK]
frame name: char [string]
coordinate 1x = float [mm]
z = float [mm]
CL_SB = float [mm]
CL_SB_center = float [mm]
CL = float [mm]
CL_PS_center = float [mm]
CL_PS = float [mm]
curved = 0-5 [int]
Structure Type Table
ID [PK]
Structural Type: char [string] [FK]
thickness = float [mm]
Density = float [kg/m3]
Equipment table
ID [PK]
Item Name: char [string]
coordinate 1x = float [mm]
coordinate 1y = float [mm]
coordinate 1z = float [mm]
coordinate 2x = float [mm]
coordinate 2y = float [mm]
coordinate 2z = float [mm]
Erection direction x = 1/0/-1 [int]
Erection direction y = 1/0/-1 [int]
Erection direction z 1/0/-1 [int]
Compartments Table
ID [PK]
System name: char [string]
coordinate 1x = float [mm]
coordinate 1y = float [mm]
coordinate 1z = float [mm]
coordinate 2x = float [mm]
coordinate 2y = float [mm]
coordinate 2z = float [mm]
Compartment type: char [string] [FK]
Seperability Table
ID [PK]
Compartment type: char [string]
Seperability hierarchy weight = float [-] [FK]

J

Block Division Generator Input Tables Texst Case Ship 2

J.1. Structural Types Table

Structural Type ID	Structural Type Name	Thickness [mm]
str-000	frame-db	11
str-001	frame	9
str-002	shell	12
str-003	girder	13
str-005	tanktop	10
str-006	tween-deck	9
str-007	tween-deck-transit	-6
str-008	wall	12
str-009	hopper-end	18
str-010	shell-bulbous	16
str-011	bulkhead-transit	-9
str-012	foundation	15
str-013	null	0
str-101	frame-aft	9
str-102	girder-aft	13
str-103	tanktop-deck-aft	9
str-104	tween-deck-aft	9
str-105	tween-deck-aft-transit	-5
str-106	main-deck-aft	9
str-107	main-deck-aft-transit	0
str-108	coaming-deck-aft	11
str-109	coaming-deck-aft-transit	-9
str-110	bottom-shell-aft	12
str-201	frame-mid	9
str-202	girder-mid	13

Structural Type ID	Structural Type Name	Thickness [mm]
str-203	tanktop-deck-mid	10
str-204	tween-deck-mid	9
str-205	tween-deck-mid-transit	-6
str-206	main-deck-mid	12
str-207	main-deck-mid-transit	-10
str-208	coaming-deck-mid	35
str-209	coaming-deck-mid-transit	-27
str-210	bottom-shell-mid	13
str-301	frame-fore	9
str-302	girder-fore	13
str-303	tanktop-deck-fore	9
str-304	tween-deck-fore	9
str-305	tween-deck-fore-transit	-7
str-306	main-deck-fore	9
str-307	main-deck-fore-transit	-6
str-308	coaming-deck-fore	12
str-309	coaming-deck-fore-transit	-9
str-310	bottom-shell-fore	11

J.2. Structural Parts Table

Part ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	Type	s-x	s-y	s-z
sp-1001	bottom-104	72800	-11200	0	83300	11200	0	bottom-shell-fore	0	0	1
sp-1002	bottom-119	83300	-11000	0	91700	11000	0	bottom-shell-fore	0	0	1
sp-1003	bottom-131	91700	-9000	0	96600	9000	0	bottom-shell-fore	0	0	1
sp-1004	tanktop-104	72800	-11200	1120	83300	11200	1120	bottom-shell-fore	0	0	-1
sp-1005	tanktop-119	83300	-11000	1120	91700	11000	1120	bottom-shell-fore	0	0	-1
sp-1006	tanktop-131	91700	-9000	2100	96600	9000	2100	bottom-shell-fore	0	0	-1
sp-1007	tween-104	72800	-11200	4200	83300	11200	4200	bottom-shell-fore	0	0	-1
sp-1008	tween-119	83300	-11000	4200	91700	11000	4200	bottom-shell-fore	0	0	-1
sp-1009	tween-131	91700	-9000	4200	96600	9000	4200	bottom-shell-fore	0	0	-1
sp-1010	main-104	72800	-11200	7500	83300	11200	7500	bottom-shell-fore	0	0	-1
sp-1011	main-119	83300	-11000	7500	91700	11000	7500	bottom-shell-fore	0	0	-1
sp-1012	main-131	91700	-9000	7500	96600	9000	7500	bottom-shell-fore	0	0	-1
sp-1013	coaming-104	72800	-11200	10500	83300	11200	10500	bottom-shell-fore	0	0	-1
sp-1014	coaming-119	83300	-11000	10500	91700	11000	10500	bottom-shell-fore	0	0	-1
sp-1015	coaming-131	91700	-9000	10500	100800	9000	10500	bottom-shell-fore	0	0	-1
sp-2001	bulkhead-104	72800	-11200	0	72800	11200	10500	frame-aft	1	0	0
sp-2002	bulkhead-119	83300	-11000	0	83300	11000	10500	frame-aft	1	0	0
sp-2003	bulkhead-131	91700	-9700	0	91700	9000	10500	frame-aft	1	0	0

J.3. Transit Table

Transit ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	Type
tr-001	tweendeck-105	73500	-2000	4200	80500	6000	4200	tween-deck-fore-transit
tr-002	tweendeck-121	84700	-5000	4200	91000	5000	4200	tween-deck-fore-transit

J.4. Decks Tables

J.4.1. Bottom Deck

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps$_{center}$	CL-PS	curve
fr-104	frame-104	72800	0	-11200	-4000	0	6000	11200	4
fr-105	frame-105	73500	0	-11200	-4000	0	6000	11200	4
fr-106	frame-106	74200	0	-11200	-4000	0	6000	11200	4
fr-107	frame-107	74900	0	-11200	-4000	0	6000	11200	4
fr-108	frame-108	75600	0	-11200	-4000	0	6000	11200	4
fr-109	frame-109	76300	0	-11200	-4000	0	6000	11200	4
fr-110	bulkhead-110	77000	0	-11200	-4000	0	6000	11200	4
fr-111	frame-111	77700	0	-11200	-4000	0	6000	11200	4
fr-112	frame-112	78400	0	-11200	-4000	0	6000	11200	4
fr-113	frame-113	79100	0	-11200	-4000	0	6000	11200	4
fr-114	frame-114	79800	0	-11200	-4000	0	6000	11200	4
fr-115	frame-115	80500	0	-11200	-4000	0	6000	11200	4
fr-116	frame-116	81200	0	-11200	-4000	0	6000	11200	4
fr-117	frame-117	81900	0	-11200	-4000	0	6000	11200	4
fr-118	frame-118	82600	0	-11200	-4000	0	6000	11200	4
fr-119	frame-119	83300	0	-11200	-4000	0	6000	11200	4
fr-120	bulkhead-120	84000	0	-11000	-5000	0	5000	11000	4
fr-121	frame-121	84700	0	-11000	-5000	0	5000	11000	4
fr-122	frame-122	85400	0	-11000	-5000	0	5000	11000	4
fr-123	frame-123	86100	0	-11000	-5000	0	5000	11000	4
fr-124	frame-124	86800	0	-11000	-5000	0	5000	11000	4
fr-125	frame-125	87500	0	-11000	-5000	0	5000	11000	4
fr-126	frame-126	88200	0	-11000	-5000	0	5000	11000	4
fr-127	frame-127	88900	0	-11000	-5000	0	5000	11000	4
fr-128	frame-128	89600	0	-11000	-5000	0	5000	11000	4
fr-129	frame-129	90300	0	-11000	-5000	0	5000	11000	4
fr-130	bulkhead-130	91000	0	-11000	-5000	0	5000	11000	4
fr-131	frame-131	91700	0	-11000	-5000	0	5000	11000	4
fr-132	frame-132	92400	0	-9000	-5000	0	5000	9000	4
fr-133	frame-133	93100	0	-9000	-5000	0	5000	9000	4
fr-134	frame-134	93800	0	-9000	-5000	0	5000	9000	4
fr-135	frame-135	94500	0	-9000	-5000	0	5000	9000	4
fr-136	frame-136	95200	0	-9000	-5000	0	5000	9000	4
fr-137	frame-137	95900	0	-9000	-5000	0	5000	9000	4
fr-138	frame-138	96600	0	-9000	-0	0	0	9000	5
fr-139	frame-139	97300	0	-9000	-0	0	0	9000	5
fr-140	frame-140	98000	0	-9000	-0	0	0	9000	5
fr-141	frame-141	98700	0	-9000	-0	0	0	9000	5
fr-142	bulkhead-142	99400	0	-9000	-0	0	0	9000	5
fr-143	frame-143	100100	0	-9000	-0	0	0	9000	5
fr-144	frame-144	100800	0	-9000	-0	0	0	9000	5

J.4.2. Tanktop Deck

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps$_{center}$	CL-PS	curve
fr-104	frame-104	72800	1120	-11200	-4000	0	6000	11200	4
fr-105	frame-105	73500	1120	-11200	-4000	0	6000	11200	4
fr-106	frame-106	74200	1120	-11200	-4000	0	6000	11200	4
fr-107	frame-107	74900	1120	-11200	-4000	0	6000	11200	4
fr-108	frame-108	75600	1120	-11200	-4000	0	6000	11200	4
fr-109	frame-109	76300	1120	-11200	-4000	0	6000	11200	4
fr-110	bulkhead-110	77000	1120	-11200	-4000	0	6000	11200	4
fr-111	frame-111	77700	1120	-11200	-4000	0	6000	11200	4
fr-112	frame-112	78400	1120	-11200	-4000	0	6000	11200	4
fr-113	frame-113	79100	1120	-11200	-4000	0	6000	11200	4
fr-114	frame-114	79800	1120	-11200	-4000	0	6000	11200	4
fr-115	frame-115	80500	1120	-11200	-4000	0	6000	11200	4
fr-116	frame-116	81200	1120	-11200	-4000	0	6000	11200	4
fr-117	frame-117	81900	1120	-11200	-4000	0	6000	11200	4
fr-118	frame-118	82600	1120	-11200	-4000	0	6000	11200	4
fr-119	frame-119	83300	2100	-11000	-4000	0	6000	11000	4
fr-120	bulkhead-120	84000	2100	-11000	-5000	0	5000	11000	4
fr-121	frame-121	84700	2100	-11000	-5000	0	5000	11000	4
fr-122	frame-122	85400	2100	-11000	-5000	0	5000	11000	4
fr-123	frame-123	86100	2100	-11000	-5000	0	5000	11000	4
fr-124	frame-124	86800	2100	-11000	-5000	0	5000	11000	4
fr-125	frame-125	87500	2100	-11000	-5000	0	5000	11000	4
fr-126	frame-126	88200	2100	-11000	-5000	0	5000	11000	4
fr-127	frame-127	88900	2100	-11000	-5000	0	5000	11000	4
fr-128	frame-128	89600	2100	-11000	-5000	0	5000	11000	4
fr-129	frame-129	90300	2100	-11000	-5000	0	5000	11000	4
fr-130	bulkhead-130	91000	2100	-11000	-5000	0	5000	11000	4
fr-131	frame-131	91700	2100	-9000	-5000	0	5000	9000	4
fr-132	frame-132	92400	2100	-9000	-5000	0	5000	9000	4
fr-133	frame-133	93100	2100	-9000	-5000	0	5000	9000	4
fr-134	frame-134	93800	2100	-9000	-5000	0	5000	9000	4
fr-135	frame-135	94500	2100	-9000	-5000	0	5000	9000	4
fr-136	frame-136	95200	2100	-9000	-5000	0	5000	9000	4
fr-137	frame-137	95900	2100	-9000	-5000	0	5000	9000	4
fr-138	frame-138	96600	2100	-9000	-0	0	0	9000	5
fr-139	frame-139	97300	2100	-9000	-0	0	0	9000	5
fr-140	frame-140	98000	2100	-9000	-0	0	0	9000	5
fr-141	frame-141	98700	2100	-9000	-0	0	0	9000	5
fr-142	bulkhead-142	99400	2100	-9000	-0	0	0	9000	5
fr-143	frame-143	100100	2100	-9000	-0	0	0	9000	5
fr-144	frame-144	100800	2100	-9000	-0	0	0	9000	5

J.4.3. Tween Deck

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps$_{center}$	CL-PS	curve
fr-104	frame-104	72800	4200	-11200	-4500	0	8000	11200	1
fr-105	frame-105	73500	4200	-11200	-4500	0	8000	11200	1
fr-106	frame-106	74200	4200	-11200	-4500	0	8000	11200	1
fr-107	frame-107	74900	4200	-11200	-4500	0	8000	11200	1
fr-108	frame-108	75600	4200	-11200	-4500	0	8000	11200	1
fr-109	frame-109	76300	4200	-11200	-4500	0	8000	11200	1
fr-110	bulkhead-110	77000	4200	-11200	-4500	0	8000	11200	1
fr-111	frame-111	77700	4200	-11200	-4500	0	8000	11200	1
fr-112	frame-112	78400	4200	-11200	-4500	0	8000	11200	1
fr-113	frame-113	79100	4200	-11200	-4500	0	8000	11200	1
fr-114	frame-114	79800	4200	-11200	-4500	0	8000	11200	1
fr-115	frame-115	80500	4200	-11200	-4500	0	8000	11200	1
fr-116	frame-116	81200	4200	-11200	-4500	0	8000	11200	1
fr-117	frame-117	81900	4200	-11200	-4500	0	8000	11200	1
fr-118	frame-118	82600	4200	-11200	-4500	0	8000	11200	1
fr-119	frame-119	83300	4200	-11200	-4500	0	8000	11200	1
fr-120	bulkhead-120	84000	4200	-11000	-5000	0	5000	11000	2
fr-121	frame-121	84700	4200	-11000	-5000	0	5000	11000	2
fr-122	frame-122	85400	4200	-11000	-5000	0	5000	11000	2
fr-123	frame-123	86100	4200	-11000	-5000	0	5000	11000	2
fr-124	frame-124	86800	4200	-11000	-5000	0	5000	11000	2
fr-125	frame-125	87500	4200	-11000	-5000	0	5000	11000	3
fr-126	frame-126	88200	4200	-11000	-5000	0	5000	11000	3
fr-127	frame-127	88900	4200	-11000	-5000	0	5000	11000	3
fr-128	frame-128	89600	4200	-11000	-5000	0	5000	11000	3
fr-129	frame-129	90300	4200	-11000	-5000	0	5000	11000	3
fr-130	bulkhead-130	91000	4200	-11000	-5000	0	5000	11000	3
fr-131	frame-131	91700	4200	-11000	-5000	0	5000	11000	3
fr-132	frame-132	92400	4200	-9000	0	0	0	9000	4
fr-133	frame-133	93100	4200	-9000	0	0	0	9000	4
fr-134	frame-134	93800	4200	-9000	0	0	0	9000	4
fr-135	frame-135	94500	4200	-9000	0	0	0	9000	4
fr-136	frame-136	95200	4200	-9000	0	0	0	9000	5
fr-137	frame-137	95900	4200	-9000	0	0	0	9000	5
fr-138	frame-138	96600	4200	-9000	0	0	0	9000	5
fr-139	frame-139	97300	4200	-9000	0	0	0	9000	5
fr-140	frame-140	98000	4200	-9000	0	0	0	9000	5
fr-141	frame-141	98700	4200	-9000	0	0	0	9000	5
fr-142	bulkhead-142	99400	4200	-9000	0	0	0	9000	5
fr-143	frame-143	100100	4200	-9000	0	0	0	9000	5
fr-144	frame-144	100800	4200	-9000	0	0	0	9000	5

J.4.4. Main Deck

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps$_{center}$	CL-PS	curve
fr-104	frame-104	72800	7500	-11200	-8000	0	8000	11200	1
fr-105	frame-105	73500	7500	-11200	-8000	0	8000	11200	1
fr-106	frame-106	74200	7500	-11200	-8000	0	8000	11200	1
fr-107	frame-107	74900	7500	-11200	-8000	0	8000	11200	1
fr-108	frame-108	75600	7500	-11200	-8000	0	8000	11200	1
fr-109	frame-109	76300	7500	-11200	-8000	0	8000	11200	1
fr-110	bulkhead-110	77000	7500	-11200	-8000	0	8000	11200	1
fr-111	frame-111	77700	7500	-11200	-8000	0	8000	11200	2
fr-112	frame-112	78400	7500	-11200	-8000	0	8000	11200	2
fr-113	frame-113	79100	7500	-11200	-8000	0	8000	11200	2
fr-114	frame-114	79800	7500	-11200	-8000	0	8000	11200	2
fr-115	frame-115	80500	7500	-11200	-8000	0	8000	11200	2
fr-116	frame-116	81200	7500	-11200	-8000	0	8000	11200	2
fr-117	frame-117	81900	7500	-11200	-8000	0	8000	11200	2
fr-118	frame-118	82600	7500	-11200	-8000	0	8000	11200	2
fr-119	frame-119	83300	7500	-11200	-8000	0	8000	11200	2
fr-120	bulkhead-120	84000	7500	-11000	-8000	0	8000	11000	2
fr-121	frame-121	84700	7500	-11000	-8000	0	8000	11000	2
fr-122	frame-122	85400	7500	-11000	-8000	0	8000	11000	2
fr-123	frame-123	86100	7500	-11000	-8000	0	8000	11000	2
fr-124	frame-124	86800	7500	-11000	-8000	0	8000	11000	2
fr-125	frame-125	87500	7500	-11000	-8000	0	8000	11000	2
fr-126	frame-126	88200	7500	-11000	-8000	0	8000	11000	2
fr-127	frame-127	88900	7500	-11000	-8000	0	8000	11000	2
fr-128	frame-128	89600	7500	-11000	-8000	0	8000	11000	2
fr-129	frame-129	90300	7500	-11000	-8000	0	8000	11000	2
fr-130	bulkhead-130	91000	7500	-11000	-8000	0	8000	11000	2
fr-131	frame-131	91700	7500	-9000	-8000	0	8000	9000	3
fr-132	frame-132	92400	7500	-9000	-8000	0	8000	9000	3
fr-133	frame-133	93100	7500	-9000	-8000	0	8000	9000	3
fr-134	frame-134	93800	7500	-9000	-8000	0	8000	9000	3
fr-135	frame-135	94500	7500	-9000	-8000	0	8000	9000	3
fr-136	frame-136	95200	7500	-9000	-8000	0	8000	9000	3
fr-137	frame-137	95900	7500	-9000	-8000	0	8000	9000	3
fr-138	frame-138	96600	7500	-9000	-8000	0	8000	9000	3
fr-139	frame-139	97300	7500	-9000	-8000	0	8000	9000	3
fr-140	frame-140	98000	7500	-9000	-8000	0	8000	9000	3
fr-141	frame-141	98700	7500	-9000	-8000	0	8000	9000	4
fr-142	frame-142	99400	7500	-9000	-8000	0	8000	9000	4
fr-143	frame-143	100100	7500	-9000	-8000	0	8000	9000	4
fr-144	frame-144	100800	7500	-9000	-8000	0	8000	9000	4

J.4.5. Coaming Deck

Frame ID	Name	c1x	c1z	CL-SB	CL-SB$_{center}$	CL	CL-Ps$_{center}$	CL-PS	curve
fr-104	frame-104	72800	10500	-11200	-8000	0	8000	11200	1
fr-105	frame-105	73500	10500	-11200	-8000	0	8000	11200	1
fr-106	frame-106	74200	10500	-11200	-8000	0	8000	11200	1
fr-107	frame-107	74900	10500	-11200	-8000	0	8000	11200	1
fr-108	frame-108	75600	10500	-11200	-8000	0	8000	11200	1
fr-109	frame-109	76300	10500	-11200	-8000	0	8000	11200	1
fr-110	bulkhead-110	77000	10500	-11200	-8000	0	8000	11200	1
fr-111	frame-111	77700	10500	-11200	-8000	0	8000	11200	2
fr-112	frame-112	78400	10500	-11200	-8000	0	8000	11200	2
fr-113	frame-113	79100	10500	-11200	-8000	0	8000	11200	2
fr-114	frame-114	79800	10500	-11200	-8000	0	8000	11200	2
fr-115	frame-115	80500	10500	-11200	-8000	0	8000	11200	2
fr-116	frame-116	81200	10500	-11200	-8000	0	8000	11200	2
fr-117	frame-117	81900	10500	-11200	-8000	0	8000	11200	2
fr-118	frame-118	82600	10500	-11200	-8000	0	8000	11200	2
fr-119	frame-119	83300	10500	-11200	-8000	0	8000	11200	2
fr-120	bulkhead-120	84000	10500	-11000	-8000	0	8000	11000	2
fr-121	frame-121	84700	10500	-11000	-8000	0	8000	11000	2
fr-122	frame-122	85400	10500	-11000	-8000	0	8000	11000	2
fr-123	frame-123	86100	10500	-11000	-8000	0	8000	11000	2
fr-124	frame-124	86800	10500	-11000	-8000	0	8000	11000	2
fr-125	frame-125	87500	10500	-11000	-8000	0	8000	11000	2
fr-126	frame-126	88200	10500	-11000	-8000	0	8000	11000	2
fr-127	frame-127	88900	10500	-11000	-8000	0	8000	11000	2
fr-128	frame-128	89600	10500	-11000	-8000	0	8000	11000	2
fr-129	frame-129	90300	10500	-11000	-8000	0	8000	11000	2
fr-130	bulkhead-130	91000	10500	-11000	-8000	0	8000	11000	2
fr-131	frame-131	91700	10500	-9000	-8000	0	8000	9000	3
fr-132	frame-132	92400	10500	-9000	-8000	0	8000	9000	3
fr-133	frame-133	93100	10500	-9000	-8000	0	8000	9000	3
fr-134	frame-134	93800	10500	-9000	-8000	0	8000	9000	3
fr-135	frame-135	94500	10500	-9000	-8000	0	8000	9000	3
fr-136	frame-136	95200	10500	-9000	-8000	0	8000	9000	3
fr-137	frame-137	95900	10500	-9000	-8000	0	8000	9000	3
fr-138	frame-138	96600	10500	-9000	-8000	0	8000	9000	3
fr-139	frame-139	97300	10500	-9000	-8000	0	8000	9000	3
fr-140	frame-140	98000	10500	-9000	-8000	0	8000	9000	3
fr-141	frame-141	98700	10500	-9000	-8000	0	8000	9000	4
fr-142	bulkhead-142	99400	10500	-9000	-8000	0	8000	9000	4
fr-143	frame-143	100100	10500	-9000	-8000	0	8000	9000	4
fr-144	frame-144	100800	10500	-9000	-8000	0	8000	9000	4

J.5. Equipment Table

Equipment ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	erect-x	erect-y	erect-z
eqp-001	bow-pump	73500	-3500	1120	77000	0	4900	0	0	0
eqp-101	bow-thruster	83750	-9000	0	91350	9000	2100	2	2	2

J.6. Compartments Table

Compartment ID	Name	c1x	c1y	c1z	c2x	c2y	c2z	Type
sys-1001	ballast-tank	91700	-9000	1120	96600	9000	4200	watertank
sys-1002	ballast-tank	91700	-9000	4200	96600	9000	7500	watertank
sys-2001	bowthrusterroom	83300	-5000	4200	91700	5000	7500	techroom
sys-2002	front-pump-room	72800	-4000	4200	80500	6000	7500	techroom
sys-2003	front-pump-room	72800	-11200	1120	83300	11200	4200	techroom
sys-2004	front-pump-room	83300	-11000	1120	91700	11000	4200	techroom
sys-4001	boatswainstore-tt	72800	-11200	4200	83300	-4000	7500	workshop
sys-4002	boatswainstore-tt	72800	6000	4200	83300	11200	7500	workshop
sys-4003	boatswainstore-tt	83300	-11200	4200	91700	-5000	7500	workshop
sys-4004	boatswainstore-tt	83300	5000	4200	91700	11200	7500	workshop
sys-4005	boatswainstore-tt	80500	-4000	4200	83300	6000	7500	workshop
sys-5001	accomodation	72800	-11200	7500	83300	11200	10500	accomodation
sys-5002	accomodation	83300	-11000	7500	91700	11000	10500	accomodation

K

Research Paper

A MODEL BASED APPROACH TO THE AUTOMATIC GENERATION OF BLOCK DIVISION PLANS

Dirk de Bruijn, TU Delft
Dr. Ir. Jenny Coenen, TU Delft

ABSTRACT

European shipyards are building increasing amounts of complex ships such as off-shore, dredging or naval ships that are engineered-to-order. The block division is made when only preliminary hull structural design, functional compartments and the location of major equipment are known. The existing production scheduling optimization algorithms use a single manually created block division as a fixed input. Automatic generation of block division plans can potentially optimize the currently created production planning solutions because all work directly related to the construction of the ship on a shipyard is decomposed by the different chosen blocks. The preliminary design information and general arrangement of the ship, implicit knowledge of engineers and detailed information from comparable reference ships are known. A block division generator is developed to create multiple feasible Block division solutions. The different block division solutions result in deviations to relevant optimization objectives. It is concluded that it is possible to automatically generate block division plans that can be effectively used in ship production optimization algorithm. Due to simplifications in the block division generator and the erection sequence optimization algorithm, no quantitative optimization potential can be determined.

Keywords: Block division, automatic, ship production, ship design

1. INTRODUCTION

1.1. *Background*

European shipyards are building increasing amounts of complex ships such as off-shore, dredging or naval ships (SEA Europe, 2014). The production of these ship types is decomposed in Blocks, combined sub-assemblies of steel structural parts and outfitting components. No detailed design and engineering are available when the Block division has to be created. Complex ships are engineered-to-order and the decomposition into Blocks is required to create the building schedules.

Automated tools for ship design and production planning increase the amount of available information in the early stage. Several production optimization algorithms have been developed to optimize the shipyard facilities in terms of resource leveling and total throughput time of the ship. Currently the Block division is in ship production optimization algorithms only a fixed input, such as (Meijer, 2008) and (Rose, 2017). Defining a ships constituent Blocks is an important prerequisite for generation of the production planning of a ship. Furthermore it dictates the decomposition of engineering work, manufacturing of panels and assembly of Blocks to a large extent. The rationale for where to put the boundaries between Blocks is often dictated by a shipyards maximum hoisting capacity, the independent strength and stiffness of the resulting Block and experience of the responsible engineer, based on preliminary design information. But other criteria might be of relevance such as choosing a Block division that is most effective in terms of overall cost, or outfitting cost, or more robust in terms of disruption of the critical path, in levelling resources such as required floor space and outsourcing.

The problem described above was subject to a dedicated research and findings were published in the master thesis with title *A model based approach to the automatic generation of block division plans.* This paper summarizes the contents and results of this thesis.

1.2. *Research Objective*

The objective of the research was to answer if it was possible to automatically generate Block division plans and whether these can be effectively used in ship production optimization algorithms. The developed method has to be able to generate Block division plans based on available information during the preliminary design stage only. The information output structure of such as model is dictated by the ship production optimization algorithm which requires certain information to be able to generate a production planning. A model architecture was created including feasibility constrains to only create feasible Block division solutions are defined as are Design Variables to be able to create different solutions and model different approaches to creating the Block division plan. Finally the results are assessed using an erection sequence schedule generating optimization algorithm in order to assess the quality and effectiveness of the different Block division solutions on the defined optimization objectives.

2. BLOCK DIVISION

2.1. *Design Input*

The information available at the preliminary design stage is the General Arrangement (GA), reference ships and experience from these previously build comparable reference ships. Long lead time equipment is also shown on the GA. This equipment is required to be integrated with the planning and erection schedule due to the size, weight and sometimes unpredictable lead times. Also functional area's and major outfitting components are located on the GA. Functional area's are referred to as Compartments, such as water tanks, the engine room and accommodation areas. Next to explicit information, implicit information is available in the shape of experience from engineers. This experience guides the engineer in manually creating Block division plans that are efficient to build. Implicitly there is already optimized for global objectives such as building time and required resources.

Hull Structural Design— Block seams are placed according to some aspects of the hull structural design. Initially seams are always placed near structural parts, but never on the stiffened side of such a part, as is shown in Figure 1.

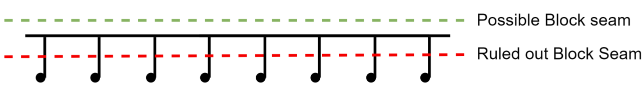


Figure 1. Stiffened panels

Implicit Knowledge— Block division engineers have created several Block division plans for different ships and have encountered various unexpected situations in the ship production process such as delays, changes to the design or other problems. They have seen their Block division plans being build and feedback from workers will be received. These experiences make them change their way of solving the Block division problem towards a more optimal solution in terms pf producibility of the ship. The Block division plan is only created to be able to build the ship as fast as possible.

Erection Strategy— The used erection strategy at a shipyard plays a major role in creating the Block division plan, referred to as Block division approach. When a shipyard erects individual Blocks to the slipway, another Block division will be preferred over when the shipyard erects Mega-Blocks, which is an assembly of multiple Blocks not yet erected onto the slipway. The developed model is initially created to be able to recreate the Block division approach at Royal IHC that builds individual Blocks as large and heavy as possible in order to reduce the amount of erection actions on the slipway. These individual Blocks are erected on the slipway and no Mega-Block configurations are used.

Design for Production— As mentioned earlier, the main objective of a shipyard is to produce ships as fast as possible. To do this the Block division must be supportive to the production processes. General principles to creating Block division plans are derived from interviews with experienced engineers. The arguments for creating a Block division can be divided into three categories. These categories are the hull structural design, the applicable erection strategy and creating a Block division that is supportive to the ship production processes.

- Erection strategy
- Closing Blocks
- Transits
- Assembly
- Maximizing pre-outfitting
- Separability of compartments
- Outsourcing

The erection strategy as mentioned determines how the Block division is generally approached in terms of resulting Blocks. Closing Blocks or decks are a way of increasing a redundant production plan because it removes long lead time items off the critical production planning path. Transits where equipment pierces a deck is aimed to remain open for accessibility of installing equipment and outfitting. The argument for assembly is to always make welds being performed under hands. This increases speed, accuracy and quality of the welds. Pre-outfitting is maximized because of the extra induced costs incurred when installing outfitting on the slipway or alongside the quay (Shank et al., 2005). Compartments are preferred not to be split because this creates unfinished conservation, outfitting and alignments. Finally capacity outsource partners has to be taken into account when Blocks are outsourced.

3. REQUIREMENTS

3.1. *Required Output*

To be able to effectively use the automatic generated Block division plans in ship production optimization algorithm the output of the developed model must be ready to use as input for the used optimization algorithm. The erection sequence planner developed by (Meijer, 2008) is chosen to find connect the information structure with. This model required limited information but includes the relevant optimization objective to be able to assess the impact of different Block division solutions on the fitness of the overall production planning. Below the required information for this optimization algorithm is shown:

- Required resources
  - Size of Blocks
  - Amount of workers
- Erection constraints
  - Location of Block
  - Closing Deck
- Lead time
  - Weight of Block

The model calculates the required resources in of required personnel. To be able to do this the size of the Blocks is required as input. Next the erection sequence constraints are automatically determined by using the location of the Blocks and position compared to each other. Also the erection sequence scheduler requires to know whether Blocks are a closing deck or not, because this is incorporated in the erection sequence constraints. Finally the lead time of the Blocks is calculated to be able to create a erection sequence schedule. This is done based on the weight per Block using parameters that state the required man hours per tonnes of each part of the ship. Research has shown that man hours per tonnes is not a good indicator for the lead time of Blocks but this research does not focus on the exact amount of increased fitness that can be obtained by changing the Block division but rather on if this relation can be proven and shown (Colthoff, 2009).

3.2. *Feasibility of Solutions*

Generally Blocks are created that are as large and heavy as possible. This is limited by the supply and facility constrains of a specific shipyard. The doors of for example the conservation hall dictate the maximum Block size and the crane capacity the maximum weight of each Block. In theory every Block division that satisfies these constraints is feasible. That does not mean it is viable in terms of optimum production. The previously mentioned Block division arguments represent the soft producibility constraints. Not satisfying them is possible but will probably result in reduced efficiency in production. The Block division generator can not draw this conclusion, this will show in the resulting optimization objective fitness. The created model incorporates only the feasibility constrains as fixed variables. The variables mathematically representing the producibility are incorporated as Design Variables and can be changed to represent other consideration of the mentioned arguments.

4. MODEL

4.1. *Overview*

Figure 2 shows the overall architecture of the created model referred to as the Block division generator (BDG). Preliminary information of a ship and the shipyard where it will be build are the main input drivers that dictate the Design Variables. Two test case ships are used to verify the results of the BDG.

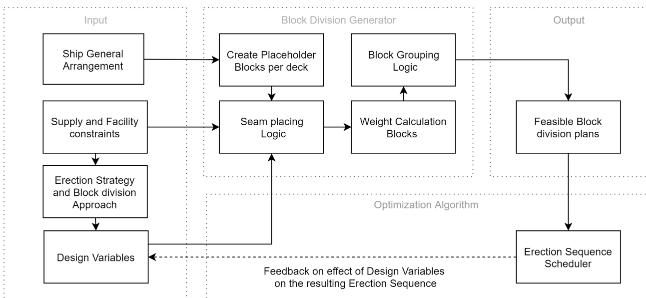


Figure 2. Overall Architecture.

4.2. *Input Test Case Ship*

Figure 3 shows the side view of the GA of test case ship 1. In the early design stage this information is only available as 2D drawings so in order to use this in the BDG it has to be translated to a 3D ship design which is mathematically described in order to process this information in the BDG.

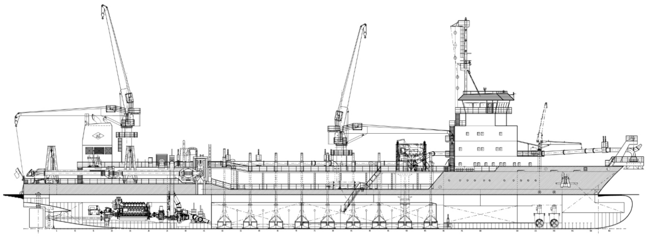


Figure 3. test case ship1

The manually created data input set for test case ship 1 is visually shown in Figure 4. As can be seen the original information is simplified and described by rectangular plates. The Figure shows all major steel structural parts shown on the GA or known by experience of comparable reference ships. next to the definition of the major steel system also all decks, longitudinal reference lines, equipment including erection direction are created. Detailed structural parts are not taken into account in this stage but are discussed in Sub Section 4.5. Figure 5 shows the defined Compartments. All

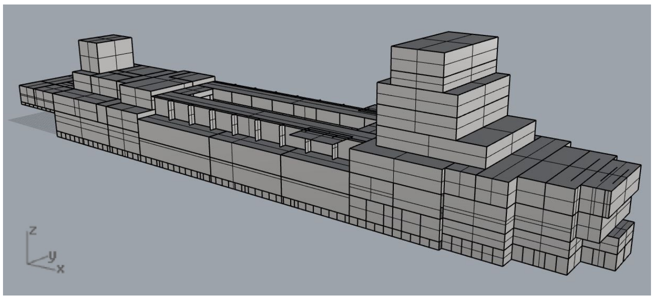


Figure 4. Simplified 3D General Arrangement

rooms and functional areas are defined by created list of Compartments. These Compartments have a different separability weight which represents the implications to the producibility of the ship relative to each other. For example water tanks are preferably not split due to the required high finish in terms of conservation dictated by legislation.

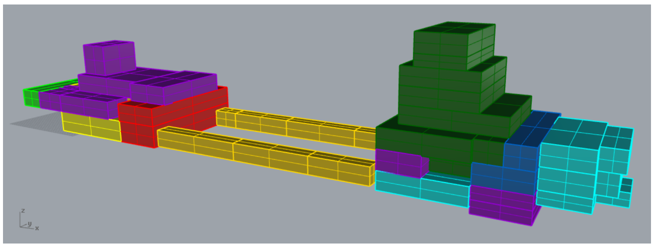


Figure 5. Test Case ship Compartments

4.3. *Placeholder Blocks*

Only the hull is assessed by the BDG because this is the only area of the ship where changing seam positions impacts the production. Special Blocks such as the suction tube inlet are out of scope, as is the superstructure. Figure 6 shows the division of the hull in four major Modules referred to as fore, mid and aft Module. For each Module Placeholder Blocks are created to make sure the whole ship will be part of the Block division solution. The BDG analyses the different Modules individually.

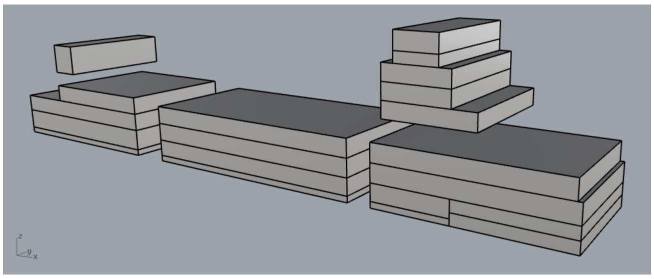


Figure 6. placeholder blocks

4.4. *Seam Placing Logic*

The Placeholder Blocks are split by two ways of placing seams. The first seams that are placed are transverse seams. These seams are placed based primarily on the before mentioned Block division arguments. The Design Variables can indicate which argument is the most important in terms of preferred or non preferred seam positions. An Optional Seam Position string is created that is filled with the found arguments and a final seam position is chosen. Per Module different analyzing directions can be chosen to include as many curved panels in one Block as possible. The implemented mechanisms in the transverse seam placing logic are arguments for Bulkhead and stiffeners, transits, (integrated) equipment and Compartments separability weights. Figure 7 shows the resulting transverse seams for the reproduction of the manually created Block division plan of test ship 1.

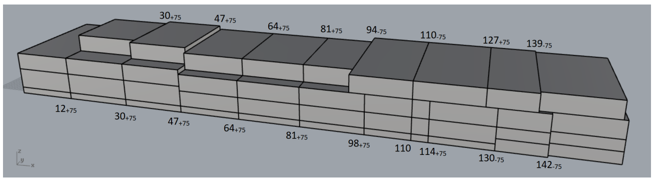


Figure 7. Verification Transverse Seams

The second seam placing logic is to divide the created Blocks in longitudinal direction. This analysis is made by assessing the breadth of the Blocks, find equipment that is either integrated or erected from the positive z direction and found Compartments. If the Placeholder Block is too wide it is split symmetrically. If integrated equipment such as the bow thruster is found it is not split in longitudinal direction. In the case equipment is found that is erected from the positive z direction a closing deck is created and two longitudinal splits are made creating three Blocks. Finally, if the found Compartments around the center line are not preferred to be split no longitudinal split is made. Figure 8 shows the resulting longitudinal seam positions for the verification case of the manually created Block division plan for test ship 1.

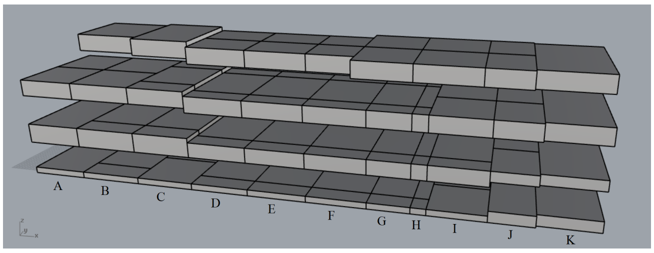


Figure 8. verification longitudinal seams

All arguments to place seams, either transverse and longitudinally, can be varied using the sets of Design Variables.

4.5. *Weight Calculations*

The next step is to calculate the weight of the created Blocks to check the feasibility constraints and to use in the lead time calculations of the optimization algorithm. The weight of the Blocks is calculated by the amount of steel material found within the barriers of the Block. Figure 9 shows an example of a Block at the coaming deck. The white line represents the seams dividing the Block. The amount of square meters of each steel structural part is calculated and multiplied by the plate thickness as part of the type of which the structural part is defined. Some weight correction factors are included to correct for secondary stiffeners.

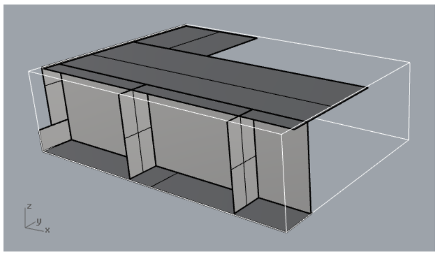


Figure 9. Coaming Structure Example

4.6. *Grouping*

The final step of the BDG is to find grouping possibilities. Smaller Blocks that are perfectly aligned can be grouped as long as combination of length does not exceed the maximum length and the weight does not exceed the feasibility weight constraint representing the crane capacity. The first possible grouping actions are looked for in the vertical direction for side Blocks, followed by longitudinal grouping over the bottom of the ship. Finally grouping possibilities are sought for in vertical direction higher than the double bottom for Blocks crossing the center line. This sequence of grouping actions is specific for the individual Block division approach and is executed to correct for the initial Placeholder per deck analysis. Without the grouping logic no cross-deck Blocks could be created.

5. ANALYSIS

5.1. *Verification*

Before analyzing different Block division solutions and the resulting production schedules the model is verified by reproducing the manually created Block division for the test case ship. Also another ship is analyzed for reproducing the manually created Block division plan.

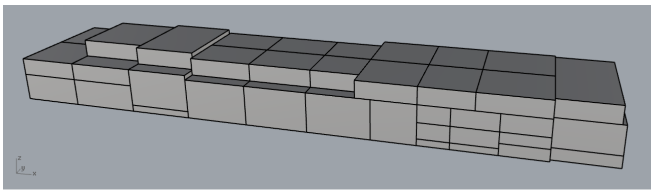


Figure 10. case1 final result

Test Case Ship 1— The Design Variables are set to the Block division approach as was used by the Block division engineers and the final result can be found in Figure 10. Some minor deviations are found that can be attributable to the implemented simplifications. The weight of the total hull is within 1% deviation of the actual measured weight of the build Blocks. All individual Blocks are within 10% deviation. The major differences can be explained by the minor differences in chosen seams.

Fore Ship Module Test Case Ship 2— Another ship was analyzed to provide more information about the ability of the model to reproduce existing Block division solutions. Only the fore ship Module of test ship 2 was analyzed due to the labour intensive character of translating the preliminary design information into an input file for the BDG. Figure 11 shows the input information simplified and visualized. Where Figure 11(1) shows the decks and bulkheads, Figure 11(2) shows the Compartments and Figure 11(3) the equipment that is taken into consideration.

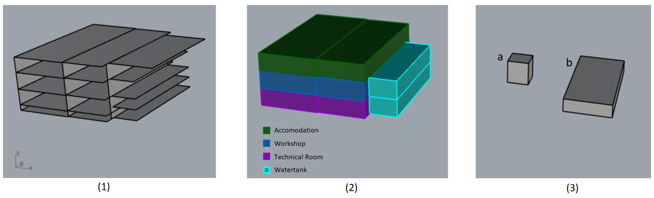


Figure 11. Input data for Test case ship 2

Figure 12 shows the automatically generated Block divisions using the same Design Variable set as used for the reproduction Block division of test ship 1. From left to right first the Placeholder Blocks are created, next the transverse seams are placed and the longitudinal seams. The weight calculation and grouping logic is not taken into account because not all structural parts are drawn due to the labour intensive character of creating the input files. The reproduction of the manually created Block division is successful except for the cross-deck Blocks, due to the lack of grouping actions.

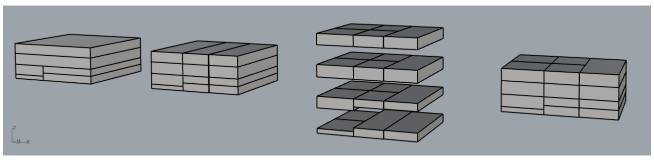


Figure 12. Block division results test case ship2

5.2. *Optimization Objectives*

Design Variable Sets— Resulting Design Variables of the translated Block division methodology to the model are only a single solutions of the different possibilities. Different sets of Design Variables can be created that represent a certain Block division approach. In order to find different Block division solutions every Design Variable is one by one altered. This results in eight Block division solutions: Case 0 up until 1g. Where Case 0 is the verification case. Case 1g is an attempt to model the Block division approach of the Ring-Mega-Block erection strategy. No attempt was made to recreate the original erection sequence, the erection sequence scheduler was used to find the first to be erected Block and all others up until all Blocks are erected.

Feasible Solutions— Figure 13 shows all feasible solutions as result of different Design Variable sets. All resulting Block division are feasible in terms of size and weight of the individual to be erected Blocks. In red and green different longitudinal seams are indicated compared to the verification Case 0. The solutions vary from 47 and 101 individual Blocks.

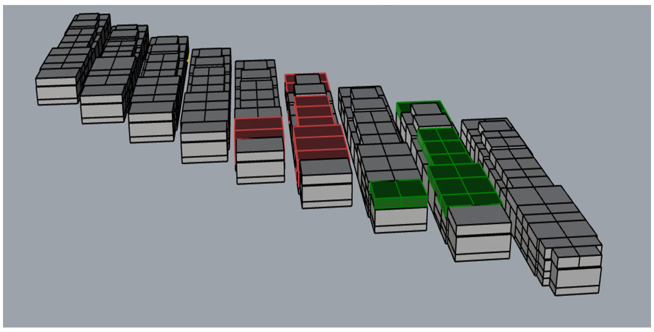


Figure 13. Multiple Feasible Solutions

Planning— To look into the effect of the different Block division solutions on the quality of the production plan, the optimization objectives as implemented in the erection sequence scheduler model are used. The different optimization objectives are stated below.

- Number of erection actions
- Erection Duration
- Block building duration
- Number of erection constraints
- Required resources

The number of Blocks is interesting due to the general objective to minimize these in order to reduce erection time. It can be looked into if this is always the actual relation. The Block building time depends on outsource partner capacity and therefor is relevant to be influenced in order to improve the quality of a production plan. The number of erection constraints provides insight in the amount of optional Blocks that can be erected on average. The required personnel is an good indicator for the shipyard's required resources to be available in order to realize the created production planning.

Impact on Planning— The results shown variation in Block building time, erection time, amount of erection conditions and required resources, as shown in Table 1. The last objective is discussed below. Case 1b and 1c for example show that more Blocks (62 and 64 Blocks respectively) result in a shorter erection time on the slipway. This is the opposite of the general understood relation between the two variables, although this also shows by the results of Case 1d and 1e. Also the amount of erection conditions and thus presumed flexibility in the production plan varies, implying an improvement to be achievable with regard to the producibility arguments.

	Erection duration	Block build duration	Number of Blocks	Erection Constraints
Unit	[days]	[days]	[#]	[#/Block]
Case 0	235	276	61	3.36
Case 1a	247	288	69	3.32
Case 1b	231	264	62	3.39
Case 1c	231	279	64	3.28
Case 1d	218	260	55	3.33
Case 1e	207	249	47	3.23
Case 1f	231	264	62	3.35
Case 1g	241	267	61	3.36
Case 2	267	267	101	3.17

Table 1
Optimization Objective results

Impact on Required Personnel— The ideal resource leveling curve is defined by (Rose, 2017). The diagonal lines at the start and end of the production period have a duration of the average time it takes to mount a Block. The total area below the ideal resource level equals the area below the required resource level. It is more ideal to have a flat required resource level due to the inflexibility in the change in the amount of workers available. For example, you can not hire workers for only one day, so more spikes is less efficient. Figure 14 shows clearly the change in required personnel for the different Block division solutions. The most optimal production plan for a Block division solution is Case 1e with a deviation of 15.73 %. Case 2 is the most unfavourable with a total deviation of 33.56%. Note that the this deviation is only the absolute deviation and no translation to the actual situation at the shipyard can be made.

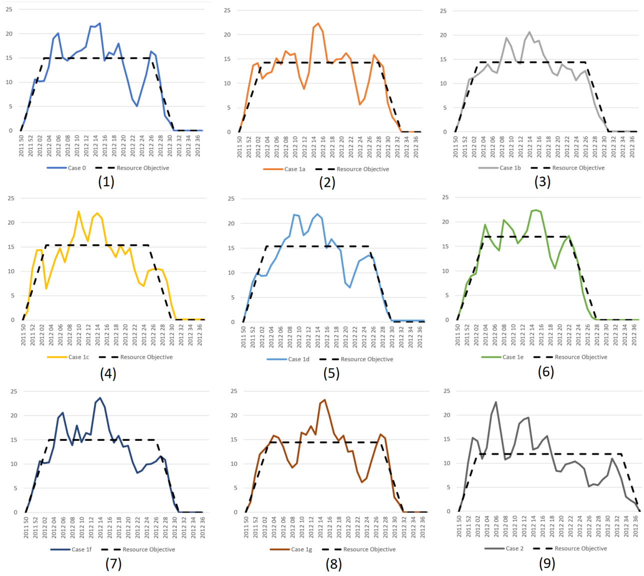


Figure 14. Required Personnel for Case up until Case 2

5.3. *Validation Square*

Because the Block division generator is a design tool, and not an optimization algorithm, the validation square is an applicable method to assess the validity of the developed model Seepersad et al., (2005). Figure 15 shows the structure of the validation square method. A design method's validity is considered proven by the combination of how useful the method is with respect to a predefined purpose. Where usefulness is defined as a combination of effectiveness and efficiency, based on qualitative and quantitative measures respectively.

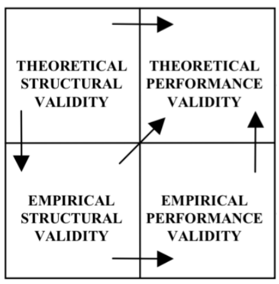


Figure 15. Validation Square (Seepersad et al., 2005)

Theoretical Structural Validity— The Block division approach is generally accepted as shown by the conducted interviews. Because there is no literature about Block division at European shipyards building complex ships these interviews are used as primary source of information. The model only uses the information that is used as input to construct the required output.

Empirical Structural Validity— The used example problems are build at a shipyard using the single Block erection strategy and are complex ships. The information available for this research is representative for the actual situations. This information is based on the available preliminary design, implicit knowledge and comparable reference ships. Although there is no formal definition that the trailing suction hopper dredger is the most representative ship, it carries high amount of complex systems on board, is build in EU and is regularly used in research that addresses this scope.

Empirical Performance Validity— The model is considered useful if it can be effectively used in optimization algorithms. To be able to assess the effectiveness of the Block Division generator in optimization algorithms it must be able to generate $n + 1$ feasible solutions to a Block division problem. The Block division generator is considered effective in optimization algorithms if the $n + 1$ solutions affect the optimization objectives of the used optimization algorithm

Theoretical Performance Validity— Two broader domains are defined. The first domain is to use the same Block division approach on a different ship. Test case ship 2 is an example of the successful reproduction of the manually created Block division for this ship. Also different Block divisions were created. The next broader domain is the same ship, but a different block division approach. Case 2 of test case ship 1 is an example of a Ring-Mega-Block erection strategy Block division approach. The end result is a decent reproduction of such Block division approach, but mainly the grouping logic must be expanded to be implemented successfully. The methodology is considered valid for the defined broader domains.

6. CONCLUSION

Only information is used that is available during the preliminary production planning stage to create the block division solutions. The block division model can reproduce manually created block division plans and can create different solutions that can be used in a ship production optimization algorithm. The different block division solutions result in deviations to relevant optimization objectives. It is concluded that it is possible to automatically generate block division plans that can be effectively used in ship production optimization algorithm. Due to simplifications in the block division generator and the erection sequence optimization algorithm, no quantitative optimization potential can be determined. Future research is recommended to focus on applicability of the methodology and improvement of the functionality of the developed model.

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