MASTER

Strategic Yard Modelling

Creating a capacity feasibility model in the proposal phase of shipbuilding

Geertsma, P.

Award date:
2021

Department of Industrial Engineering & Innovation Sciences,
Operations, Planning, Accounting and Control

Master Thesis
Strategic Yard Modelling

Creating a capacity feasibility model in the proposal phase of shipbuilding

Author:
Patrick Geertsma (0946370)

In partial fulfilment of the requirements for the degree of
Master of Science
In Operations, Management and Logistics

Supervisors:
Nico Dellaert (TU/e)
Claudia Fecarotti (TU/e)
Ricardo van Lunteren (DSNS)
Hannes Pauwelyn (DSNS)
Arjen Poortvliet (DSNS)
Bartjan Volmer (DSNS)

Vlissingen Sunday 16th May, 2021

Note

All input data used in this report are fictitious and serve for illustrative purposes only.

Abstract

DSNS (Damen Schelde Naval Shipbuilding) is a shipbuilding company that constructs highly technical military vessels. Before a ship construction project is assigned, the feasibility of constructing ships on a particular shipyard needs to be analysed. This research concerns the creation of a capacity feasibility model to aid strategic planning decisions. The created model allows insight in whether or not the capacity is sufficient for ships in a proposed project and what the costs would be if the capacity is not sufficient.

In total two models are created. The first model allows low detail input to analyse the capacity. The second model utilizes more detailed input on a block level basis. Whether the first or the second model is used depends on the amount of information available when running the model. Both models give insight in the requirements for ships in a proposal and how they relate to the yard capacities.

By utilizing extra flexibility, outsourcing and extra capacity the costs of inadequate capacity can be analysed. The model will ensure that the capacity will not be exceeded by using the before mentioned decision variables. Linear programming is applied in order to calculate the appropriate costs when the capacity is not adequate.

Both models increase the accuracy and completeness of the capacity analysis done in the proposal phase at DSNS. The second model is more accurate than the first model, however it does require more input data.

Keywords: Building Strategy, Capacity Analysis, Decision Support Model, Linear Programming, Mixed Integer Linear Programming, Shipbuilding, Strategic Planning

Managerial summary

Introduction
The shipbuilding process at Damen Schelde Naval Shipbuilding (DSNS) consist of a few phases. The first phase is the proposal phase. In this phase the customer comes to various shipbuilding companies with their demand. DSNS will create their proposal and discuss this with the customer. An important part of this is checking whether it is plausible to construct the proposed ships on certain yards. Furthermore, it is important to analyse which steps can be undertaken if the requirements exceed the capacity of a shipyard. These insights are then used to create a building strategy for the project.

Currently DSNS utilizes a simple model for this capacity feasibility problem with often unsubstantiated calculations. This research aims to create a new model with substantiated calculations that improve the accuracy and completeness of the strategic planning model. Furthermore, the new models should allow insights in the appropriate costs when the capacity is not sufficient.

Research design
The purpose of this thesis is creating a model in the proposal phase to analyse the adequacy of constructing certain projects on certain yards with limited available information. Therefor, the main research question is as follows.

How can a complete and accurate high level strategic planning model that analyses the capacity feasibility of a proposed project be created, with limited current information?

The required model encompasses the ship construction phase of shipbuilding. This phase starts when the first steel is cut on a shipyard, and ends when the ship leaves the shipyard. In total ten activities are identified in the shipbuilding process. These activities are steel processing, steel building, outfitting, piping fabrication, piping installation, painting & blasting, warehousing, quality control, project department and set to work.

Implementation & results
In total two models have been created in order to check whether construction of certain ships on certain yards is possible. The first model requires less detailed input. The second model requires more input, specifically on the construction of blocks. Two separate models have been made in order to allow a model to be run even though minimal information is ready, but still have the possibility to run a more accurate model using more detailed information.

In order to gather model input, data clustering analysis is used. This is done in order to divide ships into specific ship types. This enables the user to specify the type of the ship before running the model. Certain variables will be dependant on the ship type, mostly conversion factors. Data mining could also be used if more historic data is present. However, this was not the case at DSNS, and therefor will not be used.

The first model will be named the whole ship level model. This is because all calculations will be done on a whole ship level, no block information is required. The requirements will be split into two parts, first the activity hour requirements and secondly the facility requirements.

The activity hour requirements are first calculated on a total hour basis. So for the activity steel processing, first all hours necessary for completing steel processing for that activity are calculated. These calculation mostly consist of multiplying physical ship attributes by conversion factors.

After the total hours are calculated the hours need to be distributed. This is done by analyzing how

the hours of previously build ships are distributed. Two methods are proposed in this thesis. Firstly, regression can be used to calculate the hour distribution with a polynomial function. This will be quite an accurate representation of the data, yet slight adjustments are difficult to implement. The second method uses the beta distribution to approximate the desired distribution. This distribution will be less faithful to the historic data, but can be adjusted easier.

The facility requirements are calculated using a similar method. First, the total requirements are calculated. Afterwards, these totals are distributed using the beta distribution. The hull assembly area utilizes its own distribution, instead of an activity distribution.

After the total hours are calculated, the capacity feasibility can be analysed using linear programming. When the capacity is exceeded three decision variables can be used to gain an adequate capacity. Firstly, added flexibility in the distribution of requirements can be used, denoted by $EP_{i,t}^{Activity}$. For example, if the added flexibility is set to a maximum of 10 %, the model can lower the requirements in a certain month by 10 % by raising the requirements in other months. Additionally outsourcing ($O_{i,t}^{Activity}$) can be utilized to lower the requirements. For example, if 200 hours of steel processing hours are outsourced during a certain month, the requirements that month are also lower. Lastly, extra capacity can be added, denoted by $ECap_{i,t}^{Activity}$.

Correlations exist between certain activities and facilities. For example, when the steel processing activity is performed, steel processing area is required. So, if parts of the steel processing activity are outsourced, less area is required. Therefor, lowering the activity requirements lowers the correlated facility requirements as well.

Extra outsourcing and extra capacity both incur costs. The model will ensure that the capacity will be feasible while incurring the least amount of costs as possible.

The second model used is the block level model. This model requires more detailed input about the blocks in the ships. The reasoning behind this second model is that a more accurate model can be made when more information is available. This model will use some of the same formulation as the whole ship level model for the activities that can not be calculated on a block specific level.

The new formulations for the block level activities and facilities follow the same logic as the ship level formulations. Instead of using ship input values, like the weight of the ship, block level input values are used instead, like the weight of a block. The distribution is now done using the block fabrication plan. So when an activity is being performed on a block, the block requirements will be added to the total requirements.

Using the requirement formulations another linear programming model can be made. This time mixed integer linear programming is utilized. This is due to the fact that instead of an amount of hours being outsourced of an activity, the entire block will be outsourced for that activity. So if 500 hours need to be outsourced during, but all blocks require 1000 hours, at least 1000 hours will be outsourced.

A second change is that the added flexibility is also performed on a block level. This means that the distribution within a block can be slightly adjusted by allowing flexibility.

After both models have been created a software tool has been written in order to visualise the model in a clear way. This tool allows the user to change minor things about the model and analyse their effects.

Using the new whole ship level and block level models the completeness will be increased. This is due to the new models including activities and facilities that the previous model did not include. After analysis about 95 % of the total hours made in the ship construction process will be included.

Additionally, three different methods of calculating accuracy have been utilized, the Mean Squared Error (MSE), the Mean Absolute Deviation (MAD) and the Mean Absolute Percentage Error (MAPE). All three of these metrics show an increase of accuracy for all activities compared to the old model used. Furthermore, it can be seen that the block level model will be more accurate than the whole ship level model.

Conclusion
In order to analyse the feasibility of constructing ships on a yard two models have been created. The first model uses low detailed ship level input. The second model is more accurate, but requires more detailed block level input. The models will be used to check if the capacity is adequate. Furthermore, using linear programming models it will calculate the costs if the capacity is not adequate.

The models have an increased accuracy of more than 15% in comparison to the previously used model. Furthermore, more than 95% of all activity requirements have been included in the model. Additionally, using these models the associated costs with inadequate capacity can now be calculated.

The models are already in use at DSNS in order to create strategic plannings. To increase the accuracy and completeness a few adjustments can be made however.

Preface

This study was conducted as the last step in the fulfillment of the Master's Degree in Manufacturing Systems Engineering, a special master track of Operations, Management and Logistics at Eindhoven University of Technology (TU/e). This Master Thesis has been conducted under the supervision of N.P. Dellaert and C. Fecarotti from Eindhoven University of Technology and R. van Lunteren, H. Pauwelyn, A. Poortvliet and B. Volmer of Damen Schelde Naval Shipbuilding.

I want to thank multiple people for their tremendous help during my research. First of all, I would like to thank my first supervisor N.P. Dellaert for his enormous support. Our meetings were always insightful and were greatly beneficial. Furthermore, it gave me the confidence and encouragement to finish the project. Secondly, I would like to thank C. Feccaroti, my second supervisor, for her helpful advice during my research.

Additionally, I am incredibly grateful for all the support I got from Damen Schelde Naval Schipbuilding. First of all, I want to thank A. Poortvliet for the opportunity to perform this master thesis and providing my with all necessities I required. Secondly, I want to thank H. Pauwelyn, R. van Lunteren and B. Volmer for the massive help they gave me. Their critical eye and insightful advice were incredibly helpful. Our weekly meetings really helped me on the right path.

Lastly, I would like to thank my family and friends for their unending support during my research.

Contents

List of Figures

List of Tables

Word list

Name	Description
Block fabrication plan	A plan on how to subdivide the ship into blocks or rings Multiple modules may form a ship.
Blocks	A small part of the ship. Multiple plates pushed together. Multiple blocks may form a ring.
Building frame	Large tool where atop the block is created from the steel plates.
DSNS	Damen Schelde Naval Shipbuilding.
Hull	The (watertight) body of the ship. This is the outside of the ship.
Launching	Releasing a ship into the water
MAE, MAPE & MSE	Methods to determine accuracy of forecasting results
Modules	Multiple rings put together. E.g. the entire front part of the ship. Multiple modules may form a ship.
Outsourcing	Hiring a different company to perform certain activities on another own yard.
Pipe spools	Pre-build parts of a piping system
Quay	Structure next to the water to were ships can be docked
Rings	Multiple blocks vertically put together. If the ship would be cut with vertical slices one would see the rings of the ship. Multiple rings may form a module
Shipyard	Area where ships are made. A shipyard often consist of multiple production facilities where different activities are performed.
SYM	Strategic yard modelling, the strategic planning model DSNS currently uses. Multiple modules may form a ship.
Vessel	Used as an alternative name for ship.

1 Introduction

1.1 Company introduction

Damen Schelde Naval Shipbuilding (DSNS), a subsidiary of Damen Shipyards, is a shipbuilding company that primarily focuses on the design and production of military ships. On occasion DSNS also builds non-military ships with intricate technical design specifications. These ships are often unique to the customer and have low yearly demand.

The shipbuilding company is located in Vlissingen, the Netherlands, but often uses shipyards not directly owned by DSNS and not situated in Vlissingen. These shipyards could be owned by its parent company, Damen Shipbuilding, or owned by customers that contracted their ships with DSNS. A ship designed by DSNS is therefor often completely or in parts made in these overseas shipyards. DSNS is responsible for the design specifications and the planning of the ship, even if the ship is made in overseas shipyards. This planning involves aspects like where and when to build which parts (this part concerns the research), how the (frequently massive) parts are transported and assembly plans with design specifications.

1.2 Problem statement

Before a project starts, meaning the customer has not yet assigned a proposed contract to a particular shipbuilding company, DSNS spends quite some time preparing a preliminary planning. This is done to streamline the project, but also to effectively communicate to customers what to potentially expect. This planning encompasses many things. For example, it is important to check whether there is enough space to actually construct the ship. Another important aspect of the planning is estimating the amount of employees that will be working on the project. This helps with checking whether the workload is spread out, but also to show customers how much space they need to own for canteens, offices and changing rooms. Furthermore, these calculations also give a rough insight in the costs that DSNS will incur when executing the project.

This planning usually works as follows. A company, or in the case of DSNS often a government, proposes a contract for one or more ships to be build. DSNS will make a building strategy, a high-level planning, of the project. In this planning it is proposed where to build the ships, how manpower is roughly spread out and what extra capacities need to be acquired before production can be started. It is important to realise that this planning is made without many specifications being known, as it is proposed before the project is granted to DSNS. The planning is discussed with the potential customer before the contract is finally assigned. Afterwards more detailed, lower level, planning occurs. The main focus of the research is the higher level planning, also referred to as building strategy, discussed above.

Currently DSNS utilizes Excel and a homemade tool called "SYM" ("Strategic Yard Modelling") in order to create the high level planning. The SYM mostly helps with visualisation of the planning to clients. Together with some technical specifications a planning is constructed. Afterwards, this high level planning is proposed to the customer. If the project is accepted, a more detailed master planning is made. This planning involves splitting high level processes into low level processes.

DSNS identified that the SYM tool is quite out of date. It currently runs on Flash, a software program that is not widely supported throughout the company anymore, which makes adding potential adjustments difficult. Additionally, no advanced calculations can be done with the tool. It is primarily build for visualisation. Lastly, many calculations are often very rough estimations without a lot of substantiation. These points lead DSNS to conclude that this tool needs to be updated and improved, with new substantiated calculations.

In summary, a new model for calculating the feasibility of the project should be created. This is done by calculating whether or not the capacity on the proposed yards is sufficient enough to construct the ships within the alloted project time. This model should only use input available in the proposal phase.

1.3 Project relevance

There has been quite some research done in the creation of models concerning the shipbuilding process, which will be discussed in Chapter 2.1. However, these models require a large amount of specific data, which are not available in the proposal phase. Furthermore, these models are often concerned with the operation planning, meaning a short term planning often used for planning specific machines. In contrast, the desired model will focus on the strategic planning. No specific machines will be planned. It will be a high level planning distributing the ships over specific yards.

Such a strategic planning model that requires only low detail input has not yet been proposed. This thesis aims to create such a model

1.4 Thesis structure

In Chapter 1, an introduction to the research will be given. In this introduction the company will be introduced, the problem and its relevance will be discussed and the structure of the thesis will be given. Next, Chapter 2 will discuss appropriate literature, the research goal, the scope of the research and the main-and sub research questions. This is followed by Chapter 3 where the shipbuilding process will be analysed. Chapter 4 will determine the input necessary for the models. The first whole ship detail level model will be created in Chapter 5. Furthermore, Chapter 6 will describe the creation of a block level model. Afterwards, in Chapter 7 the model will be visualised in a clear and interactive way. Next, Chapter 8 will analyse the results of the model. Furthermore, the accuracy and completeness of the models will be discussed. Lastly, Chapter 9 discusses the conclusions and recommendations of the research.

2 Research design

2.1 Literature study

Relevant literature for this research has been summarized below. This literature study explores the shipbuilding process and the planning and simulation techniques concerning this process.

2.1.1 Shipbuilding industry

As already mentioned in Chapter 1, DSNS is a shipbuilding company that constructs ships with oftentimes difficult technical design specifications. These ships are primarily military vessels. Because of this, DSNS regularly creates unique products tailored to the needs of its customers. This often leads to no reliable historical data being available before the construction of the ship, a common occurrence in shipbuilding (Duclos et al., 2003).

Furthermore, the shipbuilding industry faces large international competition. This causes shipbuilding companies to increase their performance by allowing easy adaptation of their processes due to different technical and managerial specifications (Lamb et al., 2006). This means that although the ships are highly technical, the construction of ships needs to be able to differ from ship to ship.

2.1.2 Shipbuilding process

In shipbuilding, group technology (GT) is frequently used (Gribskov, 1988), as it is in DSNS. This involves subdividing the ship into intermediate products with similar purpose or production aspects. Ships are subdivided into modules, that consist of rings, which in turn consists of blocks that are made from panels. This is incredibly important in the way DSNS operates, as it could be the case that subdivided ship parts are constructed at different locations. This would not be possible if the ship would be constructed as an entire ship, meaning it would not be subdivided into parts.

Additionally, lean production can be effectively utilized in shipbuilding in combination with GT (Storch & Lim, 1999). Lean production focuses on the elimination of waste and frequently ensures that production is only started at the latest possible time. DSNS also applies lean production, ship production is only started after demand is received. Additionally, blocks are often only created if they can be immediately welded to other blocks. A challenge with lean production is balancing low inventory (waste) with constant production. Because of the unique nature of ships, DSNS does not have any military ships in store. This means that the production of DSNS is far from constant, sometimes an employee has nothing to do, and other times the employee is extremely busy. Furthermore, tools and raw materials are only ordered after DSNS received some demand.

2.1.3 Planning and simulation methods used in shipbuilding

The use of planning and simulation methods to streamline the (military) shipbuilding process has been studied in literature. However, many of these methods utilize more data than DSNS has available when they create their higher level planning. Furthermore, it is often assumed that ships are made at a single yard, however this is regularly not the case with DSNS. Although many of these planning and simulation methods are not directly applicable, they give an insight in the current practices in shipbuilding.

Multiple types of production planning used throughout the shipbuilding industry are defined by Jong et al. (2018). The strategic (long term), capacity (long term), master (mid term) and operational (short term) plans determine when and what (and in the case of DSNS where) will be produced. This research will not focus on the operational planning, only on the strategic, capacity and (in smaller parts) master plans. This is because these types of production planning concern the proposal phase of the ship building process. The operational plan only becomes important during the ship construction phase. These planning hierarchies as defined by Jong et al. (2018) are shown in Figure 2.1.

Stage	Planning objective	Planning result
Strategic plan	• On-time delivery • Optimal construction of product mix • Maximum dock turnover rate • Maximum utilisation of quay and dock	• Optimal product mix is configured to utilise maximum dock and quay and to reflect objectives of management strategy • Major node schedules are determined so that a complete ship is delivered on time and the dock turnover rate (annual batch number) can be maximised at the same time
Capacity plan	• Maximum utilisation of human resources from mid- and long-term perspectives • Maximum enterprise-level operation rate (utilisation) of main resources • Accurate prediction of production	• Set up capacity plan that can maximise the enterprise-level operation rate of main resources and the utilisation of available human resources • A measure is prepared to achieve a production goal, including outsourcing plan
Master plan	• Improvement of productivity by load balancing	• Validity of strategic plan and capacity plan is examined • The plan balances the loads of each process
Operational plan	• Accurate establishment of specific schedule • Optimal distribution of materials among working groups and workstages • Improvement of productivity by load balancing	• The degree of master plan is verified • Balanced distribution of materials for each working group and workstage • Preparation of specific plan that balances the loads of each process

Figure 2.1: Types of production planning as defined by Leea, Jeongb & Wooc (2018)

Zhuo et al. (2011) constructed a "compromised balance" planning approach for shipbuilding that balances Just-In-Time (minimize inventory) and smoothed production (minimize variation in working hours). The number of working hours per month was calculated using regression based on historic data. This compromised balance approach recommends storing some plates or blocks before an order is finalized. However, due to the highly specific and unique ships DSNS produces at a variety of different yards, this might be difficult to achieve.

Bao et al. (2018) created a model for (detailed) block assembly using a data driven approach. They used two major types of data in shipbuilding: contextual data (collected from manufacturing process, e.g. tools, work plans, device statuses and job site control) and content (management and design procedures). This data helps create correlations between parts and resources required for creation of parts.

An extensive detailed scheduling program for the construction of a large transport vessel has been created in the DAS project (Lee et al., 1995). They subdivided the detailed planning into four sub planning modules: erection scheduler at docks (hull assembly), curved block assembly scheduler, panelled block assembly scheduler, a neural network based manpower scheduler and a long term production planner.

Discrete event simulation can also be used for planning in shipyards. One such model was created by Chan et al. (2017). By using correlations between certain activities, a simulation model was made on a single shipyard with a particular ship with known blocks. This model was in turn used to create a Gantt chart with a proposed planning.

Further discrete event simulation modeling in shipbuilding have been done by Kiran et al. (2001). They applied this simulation model to identify bottlenecks and evaluate production schedules, resource utilization, material and work flow. Furthermore, these values have been used to check whether the capacity was adequate enough on the shipyard.

2.2 Goal

The goal of this research is to create an accurate and complete capacity model of the shipbuilding process for the construction of military naval vessels of Damen Schelde Naval Shipbuilding. This model serves the purpose of showing the feasibility of constructing a military ship on a yard. This should be realized by checking whether or not the capacity is adequate enough to perform the shipbuilding activities. In order to achieve this goal multiple research questions have been formulated in Chapter 2.4 & 2.5.1.

2.3 Scope

This research aims to create a capacity feasibility model that should be used in the proposal phase. The proposal phase in shipbuilding is the phase when the customer discusses the shipbuilding contract with possible contractors. No contracts have been awarded in this phase yet, talks will be still ongoing. The information available in this phase is very limited, as there will only be rudimentary drafts of the desired ships.

The scope of the model will only encompass the ship construction phase. This phase starts when the first steel gets worked on in the yard. This phase will end when the ship will leave the yard and be handed over to the customer. This means that all yard activities that occur during this phase will be present in the model. Any maintenance or other after sales support provided by DSNS after the ship leaves the shipyard will not be included in the model.

2.4 Main research question

As mentioned early in Chapter 1, the main purpose of this research is to created a planning tool that will help with the building strategy of a project. This planning should be made before the project is started, often before a proposed contract is awarded to DSNS. Therefor, the main research question is as follows:

How can a complete and accurate high level strategic planning model that analyses the capacity feasibility of a proposed project be created, with limited current information?

This research question encompasses the goal of the research, researching the means to creating an effective building strategy. However, before such a model can be created, various aspects need to be researched beforehand, in order to create a planning that will be fairly representative of the project. For example, it can be quite easy to just guess the number of hours that will be needed to complete a certain activity. However, this number would not be very realistic. Therefor, it is important to calculate more precise estimations for the required parameters for a planning, and make sure these calculations are substantiated.

The effectiveness and accuracy of the created model will be judged by comparing it to the old model in terms of accuracy. Before the research, a few projects that have been executed in the past have been chosen in order to compare the models. Of these projects the information that was available in the early proposal stages will be analyzed. This information will be used as input to gain the results from the old and new models. Afterwards, data about the requirements of the project will be obtained. Both the new and old yard planning model results will be compared on a monthly basis to the actual situation using the MSE (Mean Squared Error), MAD (Mean Absolute Deviation) & MAPE (Mean Absolute Percentage Error). This will be done for each category, so the accuracy of the calculated hours of steel building work will be calculated, but also the accuracy of the number of building frames per month.

The new model is deemed effective if the accuracy of the requirements per month is increased by at least 15%. Furthermore, the model is deemed complete if less than 5% of the requirements for the project are of a category not included in the model.

2.5 Sub questions

2.5.1 Estimating the requirements

In order to create a model it is important to use accurate values and distributions in order to get an accurate planning. Currently, most values and distributions are estimated using the experience of certain employees. However, improving this estimation by making use of the historical data available will improve the accuracy of the model.

How can a substantiated estimation of the requirements of selected ships throughout a project be calculated?

First, the desired input values need to be obtained. This will be done by grouping ships into distinct ship types. Each ship type will have different input values for the model. These values are than used to calculate the total requirements.

The distribution will be based on data fitting using the available historic data. The distribution will either be modelled with a polynomial function or an approximated probability distribution.

It is important that all values and distributions are substantiated. This means that when someone creates the yard planning model, that person knows for example why there is a peak at a certain time. So an important metric for this sub question is to substantiate all values and distributions used. Furthermore, the accuracy will improve using these new values. The end result should be an increase of the total accuracy of 15%, as stated before.

2.5.2 Additional activities

After the accuracy a second important aspect of the model is the completeness. Currently 8 major activities within the shipbuilding process are looked at in the yard planning model. However, there are still some areas in the model to be expanded.

How can the completeness of the yard planning model be improved with the inclusion of additional activities & facilities?

After analysis of the entire shipbuilding process of DSNS the conclusion is drawn that two activities are currently missing from the model. These are painting & blasting and warehousing. If these two activities are included, the entire shipbuilding process will be modelled. However, it is also possible to subdivide some activities into smaller, more detailed, sub activities. This could help clarification of the model.

Both the working hours and the facilities of these activities will be included in the model. Furthermore, the values and distributions of these activities will also need to be substantiated in order to increase accuracy, see Question 2.5.1. Because these activities are not included into the current model, an accuracy increase compared to the older model cannot be calculated. Therefor, it is determined that an accuracy of 80% of the requirements per month will be acceptable, meaning a MAPE of less than 20%. Furthermore, the inclusion of these new activities will need to increase the completeness of the model to over 95% (less than 5% of total hours should belong to a not included activity).

2.5.3 Ship subdivision

Currently the model uses only low detail ship level input in order to create a yard planning model. This can be useful as it can be made with very limited information. Furthermore, it used to be the case that a ship would most likely be made at a single yard. However, this is no longer the case. A ship will very often be build at multiple yards due to increasing competition and globalisation. Therefor, being able to divide the ship realistically into smaller units is important in the creation of an accurate model. Furthermore, it would help in substantiating the model, as the model maker can for example see that a certain peak is created due to building too many blocks at the same time.

How can subdividing a ship into smaller units increase the accuracy of the yard planning model?

Ships are currently divided into rings that are in turn divided into blocks. At quite an early stage of the proposal phase a block fabrication plan will be created. This is done in order to create a build order in which to assemble the blocks. This block fabrication plan will be used as input for the model to create a planning of when certain blocks will be constructed. Afterwards, these blocks are each assigned a value using the formulations of Question 2.5.1. The distribution will follow from the block fabrication plan.

2.5.4 Capacity constraints & model planning

When a ship is being build at a certain yard, the capacity of the yard is important in determining whether a ship will be constructed in time. If a capacity is reached, the required planning can no longer be followed. Currently, this is not taken into account.

How can a realistic model be created by taking into account activity correlations and shipyard capacities by making use of subcontracting?

Reaching the capacity should have some effect on the model, as it is not realistic to use more than the maximum capacity. In order to solve this issue a few things can be done: the capacity can be expanded, some work may be outsourced or more flexibility can be allowed.

It is desired of the model to create a realistic capacity analysis. This can be done by allowing the model to subcontract certain blocks, use extra flexibility or expand the capacity when the total capacity is reached. Outsourcing and adding capacity both have associated costs. By creating a linear programming model, with the objective of minimizing the costs, the most cost-effective method to construct a ship within the capacity constraints can be found. The constraints will be the capacity constraints of both activity hours and the facilities.

2.5.5 Visualisation

When a planning is created, it is often important to be able to effectively communicate this planning to other people. Furthermore, it can be helpful to be able to quickly adjust the planning, to see what consequences certain decisions have on the overall plan. The following research question deals with this.

How can visualisation and interactivity be used to clearly communicate the planning?

Visualisation and interactivity enhances communication between the customer and DSNS. It would be very useful if the planning could be altered without much hassle. This could help visualise the effect of proposed changes. Furthermore, the ability to communicate the planning to customers as clear as possible can add value to the project itself.

3 Analysis of the shipbuilding process

In total 10 activities are defined in the shipbuilding process of DSNS. These activities are defined by the use of interviews with professionals in the field, and analysis of data. The analysed data consisted of the required hours for a particular ship. These hours were all related to particular activities that were performed using the description given after the hours were catalogued.

The entire ship construction process is shown in Figure 3.1. The activities are denoted in square boxes. The unit flow is shown by the arrows. The units can be stored during or between the activities in the data base icons. The storage of tools (like building frames) or smaller materials is not shown in order to avoid confusion. The unit types are given under the unit flow.

This figure shows the total ship construction process. However, during this process multiple activities can be performed during the same month. For example, while plates are being cut for block I, block II might have already started outfitting. This means that on a whole ship level, multiple activities will be performed at the same time. However, on a block level the block level activities need to be finished before the next activity can start. In order to start painting & blasting for a particular block, steel building should be finished.

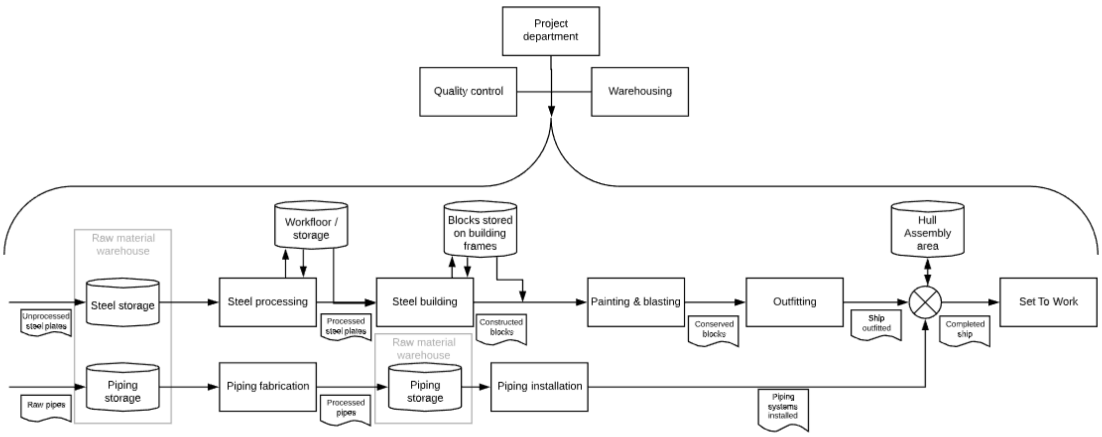

Figure 3.1: Activities in the ship construction process

Below each activity is further detailed. First, a description of the activity is given. Afterwards, the associated facilities are explained. Lastly, the current implementation of the activities in the SYM are given. These calculations are the current method of implementation at DSNS. Changes to these calculations will be proposed in Chapter 5.

3.1 Steel processing

Steel processing is the process of turning raw steel plates that arrive from the supplier into processed plates that can be used in the blocks. This process involves tasks like cutting, drilling and bending.

The steel processing activity is linked to certain facilities. In order to perform the steel processing activity, steel processing area needs to be available. The more steel that needs to be cut per month, the more area is needed. Furthermore, it is also limited by the total weight a yard can cut per month. This capacity is determined by the cutting machines at the yard. Lastly, raw steel plates need to be stored before they are processed.

In the current model (SYM) that DSNS utilizes the required steel processing hours are determined by multiplying the bare ship weight with the average hours it takes to process 1 ton of steel. These hours are then distributed over two separate activities, steel processing and steel building. This distribution is commonly about 15-20% steel processing and 80-85% steel building.

3.2 Steel building

The second activity is steel building. During this activity the processed steel plates are assembled into blocks. First, block construction is performed by welding the steel plates to each other. While this is happening steel working is done. During steel working larger steel items are installed in the block. These items could be reinforcement for engines, large stairs or other large items that will be difficult to install when the ship is assembled. The last task is hull assembly. During this task the block will be welded to the other blocks.

In order to perform this activity building frames are required. Building frames can be seen as construction areas were each block is constructed. Using large machinery these building frames can be moved around in order to move the blocks to subsequent activities. The construction of the blocks take place on that specific building frame. Furthermore, when blocks are assembled to the hull the required hull assembly area will increase. Only bottom blocks will increase this area though, as blocks that are added on top of other blocks will only increase the required height.

Currently steel building is calculated using the bare ship weight and the required hours per ton. As mentioned earlier, this total is split amongst the steel building activity and the steel processing activity.

3.3 Painting & blasting

After a block has finished the steel building process, it continues to the painting and blasting activity. The block will get painted and the welding lines of the block are smoothed out. This process takes quite a while, mainly due to the drying time of the paint. This means that irrespective of the size of the block/ring the painting & blasting activity will require the same duration, often a month. It is currently not implemented in the planning yet.

Painting & blasting is performed in the painting & blasting hall. The capacity of this hall has been proven to be quite a large bottleneck for the shipbuilding process of DSNS. This is because the blocks need to be present in the hall for a whole month, a process that is difficult to accelerate.

3.4 Piping fabrication

In order to construct a functioning ship, a lot of piping needs to be installed. Many different systems require or exhaust air, water, fuel and other gasses. Before the piping can be installed the pipes need to be fabricated. The items used in piping fabrication are called pipe spools. They are the pre-build parts of a piping system. During piping fabrication pipes are cut and bend in order to be installed in the ship.

Yards can only fabricate a set number of pipe spools per month. This number depends on the machinery available on the yard. If more spools are required to be fabricated during a particular month than the capacity allows, the capacity will be exceeded and the ship will be delayed.

Currently in the SYM the required hours are calculated using the amount of spools required ships and the predetermined amount of hours it takes per spool. These values are than multiplied together. As with steel processing & steel building this amount of hours is divided among the piping fabrication and piping installation. This is about 40% piping fabrication and 60% piping installation. The distribution is estimated by looking at similar ships.

3.5 Piping installation

Piping installation is the second activity that involves the pipe spools. During this activity the pipe spools are installed in the ship. This can be done while the ship is on a building frame, or when it is in the hull assembly area. Therefor, this activity will happen simultaneous with the steel building and outfitting activities.

As mentioned earlier, the piping installation activity hour requirements are currently calculated using the same method as the piping fabrication. This means that piping fabrication is alloted 60 % of the calculated total hours.

3.6 Outfitting

Outfitting is the process of getting the ship ready to be used. This includes aspects like furnishing, placing the engine and installing systems. At the beginning of the process the ship is bare with just the steel working (and sometimes piping) being done. After outfitting, the physical aspects of the ship are ready. It is important to note that outfitting does not include testing nor adding supplies like ammunition or food.

The amount of required hours to perform the outfitting process is calculated in a very similar way to steel working. First, the total weight of the final ship is taken (lightship weight). As already mentioned, this weight does not include provisions and other stored goods, but with outfitting items. Afterwards, the weight of the bare ship (used for steel working) and weight of the spools (used for piping) is subtracted. This weight is then multiplied by the amount of hours one ton of outfitting takes (hours/ton). The value of hours/ton is again estimated by looking at historic data of similar ships.

3.7 Warehousing

An important activity throughout the construction process is warehousing. Items such as steel plates, tools, furniture, engines and entire blocks need to be stored. The warehousing employees oversee this process. Currently no implementation of the warehousing activity is present in the SYM.

3.8 Project department

The project department ensures that the construction process stays on track. For example, sometimes details need to be elaborated or changed, even after the building has begun. For the planning, the amount of hours the project department takes is only calculated after the project is started, so when the first steel is being cut. This means that the work the project department performs before the contract is assigned to DSNS will not be taken into account. This makes sense as planning for time that is already incurred would not be very useful.

The amount of working hours for the project department is calculated in a different manner than the previous activities. For each month of the project it is estimated how many employees (FTE's) are needed that month. Each FTE adds 150 hours of work during that month. Summing the amount of required hours over all months of the project gives the total amount of hours needed for the project department.

3.9 Quality control

Quality control ensures that the resulting ship meets the standards of DSNS and the customer. This includes quality control of the welding process, furnishing, etc. This is calculated in a very similar way as the project department. The amount of FTE's working on quality control per month is estimated, which are turned into total hours.

3.10 Set to work

The setting to work process is the final commissioning of the ship. It ensures that the ship is ready to be handed over to the customer. The activity mainly consists of testing the systems and training the personnel. The total amount of working hours for this process is again calculated by estimating the FTEs per month.

4 Determining model input

The models that will be proposed in Chapters 5 & 6 require input values in order to function. These input values are values that need to be determined beforehand. There will be six types of input values used. The block level model will utilize the same types of data. However, some of these values need to be given on a block level

The first type of input value are the physical ship values. These include aspects like the length of the ship, the weight of outfitting in the ship and the number of blocks in the ship. These values are all available in the early proposal phase. This is because they are either demanded from customers, or are easily calculated from those demands. Therefor gathering this type of data is not an issue. For the block level model, physical block data is needed. This is similar to physical ship values.

Another type of input data is the yard dependant variables. These often concern the capacity available on the yards. This data is known to DSNS, and therefor does not require additional data collection

Furthermore, there are fixed variables. These variables include the amount of hours one full time employee makes each month (FTE) or the area of an average plate. These variables are internally known in DSNS, and therefor require no additional data collection

Distribution information is the fourth type of input data necessary. This is because the calculated requirements need to be distributed. Chapter 5.1.2 gives an in depth explanation as to how this data is gathered. Furthermore, in this Chapter the required formulations are also given.

Additionally, the start and duration of activities and facilities are required. These values are also known early in the proposal phase, as deadlines are given by the customer. For example, the customer will have influence over when keel-laying is done. This in turn can tell us when the first block is put into the hull assembly area, which is often equal to the start of outfitting.

The last type of input data are the type dependent variables, variables that are determined by the type of ship / block. Often these variables are conversion factors. Examples of this type of data are, the required hours/ton of activities, storage time of items and set-up times for blocks These variables are the most difficult to determine and will be discussed below.

4.1 Determining ship types

In order to determine the ship types data clustering is used. This is done by selecting certain attributes of the ships and grouping ships that have close values for those attributes.

K-means clustering assumes that data that is close to each other have a lot in common. This type of clustering is used to determine the ship types. Before this type of clustering is used the desired amount of ship types need to be given. This is represented by the variable k. Furthermore, the desired clustering axis need to be determined. These will be the required conversion factors and their related physical ship aspects.

There are multiple methods that can be used to find a sufficiently adequate k, as described by Pham et al. (2005). The simplest method is determining the amount of groups by visualisation. This is done by noticing the amount of groups appearing in the data.

A second method to find a satisfactory value for k is making use of a scree plot. This is a plot where the errors of a few values for k are plotted against each other. Beforehand, these error terms need to be determined for a few values of k. Imagine if k=1, than the most optimal point, also called centroid, in the graph is chosen so that the average distance of all data points to that centroid is minimized. Than these distances are squared. Afterwards, the squared error for k=2 is determined. Again the two centroids in the graph are determined so that the error term is minimized. The error term is calculated by taking the distance between a data point and the closest centroid. This number is than squared. Determining the optimal place for the centroid is done using a programming tool, in this case python.

Figure 4.1 give an example of the hours per ton and bare ship weight of seven ships. This data is not representative of real data, and should be purely used for demonstration purposes only. Figure 4.2 shows the centroids when the value for k is set to 3.

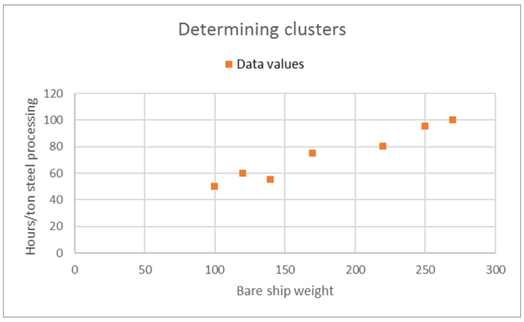

Figure 4.1: The hours per ton and bare ship weight for 7 ships

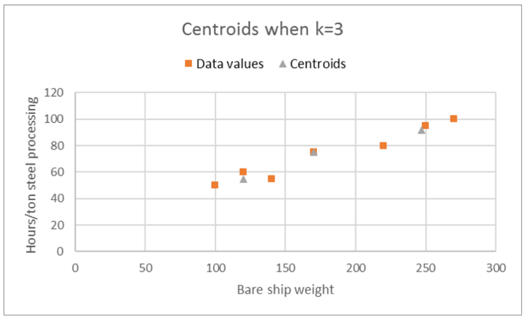

Figure 4.2: Centroids added to Figure 4.1 when the value for k is 3

Now that the squared error terms for a few values of k are known, they can be plotted against each other. This is also known as a scree plot. The scree plot for the situation as seen in the previous two figure can be seen in Figure 4.3. In order to get a good value for k the elbow needs to be found. This elbow is the point in the graph where a large change in the slope of the graph occurs. In Figure 4.3 a large change in slope occurs at both k=2 and k=3. So either two ship types or three ship types should be used in this situation. The user can determine whether 2 or 3 types is more useful.

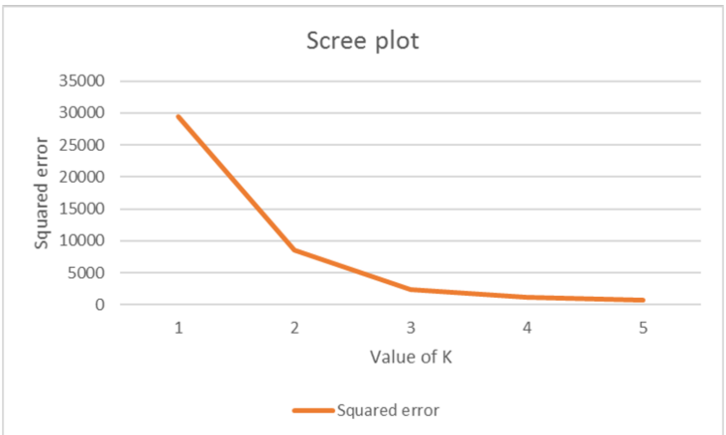

Figure 4.3: Scree plot

5 Model on whole ship detail level

In order to analyze the shipbuilding process at a very early stage, a strategic model will need to be developed. The primary aim of this model is to check whether or not the capacity is sufficient. Secondly, if the capacity is not sufficient the model should calculate the associated costs. This first, whole ship level, model is created when a lot of aspects of the desired ships are still unknown. However, it is still desirable to have an indication on what shipyards the ships in the project can be constructed.

In order to check whether it is possible to construct a ship on a specific yard two important aspects are needed. Firstly, the requirements need to be calculated. There are quite a few requirements, each will be discussed below. They are subdivided into two major categories: the staff requirements and the facility requirements. Furthermore, the capacity on the yard needs to be known. It is also important to know if it is possible to exceed this capacity, and what the accompanying costs of creating extra capacity would be.

The model will check the capacity on a monthly basis, which means that it is important to know the requirement and the capacity for each month in the project. Furthermore, because this model is created in a very early stage of the shipbuilding process, not a lot of detailed information is available.

The formulations used in the following sections require a few overarching variables. These will be given below.

Used sets and indices

- i = specific ship
- I = all ships in the project
- t = specific time in months
- T = all months in the project
- a = specific activity
- A = all activities
- f = specific facility
- F = all facilities

All activities (set A)

- SP = Steel processing
- SB = Steel building
- O = Outfitting
- PF = Piping fabrication
- PI = Piping installation
- PB = Painting & Blasting
- WP = Warehousing

- QC = Quality control
- PD = Project department
- STW = Set to work

All facilities (set F)

- SPA = Steel processing area
- BF = Building frames
- HA = Hull assembly area
- LA = Launching area
- QA = Quay area
- PBA = Painting & blasting area
- SC = Steel cut
- PP = Pipes processed
- WA = Warehousing area
- SSA = Steel storage area

5.1 Calculating the staff requirements

There are ten main activities in the shipbuilding process, as discussed before. Each of these activities have their own staff requirements. However, these requirements will be calculated using the same method. First, the total hours required throughout the project will be calculated. Afterwards, these hours are distributed over the months.

5.1.1 Calculating the total required hours over all months

In order to calculate the requirements, first the total required hours need to be calculated. Because in this phase of the shipbuilding process not a lot of details will be known about the ship, the input for these calculations cannot be very sophisticated.

The calculations will often use input values that are dependant on ship type. These input values are discussed in Chapter 4.1.

The following notations will be used.

Fixed input values:

- w_i = The total "bare ship weight" of ship i. This is the weight of just the ship itself, so without any items or provisions.
- ow_i = The total outfitting weight of ship i. This is all the weight of the outfitting items in the ship. This includes a variety of items like machines, chairs, monitors and turrets.
- s_i = The total amount of pipe spools in ship i. Pipe spools are used for a variety of systems, e.g. oxygen, fuel and water.
- nr_i = The total number of rings in ship i.

- FTE = Number of hours each Full Time Employee works per month, often this will be 150 hours
- $\lambda_i^{Activity}$ = This is the constant that converts the weight or amount of spools into hours. This is a ship type dependant value, determined in Chapter 4.1. This value will either be hours/ton or hours/spool dependant on the activity. For example, λ_i^{SP} is the hours of steel processing each ton of bare ship weight requires.

Calculated values:

- $TH_i^{Activity}$ = The total hours necessary for an activity for ship i
- $H_{i,t}^{Activity}$ = The hours spend on an activity at month t for ship i

The total hours required for steel processing will be calculated using the bare ship weight of the ship. This is the weight of just the steel in the ship itself. This number is than multiplied by the number of hours each ton of ship weight takes to steel process (hours/ton). This will be a constant linked to the type of ship.

$$TH_i^{SP} = w_i * \lambda_i^{SP} \qquad \forall i \in I$$

Steel building hours are calculated in a similar way to the steel processing hours. However, the lambda constant (hours/ton) will be a different number. It will still be dependant on the ship type.

$$TH_i^{SB} = w_i * \lambda_i^{SB} \qquad \forall i \in I$$

The required hours of outfitting will also be calculated in a similar way. However, instead of using the bare ship weight, the total outfitting weight will be used. This is again multiplied by a predetermined lambda, dependant on ship type.

$$TH_i^{O} = ow_i * \lambda_i^{O} \qquad \forall i \in I$$

Piping fabrication is quite different than the previous activities. Instead of using weight to determine the total hours, the amount of spools is used this time. This number is than multiplied by a predetermined lambda, the hours per spool.

$$TH_i^{PF} = s_i * \lambda_i^{PF} \qquad \forall i \in I$$

The calculations for piping installation are very alike the piping fabrication calculations. However, a different lambda is used this time.

$$TH_i^{PI} = s_i * \lambda_i^{PI} \qquad \forall i \in I$$

Painting & blasting is a very different process than the other activities. This is due to the majority of time going into the drying of the paint. Furthermore, the size or weight is often irrelevant in this activity, as most time is spent on the difficult crevices of a ring. Because of these factors, the total time it takes is often just dependant on the number of rings that are present in the ship. In total this process will take one month for every ring (mostly independent on the size and weight of the ring). During this time 3 employees need to be present to work on or supervise work on the ring.

$$TH_i^{PB} = nr_i * FTE * 3 \qquad \forall i \in I$$

The warehousing activity concerns itself with the storage of the outfitting weight. It will be calculated in a very similar way as outfitting, with a different value for the type dependant lambda.
$TH_i^W = ow_i * \lambda_i^W \qquad \forall i \in I$

Quality control, project department and set to work hours are all calculated using individual employees. These activities all require very little hours and do not use facilities on the yard. The total hour input of these tools will be used as input for the model. The distribution of these hours is included in this model. This means that TH_i^{QC}, TH_i^{PD} and TH_i^{STW} are all input values, but $H_{i,t}^{QC}$, $H_{i,t}^{PD}$ and $H_{i,t}^{STW}$ will be calculated. If tools are not available for these activities, then historic data and clustering can help estimate the total required hours. Often these hours are dependant on the ship type, meaning historic data can help achieve these numbers. More information can be found in Chapter 4.1.

5.1.2 Distributing the total required hours over the project months.

Now that the total required hours are calculated, the hours need to be distributed over the project months. This is because knowing the total hours is not very useful in learning whether or not the capacity (max number of employees/workload) is reached. In order to accomplish this, historical data is used. This historical data describes the requirements and physical ship attributes of a certain amount of ships that DSNS has constructed.

In total, data for 17 military ships was available. This is not a large amount of data, however DSNS does not construct that many ships on a yearly basis. Thirteen of these ships will be used to determine the requirement distributions of the ships. The data of the other four ships will be used in Chapter 8.3.2 to check the validity of the distributions.

To demonstrate how distributing the total required hours over the project months will be done, the activity steel processing will be used as an example. The other activities will follow the same method as applied to steel processing.

The duration of the steel processing activities for all ships can differ slightly. For example, it is possible that a larger ship like a frigate will require more hours than a patrol vessel. This will often lead to a larger duration of each activity in the planning as well, in order to not overload the capacity of the yard. This could mean that both ships follow the same distribution, yet the curves will not overlap. For example, if steel processing for ship 2 takes twice as long as ship 1 and both start steel processing during the same month, than the peak for ship 2 will be twice as far. An example will be shown in Figure 5.1.

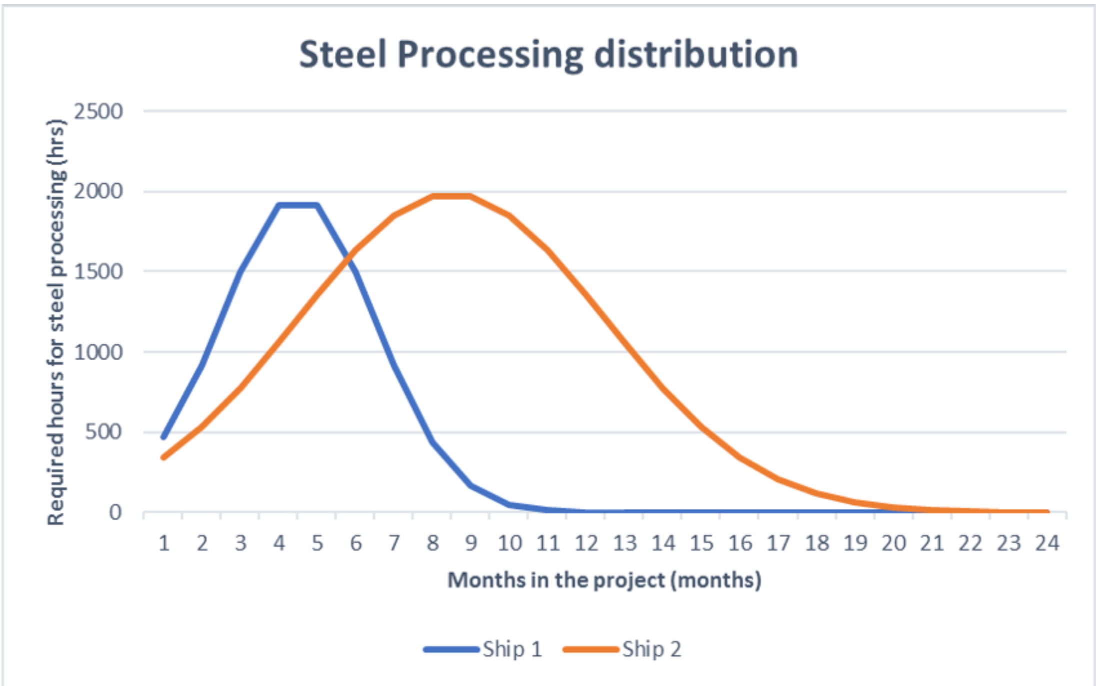

Figure 5.1: Two ships with different activity duration, yet with visually distinct curves

In order to compare the same activity of different ships, the timescales need to be standardized. This will be done using the percentage of the total duration of the activity. For example, imagine that for a particular ship steel processing will take 485 days (about 16 months). This means that each day $\frac{1}{485}\%$ of the total time passes. Using this new timescale the curves in Figure 5.1 should now overlap.

In total two methods will be proposed in order to distribute the requirements. First, the beta distribution is utilized to distribute the hours. Secondly, polynomial regression is used to find a satisfactory polynomial function. Afterwards, the advantages and disadvantages of both methods will be discussed and why the second method, the beta distribution, will be utilized by DSNS

5.1.2.1 Beta distribution

This second option will be distributing the required hours via the beta distribution. This has a few advantages and drawbacks compared to the polynomial function. A major disadvantage is that it will most likely be a less accurate portrayal of the historical data. An example of this would be if the historic data would have two peaks. This would be impossible to approximate using the beta distribution. However, analysis of the data shows that this does not occur at all for activities. There is only one peak with a gradual incline and decline, closely resembling the beta distribution.

Another downside of the beta distribution is that it is a continuous distribution. This means that it will have to be approximated to a discrete distribution. For example, the chance of x = 5 will be calculated using the approximation $P(X = 5) = P(X \leq 6) - P(X \leq 5)$.

It is important that $P(X \leq 6) - P(X \leq 5)$ is used and not $P(X \leq 5) - P(X \leq 4)$. This will be explained with an example. Imagine that for a ship, steel building starts in month 5 and takes 7 months to complete. This means that no steel building takes place before month 5, $P(X \leq 5) \approx 0$ (as the chance of X being precisely 5.00 is very small). This means that calculating $P(X \leq 4)$ would be nonsensical. Therefor $P(X = 5) = P(X \leq 6) - P(X \leq 5)$ should be utilized, and $P(X = 5) \neq P(X \leq 5) - P(X \leq 4)$.

Another important thing to notice is that when an activity start in month 5 and takes 7 months to complete, month 11 will be the final month were labour is being performed, not month 12.

A major advantage of using the beta distribution is that two variables are utilized in order to draw the curve. These variables are alpha and beta. If it is known beforehand that the curve will look different, these variables can be quite easily altered, and therefor the curve will look slightly different. For example, if it is known that the curve will be slightly more to the left, the beta can be increased.

The beta distribution works for values in between 0 and 1. So before it can be used, the months need to be converted into values between 0 and 1. Luckily, this was already done previously. The output of the beta distribution will also be values between 0 and 1. These are still yet to be converted. The output should be the required hours during that month ($H^{Activity}(t)$). In order to convert this to a percentage it has to simply be divided by $TH^{Activity}$. So if the historical data says that in month 4 100 hours are required out of 2000 hours total, than the output should be $\frac{100}{2000}$.

The following formulation will be used in order to determine the required values for the beta distribution.

$H^{Activity}(t) = P(X = t) * TH^{Activity}$
$H^{Activity}(t) = (P(X \leq (\frac{t+1-st_i^{Activity}}{dr_i^{Activity}})) - P(X \leq (\frac{t-st_i^{Activity}}{dr_i^{Activity}}))) * TH^{Activity}$

Again it is desired that the error term (ϵ) will be as small as possible. This is done by changing the variables (α & β) of the beta distribution. Using the solver tool in Excel the α & β that correspond to the lowest value of the Mean Square Error is found.

Some examples of the beta distribution can be found in Figure 5.2. As can be seen, if the alpha is smaller than the beta the distribution will lean more to the left. This means that the requirements will be necessary earlier on in the activity. If the beta is smaller, the distribution is more weighted to the right. This means that the hours will be required later. Lastly, if the alpha and beta are both the same, the distribution will be symmetrical.

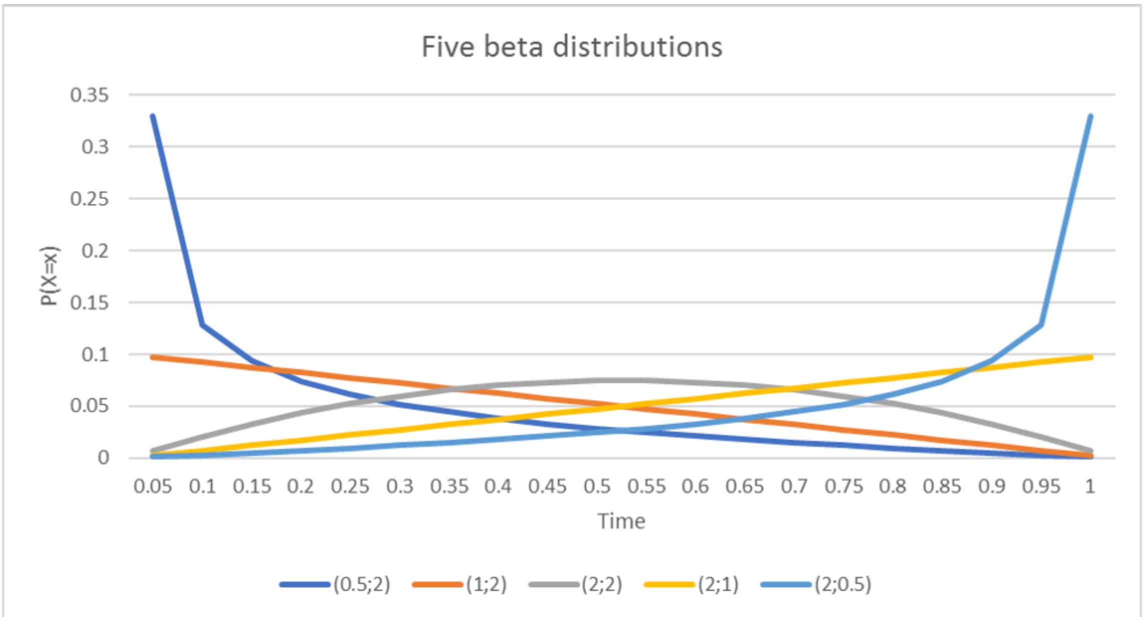

Figure 5.2: Various beta distributions with different alphas and betas $(\alpha; \beta)$

5.1.2.2 Polynomial regression

A different distribution method that can be utilized is the polynomial regression. The choice for polynomial regression was made after analysis of the distribution of the required hours. None of the distribution followed a linear line, so linear regression was out of the question. The curves were clearly polynomial functions, so polynomial regression was applicable. However, due to the advantages of the beta distribution, this method will not be utilized by DSNS.

As mentioned earlier, in order to accomplish the polynomial regression, data from military ships build in the past will be used. The desired polynomial function is given below.

$$H^{Activity}(t) = (\beta^{Activity,0} + \beta^{Activity,1} * t + \beta^{Activity,2} * t^2 + ... + \beta^{Activity,n} * t^n + \epsilon) * TH^{Activity}$$

With:

- $H^{Activity}(t)$ = required hours of an activity at time t in hours
- $TH^{Activity}$ = the total required hours of an activity
- β^n = the constant value determined by the regression analysis
- t = time in months
- n = the maximum polynomial
- ϵ = the error term, can be either positive or negative

Using historic data, the required hours of an activity at time t is known for certain ships. This means that it is possible to find the best beta's (β^n) that result in a low error ϵ. In order to determine these beta's the Mean Square Error is applied. This means that all the error terms for all months of all ships is squared. Than all these error terms are summed. The beta's that result in the lowest sum are used for the final polynomial function. Using the current data set a maximum polynomial of 4 is already quite accurate. Using a fifth polynomial term only leads to marginal improvements. The form of the final formulation will be given below.

$$H^{Activity}(t) = (\beta^{Activity,0} + \beta^{Activity,1} * t + \beta^{Activity,2} * t^2 + \beta^{Activity,3} * t^3 + \beta^{Activity,4} * t^4) * TH^{Activity}$$

So the current term is a polynomial function and is perfectly applicable for the final model. However, a major drawback is that this function is very difficult to understand without drawing its curve. This means that if it is already known that the activity of a certain ship will deviate from how that activity is normally distributed it is quite difficult to alter the curve. This is why a second method is used in order to distribute the activities.

5.1.2.3 Comparison of the polynomial function and the beta distribution

It is up to the creator of the model to determine whether a polynomial function or a beta distribution will better serve their needs. Both options are viable, and are therefor both discussed in this paper. In order to preserve both options the formulations will be replaced by $D_{i,t}^{Activity}$. Below the real formulations for this term are given.

If the polynomial function is used:
$$D_{i,t}^{Activity} = \beta^{Activity,0} + \beta^{Activity,1} * t + \beta^{Activity,2} * t^2 + \beta^{Activity,3} * t^3 + \beta^{Activity,4} * t^4$$

If the beta distribution is used:
$$D_{i,t}^{Activity} = P(X \leq (\frac{t+1-st_i^{Activity}}{dr_i^{Activity}})) - P(X \leq (\frac{t-st_i^{Activity}}{dr_i^{Activity}}))$$

The resulting formulation will become:

$$H_{i,t}^{SP} = TH_i^{SP} * D_{i,t}^{SP} \qquad \forall i \in I \wedge t \in T \wedge a \in A$$

With:

- $H_{i,t}^{Activity}$ = required hours to complete an activity for ship i at time t
- $TH_i^{Activity}$ = the required hours to complete an activity for ship i
- $D_{i,t}^{Activity}$ = percentage of the total hours of the activity of ship i that happens at month t.
- $EP_{i,t}^{Activity}$ = The extra percentage of hours of an activity that can be done at month t in ship i. A maximum will need to be given.

As mentioned earlier, both the polynomial function and the beta distribution have advantages and disadvantages. The polynomial function will be more accurate, but the beta distribution will be more adaptable. The difference in accuracy can be seen in Table 5.1. A decrease in accuracy means an increase in the MSE or MAE. The accuracy is determined by using the real historic requirement data from the set aside ships.

Activity	Percentage change MSE beta	Percentage change MAE beta distribution
Steel processing	-6.2 %	-5.9 %
Steel building	-5.7 %	-5.7 %
Outfitting	-6.7 %	-3.3 %
Piping fabrication	-7.2 %	-9.3 %
Piping installation	-4.2 %	-4.0 %
Quality control	-8.3 %	-7.1 %
Project department	-5.8 %	-6.2 %
Set to work	-10.9 %	-5.7 %

Table 5.1: Change in accuracy in comparison to the polynomial regression formulation

As can be seen in Table 5.1, the polynomial function is more accurate for all activities. This is because it will more closely resemble the data. However, due to the limited decrease in accuracy but the increase in adaptability, DSNS will utilize the beta distribution.

5.1.3 Converting hours to FTE

The current model uses hours as a unit of measurement for the activity requirements. Even so, it could be useful to use FTE as the unit of measurement. This could lead to better visibility. This is only optional though, and the main model will keep using hours as a unit.

If it is preferable to choose FTE as a unit of measurement, the formulations noted below need to be added to the model. Furthermore, all $H_{i,t}^{Activity}$ used in the of the model should be converted to $Hfte_{i,t}^{Activity}$ (relevant for the capacity constraints).

$$Hfte_{i,t}^{Activity} \geq H_{i,t}^{Activity}/FTE \qquad \forall i \in I \wedge t \in T$$

$$Hfte_{i,t}^{Activity}, integer \qquad \forall i \in I \wedge t \in T$$

With:

- $H_{i,t}^{Activity}$ = required hours to complete an activity for ship i at time t in hours
- $Hfte_{i,t}^{Activity}$ = required hours to complete an activity for ship i at time t in FTE's. This will be a variable that can only be an integer.
- FTE = number of hours each Full Time Employee works per month, often 150 hours

5.2 Calculating the facility requirements

As mentioned earlier, in the early proposal phase many details of the ship are still uncertain. Yet, it is desirable to include the facility requirements in the model.

5.2.1 Steel processing/building area

The steel processing and building area used is heavily linked to the blocks, and especially the plates, within the ship. Unfortunately, this information is not available in the early proposal stage. Therefor, a ship wide estimate needs to be developed.

A value that is known is the "bare ship weight" of the ship. This is the weight of the steel inside of the ship. Taking the weight of a plate can give an estimate of how many plates are inside of the ship. Even though not all ships use similar plates, the estimate is fairly consistent between different ships in the used database.

Now that an estimate of the number of plates can be given inside of the ship an estimate needs to be made as to how long the plates will be present on the steel processing area. Historical data shows that this will be less than one month. Unfortunately this is an average value and certain blocks, especially the blocks that hold the engine, take longer. The model will be used to check the capacity, so for the model one month per plate will be used. This causes a slight exaggeration of the area needed.

Using the fact that each plate will be taking up space on the floor for around a month and having devised a method to calculate the number of plates, the total area can be calculated if all plates would be processed during the same month. This number can then be distributed using the distribution also used for the steel processing activity, $D^{SP}_{i,t}$.

$$TSPA_i = ap * (w_i/p) \qquad \forall i \in I$$
$$SPA_{i,t} = TSPA_i * D^{SP}_{i,t} \qquad \forall i \in I \wedge t \in T$$

With:

- $TSPA_i$ = total steel processing area needed for ship i in m^2
- $SPA_{i,t}$ = steel processing area needed for ship i at month t in m^2
- $D^{SP}_{i,t}$ = percentage of the total hours of the steel processing activity activity of ship i that happens at month t.
- w_i = The total "bare ship weight" of ship i. This is the weight of just the ship itself, so without any provisions.
- ap = area of an average plate
- p = weight of an average plate

5.2.2 Building frames

Due to the lack of available data of the ship the building frames will have to be roughly estimated. This is done by multiplying the amount of blocks in a ship by the average duration that a block needs to reside on a building frame.

$$TBF_i = nb_i * drb^{SB}_i \qquad \forall i \in I$$
$$Bf_{i,t} = TBF_i * D^{SB}_{i,t} \qquad \forall i \in I \wedge t \in T$$

With:

- TBF_t = total building frame months needed for block i
- $BF_{i,t}$ = total building frame needed for block i at time t
- nb_i = an estimate of the number of blocks in ship i
- drb^{Bf}_i = the amount of months a block of ship i needs to reside on a building frame of ship i
- $D^{SB}_{i,t}$ = Percentage of the total hours of steel building of ship i that happens at month t.

5.2.3 Hull assembly area

The hull assembly area is the area where, as the name suggests, the hull of the ship is assembled. Furthermore, the outfitting activity is performed here. The most bottom blocks of the ship fill this area. However, in this early phase the blocks are not currently known. So it is necessary to once again create a rough estimation.

The distribution of the hull assembly does not follow any of the activity distributions. This is due to the fact that the hull assembly area strictly increases. The more blocks that finish painting & blasting, the more filled the hull assembly area gets. This means that again regression analysis has to be performed using historical data that shows the hull assembly area for past projects. The methods used are described in Chapter 5.1.2. However, in this case the beta distribution will have to be cumulative. During months where no hull assembly takes place $D_{i,t}^{HA} = 0$.

If the polynomial function is used:
$D_{i,t}^{HA} = \beta^{HA,0} + \beta^{HA,1} * t + \beta^{HA,2} * t^2 + \beta^{HA,3} * t^3 + \beta^{HA,4} * t^4$

If the beta distribution is used:
$D_{i,t}^{Activity} = P^{Activity}(X \leq \frac{t - st_i^{Activity}}{dr_i^{Activity}})$

The following formulation is used in order to calculate the hull assembly area required each month. As seen, the hull assembly distribution mentioned above is utilized.

$$TA_i = TL_i * TW_i \qquad \forall i \in I$$
$$HA_{i,t} = TA_i * D_{i,t}^{HA} \qquad \forall i \in I \wedge t \in T$$

With:

- TA_i = total area of ship i in m^2
- TL_i = total length of ship i in m
- TW_i = total width of ship i in m
- $HA_{i,t}$ = required hull assembly area for ship i at time t in m^2
- $D_{i,t}^{HA}$ = distribution of the hull assembly area. This will slowly become 1, meaning 100% of the total area of the ship is in the hull assembly area. If outfitting is finished and the ship is launched this number will become 0 again.

5.2.4 Launching and Quay area

Launching area is used immediately after the outfitting activity is finished. Quay area is used for a determined time, often in order to test systems or train personnel. This means that the total area of the ship fill these areas, which is the same TA as used for the hull assembly area. The launching and quay areas can either be used or not. This means that the distribution will be a binary value, either 0 or 1.

$$TA_i = TL_i * TW_i \qquad \forall i \in I$$
$$LA_{i,t} = TA_i * d_{i,t}^{L} \qquad \forall i \in I \wedge t \in T$$
$$QA_{i,t} = TA_i * d_{i,t}^{Q} \qquad \forall i \in I \wedge t \in T$$

With:

- TA_i = total area of ship i in m^2
- TL_i = total length of ship i in m
- TW_i = total width of ship i in m
- $LA_{i,t}$ = required launching area for ship i at time t in m^2
- $QA_{i,t}$ = required quay area for ship i at time t in m^2
- $d^L_{i,t}$ = a binary value determining whether or not the launching area will (1) or will not (0) be used for ship i at time t
- $d^Q_{i,t}$ = a binary value determining whether or not the quay area will (1) or will not (0) be used for ship i at time t

5.2.5 Painting and blasting hall

In the early proposal phase almost no information about blocks is known. Because painting and blasting is such a block dependant activity, it is fairly difficult to meaningfully predict the required area needed. Even so, it is possible to estimate the amount of blocks that will be required. This can be done by looking at the size of the ship. Furthermore, it is possible to estimate the size of the largest block. Because the painting & blasting activity will always take 1 month regardless of the size of the block or type of the ship (due to factors like drying times) a maximum required area can be estimated.

It is important to note that using this method, it must be assumed that during all months of the painting & blasting activity there must be space for at least one block in the hall. In order to account for that, it must be assured that the minimum area required each month should be the same as the largest block in the ship.

$$PBA_{i,t} \geq nb_i/dr^{PB}_i * Abb_i * d^{PB}_{i,t} \qquad \forall i \in I \wedge t \in T$$
$$PBA_{i,t} \geq Abb_i * d^{PB}_{i,t} \qquad \forall i \in I \wedge t \in T$$

With:

- $PBA_{i,t}$ = area of painting & blasting hall needed for ship i at time t in m^2
- nb_i = an estimate of the number of blocks in ship i
- dr^{PB}_i = duration of the painting & blasting activity of ship i in months
- Abb_i = the area of the largest block in ship i in m^2
- $d^{PB}_{i,t}$ = binary variable indicating whether the painting & blasting activity occurs for ship i at time t. If painting & blasting work is done during that time the value will be 1, otherwise it will be 0.

5.2.6 Employee facilities

Employees working on the yard also need certain facilities in order to perform their jobs. These facilities include offices, changing rooms and lunch areas. In Chapter 5.1 the required labour hours are calculated. Each type of employee requires a different amount of area in each of these categories. After analysis of the shipbuilding process there are three major employee facility areas that take up the most space on the yard.

- Washing and changing rooms. Each employee needs a place where they can wash and change.
- Canteen areas. Each employee needs to have an area where they can consume their lunch.
- Offices. Some employees, most often the foremen of the activities, require office space.

These requirements will be calculated using the following formulations.

$$WCA_{i,t} = \sum_{a \in A} RWCA^a * H^a_{i,t}/FTE \qquad \forall i \in I \wedge t \in T$$
$$CA_{i,t} = \sum_{a \in A} RCA^a * H^a_{i,t}/FTE \qquad \forall i \in I \wedge t \in T$$
$$OA_{i,t} = \sum_{a \in A} ROA^a * H^a_{i,t}/FTE \qquad \forall i \in I \wedge t \in T$$

With:

- $WCA_{i,t}$ = washing and changing area needed for ship i at time t in m^2
- $CA_{i,t}$ = canteen area needed for ship i at time t in m^2
- $OA_{i,t}$ = office area needed for ship i at time t in m^2
- $RWCA_a$ = the required washing and changing room area for one employee of activity a
- RCA_a = the required canteen area for one employee of activity a
- ROA_a = the required office area for one employee of activity a
- $H^{Activity}_{i,t}$ = required hours to complete an activity for ship i at time t in hours
- FTE = number of hours each Full Time Employee works per month, often 150 hours

5.2.7 Steel cutting and piping fabrication

Steel plates and pipe spools are getting processed by machines on the yard. Expanding the amount of available machines will increase the amount of plates and pipes that can be processed. A yard will often know how much steel weight and how many spools they can process with their machines in a month.

$$SC_{i,t} = w_i * D^{SP}_{i,t} \qquad \forall i \in I \wedge t \in T$$
$$PP_{i,t} = s_i * D^{PF}_{i,t} \qquad \forall i \in I \wedge t \in T$$

With:

- $SC_{i,t}$ = the amount of steel that needs to be cut for ship i at month t in tons
- $PP_{i,t}$ = the amount of piping that needs to be fabricated for ship i at month t in amount of pipe spools
- w_i = the total "bare ship weight" (weight of the steel) of ship i
- s_i = the total amount of pipe spools in ship i
- $D^{SP}_{i,t}$ = percentage of the total hours of steel processing of ship i that happens at month t.
- $D^{PF}_{i,t}$ = percentage of the total hours of piping fabrication of ship i that happens at month t.

5.2.8 Warehouse storage

The warehouse storage gets used for many items necessary for the outfitting activity. These could be either inventory items that need to be installed on the ship, or tools and inventory required to install those items. In the proposal phase there is no clear view of what items are necessary and when they are needed. The only available information is the estimation of the outfitting weight. Therefor this number will be used.

The first value that should be calculated is a factor transforming weight to area (wta). This value states on average how much 1 m^2 of inventory weights. This is based upon historic data. Firstly, historic data on the required items on the ship is needed, then the weight and area of those items need to be taken.

Secondly, the total required warehousing area during the project needs to be distributed over the project duration. This can be done using historic data about the usage of the items. Combining this with the required warehousing area for those items and the distribution of warehousing area can be calculated.

If historic data on the usage of items is unavailable, the distribution of warehousing hours ($D_{i,t}^{W}$) can also be used. Using the average time an item remains in inventory, an estimation can be made when the most inventory was present. This distribution can be used if the assumption is made that with more inventory and therefor more used area comes more required working hours. This assumption seems logical when comparing the distribution $D_{i,t}^{WA}$ and $D_{i,t}^{W}$ with the used data sets.

$TWA_i = ow_i * wta * T_i^W \qquad \forall i \in I$
Either:
$WA_{i,t} = TWA_i * D_{i,t}^{WA} \qquad \forall i \in I \wedge t \in T$
Or:
$WA_{i,t} = TWA_i * D_{i,t}^{W} \qquad \forall i \in I \wedge t \in T$
Dependant on the available historic data
With:

- TWA_i = the total warehousing area needed for ship i in m^2
- $WA_{i,t}$ = the warehousing area needed for ship i at time t in m^2 ship i at month t in amount of pipe spools
- ow_i = the total outfitting weight of the outfitting items in ship i
- T_i^w = the average time an item for ship i remains in the warehouse
- wta = the conversion factor of weight to area ($\frac{m^2}{tons}$)
- $D_{i,t}^{W}$ = percentage of the total warehousing area required for ship i that is stored during month t
- $D_{i,t}^{W}$ = percentage of the total hours of warehousing of ship i that happens at month t

5.2.9 Steel storage

In order for the steel processing activity to start, steel plates will have to be ordered and delivered. Without any steel plates in the inventory, steel processing cannot be done. Steel plates are often stored on a pile on the ground, as they are too heavy to be put on shelves. Often each different plate type has their own pile. This is because if there are multiple plate types on the same pile, and a particular plate is needed, other plates will need to be lifted. This can cause quite a problem, as lifting the plates is time consuming.

In order to estimate the number of piles necessary historic data can be consulted. The ship types discussed can be used to approximate the number of piles necessary for a new ship. Otherwise experts need to estimate this number. The size of each pile is often consistent across yards, so this number will be fixed.

This number will be a maximum area required, as it assumes that all plate types are necessary when the steel processing activity occurs.

Additionally, it is important to realise that for certain often used plate types the floor should be reinforced. This is due to the fact that a stack of a lot of plates can often be quite heavy, which would damage the ground considerably without reinforcement. Lastly, some plates cannot be stored next to other plates, as the materials would become damaged. These factors should be taken into consideration in the planning, but are not added to the ship level model.

$$SSA_{i,t} = npt_i * pa * d_{i,t}^{SSA} \qquad \forall i \in I \wedge t \in T$$

With:

- $SSA_{i,t}$ = the amount area needed to store steel plates of ship i at time t in m^2
- npt_i = the number of steel plate types in ship i
- pa = average area required to store one pile of plates in m^2
- $d_{i,t}^{SSA}$ = binary value determining whether or not plates need to be stored during those months. A 1 means plate storage is necessary, a 0 means no plates are stored. When $D_{i,t}^{SP} \geq 0$ than $d_{i,t}^{SSA} = 1$

5.3 Creation of the whole ship level model

In the previous sections the requirements have been calculated on a monthly basis. This means that if the capacity will remain constant, and no flexibility in the requirements is allowed, the adequacy of the capacities can be determined. If the requirements exceed the capacity, the ships cannot be constructed on that yard.

However, setting the capacity as a hard requirement might not be very realistic. If the capacity is reached DSNS might choose to enlarge the capacity or outsource certain aspects of the activity. This is often done by hiring more personnel or expanding the current yard facilities. It will be assumed that the possible expansions will be known beforehand. This variable is $ECap_t^{Activity}$ in the model.

Extra capacity can not only be added for activity hour requirements, but also facility requirements. For example, if the steel processing area is not sufficient enough the steel processing activity can either be outsourced, or more area can be added. This means that $ECap_t^{Facility}$ should also be added to the model.

Furthermore, some aspects of the shipbuilding process can also be outsourced. These tasks no longer require capacity on the yard, but will instead be performed by third parties. This is represented by the $O_t^{Activity}$ variable. This variable symbolizes the total amount of hours that is outsourced for a particular activity. Outsourcing is always done on an activity basis. However, if a particular activity is outsourced it could reduce the requirements for facilities that are associated with that activity.

Another option to ensure that the capacity will not be exceeded is altering the requirements. It might be possible for DSNS to alter the schedule slightly in order to distribute the requirements better over the given months. It should be noted that the total requirement should stay the same. This is captured in the extra flexibility $EP_{i,t}^{Activity}$ variable.

This new variable $EP_{i.t}^{Activity}$ allows the model to increase the requirements one month by lowering the requirements in other months. In order to do this, the variable needs to be bounded. When no flexibility is allowed, $EP_{i,t}^{Activity} = 1$. If the maximum amount of flexibility that is allowed is 10%, than $0.9 \leq EP_{i,t}^{a} \leq 1.1$. In general if fl is the allowed flexibility in percentages, than $(1 - fl) \leq EP_{i,t}^{a} \leq (1 + fl)$.

It is important that when the added flexibility is used, the total requirements necessary do not decrease or increase. Otherwise the added flexibility can be used to just lower all the requirements, like setting $EP_{i,t}^{Activity} = 0.9$ for all months if the maximum flexibility allowed is 10%. This means that the sum of the requirements in all months should once again sum to the total requirements, shown in the formulation below.

$$\sum_{t \in T} H_{i,t}^{a} * EP_{i,t}^{a} = TH_{i}^{a} \qquad \forall a \in A \wedge i \in I$$

As mentioned in Chapter 3, some activities are related to specific facilities. When flexibility is added to those activities, or parts of the activity are outsourced. The assumption will be made that if 10% more hours of a certain activity is required, this means that 10% increase in facilities, like area, is also required. An example of this is the required steel processing area. If due to the added flexibility 10% more steel processing is done during month t for particular ship, than this ship will also require 10% more steel processing area during that month. Therefor $SPA_{i,t}$ will be multiplied by $EP_{i,t}^{SP}$.

The same logic follows for outsourcing. If during a particular month 10% of the steel processing activity is outsourced, this will in general also mean that the steel processing area requirement will be reduced by 10%. However, the outsourcing is not done on a percentage basis, but on a total hour basis. This means that the total hours outsourced should be translated into a percentage outsourced. This is done using $\frac{O_t^{SP}}{\sum_{i \in I} H_{i,t}^{SP} * EP_{i,t}^{SP}}$. This will be the percentage of steel processing that is outsourced during month t. If this is subtracted from 1, the percentage of the total remaining requirements is calculated.

Not all facility requirements can be reduced using added flexibility and outsourcing. For example, the required hull assembly, launching and quay area will always be equal to the total ship size. Even if parts are outsourced, in the end the ship must be completely assembled and the completed ship will be launched. Furthermore, if even a part of the steel processing activity occurs on the yard, steel plates will be necessary. Because only ship level input is used, it is currently not known how many plate types are still required. Therefor, it is assumed that even if parts of the steel processing activity are outsourced, the required steel plate piles, and therefor the required steel storage area, do not decrease.

Activity working hours requirements

$$\sum_{i \in I} H_{i,t}^{a} * EP_{i,t}^{a} \leq Cap_{t}^{a} + ECap_{t}^{a} + O_{t}^{a} \qquad \forall t \in T \wedge a \in A$$
$$\sum_{t \in T} H_{i,t}^{a} * EP_{i,t}^{a} = TH_{i}^{a} \qquad \forall a \in A \wedge i \in I$$

Facility requirements

$(1 - \frac{O_t^{SP}}{\sum_{i \in I} H_{i,t}^{SP} * EP_{i,t}^{SP}}) * \sum_{i \in I} SPA_{i,t} * EP_{i,t}^{SP} \leq Cap_t^{SPA} + ECap_t^{SPA}$ $\forall t \in T$

$(1 - \frac{O_t^{SB}}{\sum_{i \in I} H_{i,t}^{SB} * EP_{i,t}^{SB}}) * \sum_{i \in I} BF_{i,t} * EP_{i,t}^{SB} \leq Cap_t^{BF} + ECap_t^{BF}$ $\forall t \in T$

$\sum_{i \in I} HA_{i,t} \leq Cap_t^{HA} + ECap_t^{HA}$ $\forall t \in T$

$\sum_{i \in I} LA_{i,t} \leq Cap_t^{LA} + ECap_t^{LA}$ $\forall t \in T$

$\sum_{i \in I} QA_{i,t} \leq Cap_t^{QA} + ECap_t^{QA}$ $\forall t \in T$

$(1 - \frac{O_t^{PB}}{\sum_{i \in I} H_{i,t}^{PB} * EP_{i,t}^{PB}}) * \sum_{i \in I} PBA_{i,t} * EP_{i,t}^{PB} \leq Cap_t^{PBA} + ECap_t^{PBA}$ $\forall t \in T$

$(1 - \frac{O_t^{SP}}{\sum_{i \in I} H_{i,t}^{SP} * EP_{i,t}^{SP}}) * \sum_{i \in I} SC_{i,t} * EP_{i,t}^{SC} \leq Cap_t^{SC} + ECap_t^{SC}$ $\forall t \in T$

$(1 - \frac{O_t^{PF}}{\sum_{i \in I} H_{i,t}^{PF} * EP_{i,t}^{PF}}) * \sum_{i \in I} PP_{i,t} * EP_{i,t}^{PF} \leq Cap_t^{PP} + ECap_t^{PP}$ $\forall t \in T$

$(1 - \frac{O_t^{W}}{\sum_{i \in I} H_{i,t}^{W} * EP_{i,t}^{W}}) * \sum_{i \in I} WA_{i,t} * EP_{i,t}^{W} \leq Cap_t^{WA} + ECap_t^{WA}$ $\forall t \in T$

$\sum_{i \in I} SSAi, t \leq Cap_t^{SSA} + ECap_t^{SSA}$ $\forall t \in T$

5.4 The final whole ship level model

Below the linear programming model using only whole ship level input is given. This model is created using the formulations discussed in previous sections. The appropriate variables are shown in Appendix A.

Objective function
$min \sum_{t \in T} \sum_{a \in A} O_t^a * c^a + ECap_t^a * ec^a + \sum_{f \in F} ECap_t^f * ec^f$

Subject to:
Activity working hours requirements
$\sum_{i \in I} H_{i,t}^{SP} * EP_t^{SP} \leq Cap_t^{SP} + ECap_t^{SP} + O_t^{SP}$ $\forall t \in T$
$\sum_{i \in I} H_{i,t}^{SB} * EP_t^{SB} \leq Cap_t^{SB} + ECap_t^{SB} + O_t^{SB}$ $\forall t \in T$
$\sum_{i \in I} H_{i,t}^{O} * EP_t^{O} \leq Cap_t^{O} + ECap_t^{O} + O_t^{O}$ $\forall t \in T$
$\sum_{i \in I} H_{i,t}^{PF} * EP_t^{PF} \leq Cap_t^{PF} + ECap_t^{PF} + O_t^{PF}$ $\forall t \in T$
$\sum_{i \in I} H_{i,t}^{PI} * EP_t^{PI} \leq Cap_t^{PI} + ECap_t^{PI} + O_t^{PI}$ $\forall t \in T$
$\sum_{i \in I} H_{i,t}^{PB} * EP_t^{PB} \leq Cap_t^{PB} + ECap_t^{PB} + O_t^{PB}$ $\forall t \in T$
$\sum_{i \in I} H_{i,t}^{W} * EP_t^{W} \leq Cap_t^{W} + ECap_t^{W} + O_t^{W}$ $\forall t \in T$
$\sum_{i \in I} H_{i,t}^{QC} * EP_t^{QC} \leq Cap_t^{QC} + ECap_t^{QC} + O_t^{QC}$ $\forall t \in T$

$\sum_{i \in I} H_{i,t}^{PD} * EP_t^{PD} \leq Cap_t^{PD} + ECap_t^{PD} + O_t^{PD}$ $\forall t \in T$
$\sum_{i \in I} H_{i,t}^{STW} * EP_t^{STW} \leq Cap_t^{STW} + ECap_t^{STW} + O_t^{STW}$ $\forall t \in T$

$\sum_{t \in T} H_{i,t}^a * EP_t^a = TH_i^a$ $\forall i \in I \wedge a \in A$

Facility requirements
$(1 - \frac{O_t^{SP}}{\sum_{i \in I} H_{i,t}^{SP} * EP_{i,t}^{SP}}) * \sum_{i \in I} SPA_{i,t} * EP_{i,t}^{SP} \leq Cap_t^{SPA} + ECap_t^{SPA}$ $\forall t \in T$
$(1 - \frac{O_t^{SB}}{\sum_{i \in I} H_{i,t}^{SB} * EP_{i,t}^{SB}}) * \sum_{i \in I} BF_{i,t} * EP_{i,t}^{SB} \leq Cap_t^{BF} + ECap_t^{BF}$ $\forall t \in T$
$\sum_{i \in I} HA_{i,t} \leq Cap_t^{HA} + ECap_t^{HA}$ $\forall t \in T$
$\sum_{i \in I} LA_{i,t} \leq Cap_t^{LA} + ECap_t^{LA}$ $\forall t \in T$
$\sum_{i \in I} QA_{i,t} \leq Cap_t^{QA} + ECap_t^{QA}$ $\forall t \in T$
$(1 - \frac{O_t^{PB}}{\sum_{i \in I} H_{i,t}^{PB} * EP_{i,t}^{PB}}) * \sum_{i \in I} PBA_{i,t} * EP_{i,t}^{PB} \leq Cap_t^{PBA} + ECap_t^{PBA}$ $\forall t \in T$
$(1 - \frac{O_t^{SP}}{\sum_{i \in I} H_{i,t}^{SP} * EP_{i,t}^{SP}}) * \sum_{i \in I} SC_{i,t} * EP_{i,t}^{SC} \leq Cap_t^{SC} + ECap_t^{SC}$ $\forall t \in T$
$(1 - \frac{O_t^{PF}}{\sum_{i \in I} H_{i,t}^{PF} * EP_{i,t}^{PF}}) * \sum_{i \in I} PP_{i,t} * EP_{i,t}^{PF} \leq Cap_t^{PP} + ECap_t^{PP}$ $\forall t \in T$
$(1 - \frac{O_t^{W}}{\sum_{i \in I} H_{i,t}^{W} * EP_{i,t}^{W}}) * \sum_{i \in I} WA_{i,t} * EP_{i,t}^{W} \leq Cap_t^{WA} + ECap_t^{WA}$ $\forall t \in T$
$\sum_{i \in I} SSAi,t \leq Cap_t^{SSA} + ECap_t^{SSA}$ $\forall t \in T$

And:
$(1 - fl) \leq EP_{i,t}^a \leq (1 + fl)$ $\forall a \in A \wedge t \in T \wedge i \in I$
$ECap_t^a \geq 0$ $\forall a \in A \wedge t \in T$
$ECap_t^f \geq 0$ $\forall f \in F \wedge t \in T$
$O_t^a \geq 0$ $\forall a \in A \wedge t \in T$

Labour hours calculations
Total hour calculations
$TH_i^{SP} = w_i * \lambda_i^{SP}$ $\forall i \in I$
$TH_i^{SB} = w_i * \lambda_i^{SB}$ $\forall i \in I$
$TH_i^{O} = ow_i * \lambda_i^{O}$ $\forall i \in I$
$TH_i^{PF} = s_i * \lambda_i^{PF}$ $\forall i \in I$
$TH_i^{PI} = s_i * \lambda_i^{PI}$ $\forall i \in I$
$TH_i^{PB} = nr_i * FTE * 3$ $\forall i \in I$
$TH_i^{W} = ow_i * \lambda_i^{W}$ $\forall i \in I$

Distribution of the hours
If the polynomial function is used:
$D_{i,t}^a = \beta^{a,0} + \beta^{a,1} * t + \beta^{a,2} * t^2 + \beta^{a,2} * t^2 + \beta^{a,3} * t^3 + \beta^{a,4} * t^4$ $\forall i \in I \wedge t \in T \wedge a \in A$

If the beta distribution is used:
$H^{Activity}(t) = (P(X \leq (\frac{t+1-st_i^{Activity}}{dr_i^{Activity}})) - P(X \leq (\frac{t-st_i^{Activity}}{dr_i^{Activity}}))) * TH^{Activity}$

The resulting formulation will become:

$H^a_{i,t} = TH^a_i * D^a_{i,t} \qquad \forall i \in I \wedge t \in T \wedge a \in A$

Facility requirements calculations

Steel processing area

$TSPA_i = ap * (w_i/p) \qquad \forall i \in I$
$SPA_{i,t} = TSPA_i * D^{SP}_{i,t} \qquad \forall i \in I \wedge t \in T$

Building frames

$TBf_i = nb_i * drb^{Bf}_i \qquad \forall i \in I$
$Bf_{i,t} = TBf_i * D^{SB}_{i,t} \qquad \forall i \in I \wedge t \in T$

Hull assembly area

If the polynomial function is used:
$D^{HA}_{i,t} = \beta^{HA,0} + \beta^{HA,1} * t + \beta^{HA,2} * t^2 + \beta^{HA,3} * t^3 + \beta^{HA,4} * t^4$
If the beta distribution is used:
$D^{Activity}_{i,t} = P^{Activity}(X \leq t)$
$TA_i = TL_i * TW_i \qquad \forall i \in I$
$HA_{i,t} = TA_i * D^{HA}_{i,t} \qquad \forall i \in I \wedge t \in T$

Launching and Quay area

$TA_i = TL_i * TW_i \qquad \forall i \in I$
$LA_{i,t} = TA_i * d^L_{i,t} \qquad \forall i \in I \wedge t \in T$
$QA_{i,t} = TA_i * d^Q_{i,t} \qquad \forall i \in I \wedge t \in T$

Painting and blasting hall

$PBA_{i,t} \geq nb_i/dr^{PB}_i * Abb_i * d^{PB}_{i,t} \qquad \forall i \in I \wedge t \in T$
$PBA_{i,t} \geq Abb_i * d^{PB}_{i,t} \qquad \forall i \in I \wedge t \in T$

Employee facilities

$WCA_{i,t} = \sum_{a \in A} RWCA^a * H^a_{i,t}/FTE \qquad \forall i \in I \wedge t \in T$
$CA_{i,t} = \sum_{a \in A} RCA^a * H^a_{i,t}/FTE \qquad \forall i \in I \wedge t \in T$
$OA_{i,t} = \sum_{a \in A} ROA^a * H^a_{i,t}/FTE \qquad \forall i \in I \wedge t \in T$

Steel cutting and piping fabrication

$SC_{i,t} = w_i * D^{SP}_{i,t} \qquad \forall i \in I \wedge t \in T$
$PP_{i,t} = s_i * D^{PF}_{i,t} \qquad \forall i \in I \wedge t \in T$

Warehouse storage

$TWA_i = ow_i * wta * T^W_i \qquad \forall i \in I$
$WA_{i,t} = TWA_i * D^W_{i,t} \qquad \forall i \in I \wedge t \in T$

Steel storage

$SSA_{i,t} = npt_i * pa * d^{SSA}_{i,t} \qquad \forall i \in I \wedge t \in T$

6 Model on block detail level

In later stages of the proposal phase more details will be known about the project. In this case a more detailed model can be created. This chapter concerns the creation of this more detailed model.

As discussed earlier in the shipbuilding process the ship can be subdivided into smaller parts called blocks. The more detailed model will use this subdivision to have a better understanding of the requirements of the shipbuilding process.

The requirements for the project will be calculated on a monthly basis. Afterwards, these requirements will be compared to the capacity during that month in order to check whether or not the capacity is adequate for the construction of all the ships in the project.

As discussed earlier the shipbuilding process consists of ten main activities. However, some activities are performed on a block level and some on a whole ship level. The activities that are performed on a whole ship level will be calculated using the same method as the whole ship model. New formulations will be made for the block level activities.

The activities that will be calculated on a whole ship level will be discussed below. Furthermore, a short explanation will be given as to why a block level analysis will not be performed for these activities. The requirement formulations for these activities can be found in Chapter 5.

- Piping fabrication and piping installation. This is due to many uncertainties in the proposal phase about how certain pipes will be installed into the ship. These pipes often stretch multiple blocks and it will be difficult to assign certain pipes to certain blocks, as this is currently not done in the proposal phase. Pipes are often seen on a system level, like oxygen, fuel or waste, rather than on a block level.
- Warehousing. Although it is possible to assign items to particular blocks, there are a lot of unknowns in the proposal phase about where items are situated. Furthermore, it will be difficult to know in such an early stage when items will arrive. Therefor, a block level analysis of the warehousing activity will not be performed. However, the warehousing facilities will be done on a block level.
- Quality control. The quality control will be done over the entire shipbuilding process. It is difficult in such an early phase to assign this activity to particular blocks.
- Project department. The project department will mostly concern itself to managing the entire shipbuilding process during the ship construction. This means that relating it to particular blocks will not be possible.
- Set to work. This activity concerns mostly testing the entire ship and teaching the future crew all the functionalities. Relating this activity to particular blocks will therefor not be possible.

A block level model will be constructed for the following activities. This is due to the fact that these four activities can all be related to blocks.

- Steel processing. Each plate that is processed during this activity belongs in exactly one block. This means that all the hours associated to this plate can be directly linked to a block.
- Steel building. The block is constructed in the steel building activity. Therefor, all labour incurred in this activity can be directly linked to a particular block.

- Outfitting. This activity is performed inside of the block. For example, all furniture that will be installed are associated with a particular block.
- Painting & blasting. This activity is also done on a block by block basis. Each time a block finishes steel building it is transported into the painting & blasting hall. This means all work done relates to a particular block.

The required indices and sets used for block level calculations have been expanded in comparison to the whole ship model. These additions are mentioned below.

- k = a particular block
- K = all block in the project
- K_i = all blocks in ship i
- l = a particular plate type
- L = all plates types in the project
- L_k = all plates types in block k
- m = a particular item type
- M = all item types used in the project
- M_k = all item types in block k
- A^* = all whole ship level activities
- $A^{'}$ = all block level activities

It can be seen that the indices for plates and items are based on their types. A plate type is a particular type of plate used, separate from a different plate type. Aspects that differentiate a plate type from another plate type are the length, width, thickness and material of the plate. A particular plate type can be used in multiple blocks. The number of plates of type l in block k is given by the variable $n_{k,l}$.

As mentioned, items indices are also based on their types. An item type could be a particular chair used in the ship. The same item type can be present in multiple different blocks. The amount of items of type m in a particular block k is notified with $ni_{k,m}$.

6.1 Calculating the staff requirements

First, the staff requirements need to be calculated. This is done via the usage of the same ten activities discussed before. The method used will be similar to the whole ship detail level, however will now be applied to the individual blocks of a ship. Furthermore, the distribution is based on the block fabrication plan. This means that for the block level activities the beta distributions will not be utilized.

As mentioned earlier for the six activities that will be calculated on a whole ship level, no changes are made in comparison to the whole ship model. Their formulations can be found in Chapter 5.

6.1.1 Steel processing

The first activity that will utilize block level input is steel processing. Steel processing is dependant on the steel plates that make up the total block. Two methods will be proposed to calculate the required steel processing hours per block. The first method will be less accurate, but requires fewer input details. The second method will require precise information about the steel plates used.

Both methods are similar, however the second method uses specific plates types, and is therefor likely more accurate. The first method uses information about the average plate in a block. These averages are dependant on the block type. It could for instance be that plates used in bottom blocks are larger than plates in middle blocks.

The first part of the total steel processing hour requirement formulation is the constant set-up time. The set-up time is required for each plate. It includes fixed times like the transport of the plate, which are independant on the size of the plate.

The second part of the formulations are the variable times. These times are dependant on the size of the plate. These hours include the actual cutting, drilling and bending of the steel plates.

First method

$$TH_{i,k}^{SP} = np_k * c_k^{SP} + np_k * v_k * y_k^{SP} \qquad \forall i \in I \land k \in K_i$$

Second method

$$TH_{i,k}^{SP} = \sum_{l \in L_k} n_{k,l} * c_l^{SP} + n_{k,l} * v_l * y_l^{SP} \qquad \forall i \in I \land k \in K_i$$

Distributing the hours

$$H_{i,t}^{SP} = \sum_{k \in K_i} \frac{TH_{i,t,k}^{SP}}{dr_k^{SP}} * x_{t,k}^{SP} \qquad \forall i \in I \land t \in T$$

With:

- $TH_{i,k}^{SP}$ = the total required hours to finish steel processing for block k in ship i
- $H_{i,t}^{SP}$ = the required steel processing hours for ship i during month t
- c_k^{SP} = the average required setup time for steel processing of a plate in block k
- c_l^{SP} = the required setup time for steel processing of plate type l
- dr_k^{SP} = the duration of the steel processing activity for block k
- $x_{t,k}^{SP}$ = binary variable indicating whether steel processing on block k takes place at time t
- np_k = the number of plates of any type in block k
- $n_{k,l}$ = the number of plates of type l in block k
- v_k = the average volume of a plate in block k in m^3
- v_l = the volume of plate type l in m^3
- y_k^{SP} = the required hours to process one m^3 of plates in block k
- y_l^{SP} = the required hours to process one m^3 of plate l

6.1.2 Steel building

The steel building activity is the second activity that is block dependant. This activity consists of two major stages. First, the block gets constructed from the plates. Secondly, the block is assembled to the rest of the blocks (if any previous blocks are present in the hull assembly area).

The required block construction hours required are split into two parts, the constant set-up times and the variable construction times. The constant set-up time for a block is independent on the type of block. Tasks that take up set-up time are planning, transport and cleaning times. The variable times are caused by tasks like welding the plates together. The more plates that need to be welded, the more block construction hours are required.

The second part of ship building is hull construction. Hull construction includes the welding time of a block to another block. It only occurs in the months were hull assembly occurs for a particular block.

$$TH_{i,k}^{SB,BC} = c_k^{SB} + n_k * y_k^{BC} \qquad \forall i \in I \wedge k \in K_i$$
$$H_{i,t}^{SB} = \sum_{k \in K_i} \frac{TH_{i,t,k}^{SB,BC}}{dr_{i,k}^{BC}} * x_{t,k}^{BC} + y_k^{HA} * x_{t,k}^{HA} \qquad \forall i \in I \wedge t \in T$$

With:

- $TH_{i,k}^{SB,BC}$ = the total required hours to finish block construction tasks of the steel building activity for block k in ship i
- $H_{i,t}^{SB}$ = the required steel building hours for ship i during month t
- n_k = the number of plates in block k
- y_k^{BC} = the welding time to weld a new plate to block k
- y_k^{HA} = the welding time to weld block k to the hull
- c_k^{SB} = the required setup time for steel building of block k
- dr_k^{BC} = the duration of the block construction tasks in the steel building activity for block k
- $x_{t,k}^{BC}$ = binary variable indicating whether block construction on block k takes place at time t
- $x_{t,k}^{HA}$ = binary variable indicating whether hull assembly on block k takes place at time t

6.1.3 Outfitting

The third activity where the hours will be calculated on a block basis is outfitting. Outfitting concerns itself with the installation of items in the ship. These items are all associated with the block they will be installed in.

This thesis proposes two methods of calculating the total required outfitting hours. The first method requires the least amount of data. This method requires the total volume of items that are to be installed. This is multiplied by the average time it takes to install one m^3 of items.

The second method requires more detailed input. It uses the precise items that are to be installed in the block. This information will only be available very late in the proposal phase, therefor the first method will be necessary in case this information remains unavailable. Instead of averaging the required hours over each item, each item type will be looked at individually. This will average out to the first method, as large items often require more time to install than smaller items.

As seen in the formulations, the required hours consist of two parts, the constant set-up times and the variable times. The constant set-up time symbolizes the constant time necessary for each block in order to perform outfitting, like the hours required for planning or cleaning. These constant times will be shorter than the variable times in the outfitting activity.

The variable part consist of tasks concerning the installation of items. This means the more items that need to be installed, the more time that is required.

First method

$$TH^O_{i,k} = c^O_k + ov_k * y^O_k \qquad \forall i \in I \wedge k \in K_i$$

Second method

$$TH^O_{i,k} = c^O_k + \sum_{m \in M_k} tii_m * ni_{k,m} \qquad \forall i \in I \wedge k \in K_i$$

$$H^O_{i,t} = \sum_{k \in K_i} \frac{TH^O_{i,t,k}}{d^O_{i,k}} * x^O_{t,k} \qquad \forall i \in I \wedge t \in T$$

With:

- $TH^O_{i,k}$ = the total required hours to finish outfitting for block k in ship i
- $H^O_{i,t}$ = the required outfitting hours for ship i during month t
- ov_k = the outfitting volume of block k in m^3
- tii_m = time to install one item of type m in hours
- $ni_{k,m}$ = number of items of type m in block k
- y^O_k = the hours required to outfit one m^3 of items, dependant on the block type of block k
- c^O_k = the required setup time for outfitting of block k
- d^O_k = the duration of the outfitting activity for block k
- x^O_k = binary variable indicating whether outfitting on block k takes place at time t

6.1.4 Painting & Blasting

Painting & Blasting is always done on a total block level. When painting and blasting is being performed for one part of the block, it will be performed on the entire block. Furthermore, due to certain constant times, like the time to let the paint dry, each block will take one month to finish the activity.

$$H^{PB}_{i,t} = \sum_{k \in K_i} x^O_{t,k} * hpb \qquad \forall i \in I \wedge t \in T$$

With:

- $H^{PB}_{i,t}$ = the required painting and blasting hours for ship i during month t
- hpb = the hours to paint and blast one block

- x_k^{PB} = binary variable indicating whether painting and blasting on block k takes place at time t

6.2 Calculating the facility requirements

6.2.1 Steel processing/building area

The steel processing area required can be calculated on a block level. First the total area necessary for one block will be calculated. This is done using the plate measurements with a margin. The assumption will be that the plate will be present for one month. This is then multiplied by the number of plates used in the block. The block fabrication plan is used to distribute the total required area.

$$TSPA_{i,k} = \sum_{l \in L_k} (l_l + ml) * (w_l * mw) * np_{k,l} \qquad \forall i \in I \wedge k \in K_i$$
$$SPA_{i,t} = \sum_{k \in K_i} \frac{TA_{i,k}}{dr_k^{SP}} * x_{t,k}^{SP} \qquad \forall i \in I \wedge t \in T$$

With:

- $TSPA_{i,k}$ = total steel processing area needed for block k in ship i in m^2
- $SPA_{i,t}$ = steel processing area needed for ship i at month t in m^2
- l_l = length of plate l in meters
- w_l = width of plate l in meters
- ml = extra margin (for mobility) for length in m
- mw = extra margin (for mobility) for width in m
- $np_{l,k}$ = number of plates of type l in block k
- dr_k^{SP} = the duration of the steel processing activity for block k
- $x_{t,k}^{SP}$ = binary variable indicating whether steel processing on block k takes place at time t

6.2.2 Building frames

When a block is being constructed, a building frame is required. It could even be the case that very large blocks require more than one building frame for construction.

$$Bf_{i,t} = \sum_{k \in K_i} nbf_k * x_{t,k}^{BC} \qquad \forall i \in I \wedge t \in T$$

With:

- $Bf_{i,t}$ = number of building frames needed for ship i at time t
- nbf_k = number of building frames needed to construct block k (often just 1)
- $x_{t,k}^{BC}$ = binary variable indicating whether block construction on block k takes place at time t. This variable will be 1 if block construction is performed on block k during month t, and 0 if no block construction occurs.

6.2.3 Hull assembly area

The required hull assembly area is increased each time a bottom block is assembled to the rest of the hull. Only bottom blocks increase the required area as the other blocks will be assembled on top of these bottom blocks. These blocks will only increase the heigh, but not the area.

$$HA_{i,t} = \sum_{k \in K_i} aa_k * x_{t,k}^{HAA} \qquad \forall i \in I \wedge t \in T$$

With:

- $HA_{i,t}$ = hull assembly area needed for the base blocks of ship i at time t in m^2
- aa_k = area the block adds to the hull assembly area in m^2. Will be ≥ 0 for base block, but will be 0 for non-base blocks.
- $x_{t,k}^{HAA}$ = binary variable indicating whether block k has been added to the hull assembly at time t. This will be a 1 when the block is present in the hull assembly area, will be 0 before it is added and will turn 0 again when the ship is launched.

6.2.4 Launching and Quay area

As the launching and quay area concerns the entire ship, and is not performed on a block level, the formulations created in Chapter 5.2.4 will be used.

6.2.5 Painting and blasting hall

While a block undergoes the painting & blasting activity, space is required in the painting & blasting hall. The area required is the same as the area of the block, and is only required during the month painting & blasting is done on the block.

$$PBA_{i,t} = \sum_{k \in K_i} a_k * x_{t,k}^{PB} \qquad \forall i \in I \wedge t \in T$$

With:

- $PBA_{i,t}$ = the required painting and blasting area for ship i during month t in m^2
- a_k = the area of block k in m^2
- x_k^{PB} = binary variable indicating whether painting and blasting on block k takes place at time t

6.2.6 Employee facilities

The required employee facilities are based on the required hours for each activity. For some activities the required hours calculation are done on a block level basis. The employee facility requirements will use the outcomes of these new formulations as new input. However, the formulations for calculating the employee facilities will be the same as proposed in Chapter 5.2.6, even though the output might differ slightly due to new input values.

6.2.7 Limits on steel cutting and piping fabrication

Steel cutting is a task heavily related to blocks, as it is done during the steel processing activity. However, piping fabrication is not. Therefor, the amount of steel cut per month will be calculated using a new formulation, but the amount of pipe spools fabricated per month will be calculated using the formulations given in Chapter 5.2.7.

$$TSC_{i,k} = \sum_{l \in L_k} wg_l * np_{l,k} \qquad \forall i \in I \wedge k \in K_i$$
$$SC_{i,t} = \sum_{k \in K_i} \frac{SC_{i,k}}{dr_k^{SP}} * x_{t,k}^{SP} \qquad \forall i \in I \wedge t \in T$$

With:

- $TSC_{i,k}$ = total weight of steel plates that need to be cut for block k in ship i in kg
- $SC_{i,t}$ = steel needed to be cut for ship i at month t in kg
- wg_l = weight of plate l in kg
- $np_{l,k}$ = number of plates of type l in block k
- dr_k^{SP} = the duration of the steel processing activity for block k
- $x_{t,k}^{SP}$ = binary variable indicating whether steel processing on block k takes place at time t

6.2.8 Warehouse storage

The warehouse storage concerns the storage of items necessary for the outfitting activity. This will be calculated using two different methods. The first method can be used when no specific item data is available. The second method uses item data, and therefor requires more specific input.

The first method uses the outfitting weight of each block in order to calculate the required storage volume needed for that block. It assumes that the outfitting volume will be used up linearly. When outfitting first starts for a block, all items are in the warehouse. During the outfitting activity more and more of the volume gets put into the ship. After outfitting is completed for that block, no storage area is needed for that particular block.

An addition to the first formulation is the second part, $ov_k * x_{t,k}^{WO}$. This part of the formulation enables the volume required for a particular block to arrive a set amount of months earlier. Therefor, the required volume during the month before outfitting on the block starts is the full outfitting volume. The variable $x_{t,k}^{WO}$ will be 1 in the months leading up to the start of block outfitting were the items have already arrived. This part can also be deleted if the required volume does not arrive earlier.

First method:
$$BWA_{k,t} = \left(1 - \frac{t - s_k^O}{dr_k^O}\right) * ov_k * x_{t,k}^O + ov_k * x_{t,k}^{WO} \qquad \forall t \in T \wedge k \in K$$
$$WA_t = \sum_{k \in K} BWA_{k,t} \qquad \forall t \in T$$

The second method utilizes the required items in the ship for a more precise overview. The assumption will be that when an item is required for outfitting, all items of the same type arrive at the same time. This is quite a logical assumption for DSNS, as when items of a particular type are ordered all those items are ordered at once. This is mainly due to the fixed costs of ordering items from a supplier.

As can be seen in the formulation, if the first item of type m is needed, all type m items are in the warehouse. Then the items get used up when blocks finish their outfitting activity.

Second method:
$$WA_{m,t} = \sum_{k \in K} n_{k,m} * v_m * (1 - x_{k,t}^{OF}) * x_{m,t}^{MO} \qquad \forall t \in T \wedge m \in M$$

$WA_t = \sum_{m \in M} WA_{m,t}$ $\forall t \in T$

With:

- $BWA_{k,t}$ = warehouse area needed for block k at time t in m^3
- $WA_{m,t}$ = warehouse area needed for item type m at time t in m^3
- WA_t = warehouse area at time t in m^3
- ov_k = the outfitting volume of block k in m^3
- $x^O_{t,k}$ = binary value indicating whether outfitting occurs on block k at time t
- $x^{WO}_{t,k}$ = binary value indicating whether items are already in storage before the start of outfitting for block k at time t
- $n_{k,m}$ = number of items of type m in block k
- v_m = volume of items of type m
- $x^{OF}_{k,t}$ = binary value indicating whether the outfitting activity has finished for block k at time t
- $x^{MO}_{m,t}$ = binary value indicating whether item type m has arrived at the warehouse at time t

6.2.9 Steel storage

The plates required for the steel processing activity also need to be stored. This is done on storage piles, where each individual plate type has its own pile, see Chapter 5.2.9.

The required steel plate storage is calculated by multiplying the required area for a plate type by a binary value ($x^{SS}_{l,t}$) indicating whether the plate type will be used during that month. So each plate that is stored during that month increases the required area.

In order to calculate $x^{SS}_{l,t}$ the two inequalities given below are used. They ensure that when plate type l is required during that month, $x^{SS}_{l,t}$ will be 1. Furthermore, if plate type l is not required, the value will be 0. An example is given in Chapter 8.

$SSA_t = \sum_{l \in L} x^{SS}_{l,t} * A_l$ $\forall t \in T$
$\sum_{i \in I} \sum_{k \in K_i} np_{k,l} * x^{SP}_{t,k} \geq 0.01 - M * (1 - x^{SS}_{l,t})$ $\forall l \in L \wedge t \in T$
$\sum_{i \in I} \sum_{k \in K_i} np_{k,l} * x^{SP}_{t,k} \leq M * x^{SS}_{l,t}$ $\forall l \in L \wedge t \in T$
$x^{SS}_{l,t} \in \{0, 1\}$

With:

- SSA_t = required steel storage area needed during month t in m^2. This is not done on a ship basis, as identical plates meant for different ship will be stored on the same pile
- $np_{k,l}$ = number of plates of type l in block k
- A_l = area necessary for a storage pile for a plate of type l
- $x^{SS}_{l,t}$ = binary variable indicating whether a plate of time l will be stored at time t
- $x^{SP}_{t,k}$ = binary variable indicating whether steel processing on block k takes place at time t
- M = a very high constant, could be set to 1,000,000 for example

6.3 Creation of the block level model

Just like the whole ship level model, the block level model will also check the feasibility of the capacity. These formulation are done on a yard level. Therefor, they will not change in the block level model. The formulations can be found in Chapter 5.3.

The same decision variables discussed in Chapter 5.3 will be used in this model. This means the decision variables concerning the added flexibility $EP_{i,t}^{Activity}$, the amount of subcontracting / outsourcing $O_{i,t}^{Activity}$ and the extra capacity $ECap_t^{Activity}$ & $ECap_t^{Facility}$ are added to the model.

However, an extra decision variables is added, $o_k^{Activity}$. This variable replaces $O_{i,t}^{Activity}$ for block level activities. The decision variable $o_k^{Activity}$ signals whether block k is outsourced for a certain activity. If the variable is one the block is outsourced, if it is zero the block is not outsourced. As can be seen, the new outsourcing variable is not dependant on time. This is because a block can either be outsourced for an activity or not. It is impossible to outsource one month of an activity for a block and not outsource the subsequent months. As this new outsourcing variable is a binary variable, the model will be a mixed integer linear programming model.

The last extra decision variable will be $EP_{k,t}^{Activity}$. This decision variable is similar to the ship added flexibility variable, however this time it is on a block level.

The flexibility and outsourcing decision variables are now on a block level. The capacity constraints are still on a whole ship level. This means that those two decision variables will have to be implemented when the requirements are being calculated. When outsourcing on a block level for a particular activity occurs, the requirements for that activity will become zero for that particular block. This results in the following formulations

$$H_{i,t}^{SP} = \sum_{k \in K_i} (\frac{TH_{i,t,k}^{SP}}{dr_k^{SP}} * x_{t,k}^{SP}) * (1 - o_k^{SP}) * EP_{k,t}^{SP} \qquad \forall i \in I \wedge t \in T$$

$$H_{i,t}^{SB} = \sum_{k \in K_i} (\frac{TH_{i,t,k}^{SB,BC}}{dr_{i,k}^{BC}} * x_{t,k}^{BC} + y_k^{HA} * x_{t,k}^{HA}) * (1 - o_k^{SB}) * EP_{k,t}^{SB} \qquad \forall i \in I \wedge t \in T$$

$$H_{i,t}^{O} = \sum_{k \in K_i} (\frac{TH_{i,t,k}^{O}}{d_{i,k}^{O}} * x_{t,k}^{O}) * (1 - o_k^{O}) * EP_{k,t}^{O} \qquad \forall i \in I \wedge t \in T$$

$$H_{i,t}^{PB} = \sum_{k \in K_i} (x_k^{O} * hpb) * (1 - o_{t,k}^{PB}) * EP_{k,t}^{PB} \qquad \forall i \in I \wedge t \in T$$

It is important to ensure that the block requirements each month sum to the total block requirements. Otherwise, the added flexibility term could be less than one during all months, as that would lead to the lowest requirements. This is ensured using the following formulations.

$$\sum_{t \in T} H_{i,t}^{SP} = \sum_{t \in T} \sum_{k \in K_i} (\frac{TH_{i,t,k}^{SP}}{dr_k^{SP}}) * x_{t,k}^{SP} * (1 - o_{t,k}^{SP}) \qquad \forall i \in I$$

$$\sum_{t \in T} H_{i,t}^{SB} = \sum_{t \in T} \sum_{k \in K_i} (\frac{TH_{i,t,k}^{SB,BC}}{dr_{i,k}^{BC}} * x_{t,k}^{BC} + y_k^{HA} * x_{t,k}^{HA}) * (1 - o_{t,k}^{SB}) \qquad \forall i \in I$$

$$\sum_{t \in T} H_{i,t}^{O} = \sum_{t \in T} \sum_{k \in K_i} (\frac{TH_{i,t,k}^{O}}{d_{i,k}^{O}} * x_{t,k}^{O}) * (1 - o_{t,k}^{O}) \qquad \forall i \in I$$

$$\sum_{t \in T} H_{i,t}^{PB} = \sum_{t \in T} \sum_{k \in K_i} (x_{t,k}^{O} * hpb) * (1 - o_{t,k}^{PB}) \qquad \forall i \in I$$

When an activity for a block is outsourced the related facility requirements for that block will also disappear.

$$SPA_{i,t} = \sum_{k \in K_i} \frac{TA_{i,k}}{(dr_k^{SP}} * x_{t,k}^{SP}) * (1 - o_k^{SP}) * EP_{k,t}^{SP} \qquad \forall i \in I \wedge t \in T$$

$Bf_{i,t} = \sum_{k\in K_i} (nbf_k * x^{BC}_{t,k}) * (1 - o^{SB}_k) * EP^{SB}_{k,t}$ $\forall i \in I \wedge t \in T$
$PBA_{i,t} = \sum_{k\in K_i} (a_k * x^{PB}_{t,k}) * (1 - o^{PB}_k) * EP^{PB}_{k,t}$ $\forall i \in I \wedge t \in T$
$SC_{i,t} = \sum_{k\in K_i} \frac{SC_{i,k}}{(dr^{SP}_k} * x^{SP}_{t,k}) * (1 - o^{SP}_k) * EP^{SP}_{k,t}$ $\forall i \in I \wedge t \in T$

6.4 The final block ship level model

The final block ship level linear programming model is given below. As can be seen, the costs are still minimized. Furthermore, the requirements are limited by the maximum capacity of those requirements. The variables used are discussed in Chapter B.

Objective function

$$min \sum_{t\in T} \sum_{a\in A^*} O^a_t * c^a + ECap^a_t * ec^a + \sum_{t\in T} \sum_{a\in A'} o^a_t * c^a + ECap^a_t * ec^a + \sum_{f\in F} ECap^f_t * ec^f$$

Subject to:

Activity working hours requirements

$\sum_{i\in I} H^{SP}_{i,t} \leq Cap^{SP}_t + ECap^{SP}_t$ $\forall t \in T$
$\sum_{i\in I} H^{SB}_{i,t} \leq Cap^{SB}_t + ECap^{SB}_t$ $\forall t \in T$
$\sum_{i\in I} H^{O}_{i,t} \leq Cap^{O}_t + ECap^{O}_t$ $\forall t \in T$
$\sum_{i\in I} H^{PF}_{i,t} \leq Cap^{PF}_t + ECap^{PF}_t + O^{PF}_t$ $\forall t \in T$
$\sum_{i\in I} H^{PI}_{i,t} \leq Cap^{PI}_t + ECap^{PI}_t + O^{PI}_t$ $\forall t \in T$
$\sum_{i\in I} H^{PB}_{i,t} = Cap^{PB}_t + ECap^{PB}_t$ $\forall t \in T$
$\sum_{i\in I} H^{W}_{i,t} \leq Cap^{W}_t + ECap^{W}_t + O^{W}_t$ $\forall t \in T$
$\sum_{i\in I} H^{QC}_{i,t} \leq Cap^{QC}_t + ECap^{QC}_t + O^{QC}_t$ $\forall t \in T$
$\sum_{i\in I} H^{PD}_{i,t} \leq Cap^{PD}_t + ECap^{PD}_t + O^{PD}_t$ $\forall t \in T$
$\sum_{i\in I} H^{STW}_{i,t} \leq Cap^{STW}_t + ECap^{STW}_t + O^{STW}_t$ $\forall t \in T$

Facility requirements

$\sum_{i\in I} SPA_{i,t} \leq Cap^{SPA}_t + ECap^{SPA}_t$ $\forall t \in T$
$\sum_{i\in I} BF_{i,t} \leq Cap^{BF}_t + ECap^{BF}_t$ $\forall t \in T$
$\sum_{i\in I} HA_{i,t} \leq Cap^{HA}_t + ECap^{HA}_t$ $\forall t \in T$
$\sum_{i\in I} LA_{i,t} \leq Cap^{LA}_t + ECap^{LA}_t$ $\forall t \in T$
$\sum_{i\in I} QA_{i,t} \leq Cap^{QA}_t + ECap^{QA}_t$ $\forall t \in T$
$\sum_{i\in I} PBA_{i,t} \leq Cap^{PBA}_t + ECap^{PBA}_t$ $\forall t \in T$
$\sum_{i\in I} SC_{i,t} \leq Cap^{SC}_t + ECap^{SC}_t$ $\forall t \in T$
$\sum_{i\in I} PP_{i,t} \leq Cap^{PP}_t + ECap^{PP}_t + \frac{O^{PF}_t}{\sum_{i\in I} H^{PF}_{i,t}} * PP^{i,t}$ $\forall t \in T$
$\sum_{i\in I} WA_{i,t} \leq Cap^{WA}_t + ECap^{WA}_t + \frac{O^{W}_t}{\sum_{i\in I} H^{W}_{i,t}} * WA^{i,t}$ $\forall t \in T$
$\sum_{i\in I} SSAi, t \leq Cap^{SSA}_t + ECap^{SSA}_t$ $\forall t \in T$

And:

$(1 - fl) \leq EP^a_{i,t} \leq (1 + fl)$ $\forall a \in A \wedge t \in T \wedge i \in I$
$(1 - fl) \leq EP^a_{k,t} \leq (1 + fl)$ $\forall a \in A \wedge t \in T \wedge k \in K$
$ECap^a_t \geq 0$ $\forall a \in A \wedge t \in T$
$ECap^f_t \geq 0$ $\forall f \in F \wedge t \in T$

$O_t^a \geq 0$ $\quad \forall a \in A \wedge t \in T$
$o_{t,k}^a \in \{0,1\}$ $\quad \forall a \in A \wedge t \in T \wedge k \in$

New hours calculations
Steel processing
If the first steel processing formulation is used:
$TH_{i,k}^{SP} = c_k^{SP} * n_k + v_k * n_k * y_k^{SP}$ $\quad \forall i \in I \wedge k \in K_i$
If the second steel processing formulation is used:
$TH_{i,k}^{SP} = \sum_{l \in L_k} n_{k,l} * c_l^{SP} + n_{k,l} * v_l * y_l^{SP}$ $\quad \forall i \in I \wedge k \in K_i$

$H_{i,t}^{SP} = \sum_{k \in K_i} \frac{TH_{i,t,k}^{SP}}{dr_k^{SP}} * x_{t,k}^{SP} * (1 - o_{t,k}^{SP}) * EP_{k,t}^{SP}$ $\quad \forall i \in I \wedge t \in T$
$\sum_{t \in T} H_{i,t}^{SP} = \sum_{t \in T} \sum_{k \in K_i} \frac{TH_{i,t,k}^{SP}}{dr_k^{SP}} * x_{t,k}^{SP} * (1 - o_{t,k}^{SP})$ $\quad \forall i \in I$

Steel building
$TH_{i,k}^{SB,BC} = n_k * y_k^{BC} + c_k^{SB}$ $\quad \forall i \in I \wedge k \in K_i$
$H_{i,t}^{SB} = \sum_{k \in K_i} (\frac{TH_{i,t,k}^{SB,BC}}{dr_{i,k}^{BC}} * x_{t,k}^{BC} + y_k^{HA} * x_{t,k}^{HA}) * (1 - o_{t,k}^{SB}) * EP_{k,t}^{SB}$ $\quad \forall i \in I \wedge t \in T$
$\sum_{t \in T} H_{i,t}^{SB} = \sum_{t \in T} \sum_{k \in K_i} (\frac{TH_{i,t,k}^{SB,BC}}{dr_{i,k}^{BC}} * x_{t,k}^{BC} + y_k^{HA} * x_{t,k}^{HA}) * (1 - o_{t,k}^{SB}) \forall i \in I$

Outfitting
If the first outfitting formulation is used:
$TH_{i,k}^{O} = ov_k * y_k^{O} + c_k^{O}$ $\quad \forall i \in I \wedge k \in K_i$
If the first outfitting formulation is used:
$TH_{i,k}^{O} = c_k^{O} + \sum_{m \in M_k} tii_m * ni_{k,m}$ $\quad \forall i \in I \wedge k \in K_i$

$H_{i,t}^{O} = \sum_{k \in K_i} (\frac{TH_{i,t,k}^{O}}{d_{i,k}^{O}} * x_{t,k}^{O}) * (1 - o_{t,k}^{O}) * EP_{k,t}^{O}$ $\quad \forall i \in I \wedge t \in T$
$\sum_{t \in T} H_{i,t}^{O} = \sum_{t \in T} \sum_{k \in K_i} (\frac{TH_{i,t,k}^{O}}{d_{i,k}^{O}} * x_{t,k}^{O}) * (1 - o_{t,k}^{O}) \forall i \in I$

Painting & blasting
$H_{i,t}^{PB} = \sum_{k \in K_i} (x_{t,k}^{O} * hpb) * (1 - o_{t,k}^{PB}) * EP_{k,t}^{PB}$ $\quad \forall i \in I \wedge t \in T$

$\sum_{t \in T} H_{i,t}^{PB} = \sum_{t \in T} \sum_{k \in K_i} (x_{t,k}^{O} * hpb) * (1 - o_{t,k}^{PB})$ $\quad \forall i \in I$

Whole ship hours calculations

$TH_i^{PF} = s_i * \lambda_i^{PF}$ $\quad \forall i \in I$
$TH_i^{PI} = s_i * \lambda_i^{PI}$ $\quad \forall i \in I$
$TH_i^{W} = ow_i * \lambda_i^{W}$ $\quad \forall i \in I$

Distribution of the whole ship hours
If the polynomial function is used:
$D_{i,t}^a = \beta^{a,0} + \beta^{a,1} * t + \beta^{a,2} * t^2 +$ $\quad \forall i \in I \wedge t \in T \wedge a \in A^*$
$\beta^{a,2} * t^2 + \beta^{a,3} * t^3 + \beta^{a,4} * t^4$

If the beta distribution is used:
$H^{Activity}(t) = (P(X \leq (\frac{t+1-st_i^{Activity}}{dr_i^{Activity}})) - P(X \leq (\frac{t-st_i^{Activity}}{dr_i^{Activity}}))) * TH^{Activity}$

The resulting formulation will become:
$H_{i,t}^a = TH_i^a * D_{i,t}^a * EP_{i,t}^a$ $\quad \forall i \in I \wedge t \in T \wedge a \in A^*$
$\sum_{t \in T} H_{i,t}^a = TH_i^a$ $\quad \forall i \in I \wedge a \in A^*$

Facility requirements calculations

Steel processing area
$TSPA_{i,k} = \sum_{l \in L_k} (l_l + ml) * (w_l * mw) * np_{l,k}$ $\quad \forall i \in I \wedge k \in K_i$
$SPA_{i,t} = \sum_{k \in K_i} \frac{TA_{i,k}}{(dr_k^{SP}} * x_{t,k}^{SP}) * (1 - o_{t,k}^{SP})$ $\quad \forall i \in I \wedge t \in T$

Building frames
$Bf_{i,t} = \sum_{k \in K_i} (nbf_k * x_{t,k}^{BC}) * (1 - o_{t,k}^{SB})$ $\quad \forall i \in I \wedge t \in T$

Hull assembly area
$HA_{i,t} = \sum_{k \in K_i} aa_k * x_{t,k}^{HAA}$ $\quad \forall i \in I \wedge t \in T$

Launching and Quay area
$TA_i = TL_i * TW_i$ $\quad \forall i \in I$
$LA_{i,t} = TA_i * d_{i,t}^L$ $\quad \forall i \in I \wedge t \in T$
$QA_{i,t} = TA_i * d_{i,t}^Q$ $\quad \forall i \in I \wedge t \in T$

Painting and blasting hall
$PBA_{i,t} = \sum_{k \in K_i} (a_k * x_{t,k}^O) * (1 - o_{t,k}^{PB})$ $\quad \forall i \in I \wedge t \in T$

Employee facilities
$WCA_{i,t} = \sum_{a \in A} RWCA^a * H_{i,t}^a / FTE$ $\quad \forall i \in I \wedge t \in T$
$CA_{i,t} = \sum_{a \in A} RCA^a * H_{i,t}^a / FTE$ $\quad \forall i \in I \wedge t \in T$
$OA_{i,t} = \sum_{a \in A} ROA^a * H_{i,t}^a / FTE$ $\quad \forall i \in I \wedge t \in T$

Steel cutting and piping fabrication
$TSC_{i,k} = \sum_{l \in L_k} wg_l * np_{l,k}$ $\quad \forall i \in I \wedge k \in K_i$
$SC_{i,t} = \sum_{k \in K_i} \frac{SC_{i,k}}{(dr_k^{SP}} * x_{t,k}^{SP}) * (1 - o_{t,k}^O)$ $\quad \forall i \in I \wedge t \in T$
$PP_{i,t} = s_i * D_{i,t}^{PF}$ $\quad \forall i \in I \wedge t \in T$

Warehouse storage
If the first warehouse storage formulation is used: $BWA_{k,t} = (1 - \frac{t-s_k^O}{dr_k^O}) * ov_k$ $\quad \forall t \in T_k^O \wedge k \in K$
$BWA_{k,(s_k^O-1)} = ov_k$ $\quad k \in K$
$WA_t = \sum_{k \in K} BWA_{k,t}$ $\quad \forall t \in T$

If the second warehouse storage formulation is used: $WA_{m,t} = \sum_{k \in K} n_{k,m} * (1 - x_{k,t}^{OF}) * x_{m,t}^{MO}$ $\forall t \in T \wedge m \in M$
$WA_t = \sum_{m \in M} WA_{m,t}$ $\quad \forall t \in T$

Steel storage

$SSA_t = \sum_{l \in L} x^{SS}_{l,t} * A_l$ $\qquad \forall t \in T$

$\sum_{i \in I} \sum_{k \in K_i} np_{l,k} * x^{SP}_{t,k} \geq M * (1 - x^{SS}_{l,t})$ $\qquad \forall l \in L \wedge t \in T$

$\sum_{i \in I} \sum_{k \in K_i} np_{l,k} * x^{SP}_{t,k} \leq M * x^{SS}_{l,t}$ $\qquad \forall l \in L \wedge t \in T$

7 Visualisation

Visualisation is an important aspect in the comprehension and communication of scientific data (Shaheen et al., 2017). Presenting data in a graphical form makes the information easier to understand. Furthermore, it aids in explaining facts and decision making (Sadiku et al., 2016).

DSNS also places a lot of importance on visualisation. This is because DSNS wants to communicate the outcomes of the created models in discussions with customers, where a lot of input information will be provided. For example, the customer might want to see the impact of enlarging the ship, therefor adding to its size and weight. So the model should be able to handle quick changes of this input information, while still showing whether or not the capacity will be exceeded.

The linear programming models are implemented in Python, therefor the visualisation code will also be written there. For this purpose TKinter, a Python module, is used. This allows for the creation of a GUI (Graphic User Interface) where users can change certain aspects at will.

In order to create such a model, input data needs to be read first. After the input data is extracted, the model should use the requirement formulations proposed in Chapters 5 & 6. These calculation should be added into the Python model. Using a linear programming tool for Python, in this circumstance PuLP, the whole ship detail level model and the block level model can be made.

As mentioned earlier the model should allow for quick changes in scenarios. In order to facilitate this multiple options will be programmed in order to allow for these quick changes. Beforehand scenarios will be created and inserted into the model, however the exact details of these scenarios can be changed while using the program. This scenario information includes the ships, their start date and the yard that will be analysed. This information can also be adjusted in the program.

Furthermore, options to extend the project time or inflate the requirements are also build into the program. This is to test what would happen if certain delays during the project present themselves.

Additionally, one can choose to either use the whole ship model or the block level model while using the program. This is to allow the user to use a block level model, without forcing them to always use this method. For example, the user might have low detail input information and want to use the whole ship level model instead.

Lastly, various options unrelated to input data are present in the model as well. These options are given below.

- Choice whether hours or FTE's will be used.
- Choice whether a distinction between foremen and standard employees is used.
- Choice whether the capacity is strict, or can be exceeded. This can be used to examine certain aspects of the scenario.
- Choice between certain calculation methods.

8 Model results

8.1 Results of the whole ship level model

8.1.1 Model requirement formulations

In order to work with the model, input data needs to be given. Due to confidentially reasons, this input data does not come from actual ships and yards. The ship input data can be found in Chapter D, the yard input data is given in Chapter C.

8.1.1.1 Total hour calculations

The first thing the model should calculate are the total required hours per activity. The formulations to calculate these values are given in Chapter 5.1.1. For demonstration purposes, the total hours for ship A and ship C will be calculated below. These two ships are chosen due to there different ship types. Notice how all $\lambda_i^{Activity}$ are the same for each ship of the same ship type. Ships A and B are both of type I, therefor the $\lambda_i^{Activity}$ are identical. Ship C is of type II, and therefor will use different values for $\lambda_i^{Activity}$.

Steel processing

$TH_i^{SP} = w_i * \lambda_i^{SP} \qquad \forall i \in I$

$TH_{ShipA}^{SP} = 600 * 100 = 60,000\, hours$

$TH_{ShipC}^{SP} = 1000 * 80 = 80,000\, hours$

Steel building

$TH_i^{SB} = w_i * \lambda_i^{SB} \qquad \forall i \in I$

$TH_{ShipA}^{SB} = 600 * 150 = 90,000\, hours$

$TH_{ShipC}^{SB} = 1000 * 120 = 120,000\, hours$

Outfitting

$TH_i^{O} = ow_i * \lambda_i^{O} \qquad \forall i \in I$

$TH_{ShipA}^{O} = 300 * 150 = 45,000\, hours$

$TH_{ShipC}^{O} = 500 * 150 = 75,000\, hours$

Piping fabrication

$TH_i^{PF} = s_i * \lambda_i^{PF} \qquad \forall i \in I$

$TH_{ShipA}^{PF} = 60 * 80 = 4,800\, hours$

$TH_{ShipC}^{PF} = 100 * 75 = 7,500\, hours$

Piping installation

$TH_i^{PI} = s_i * \lambda_i^{PI} \qquad \forall i \in I$

$TH_{ShipA}^{PI} = 60 * 80 = 4,800\, hours$

$TH_{ShipC}^{PI} = 100 * 70 = 7,000\, hours$

Painting & blasting

$TH_i^{PB} = nr_i * FTE * 3 \qquad \forall i \in I$

$TH^{PB}_{ShipA} = 6 * 150 * 3 = 2,700\, hours$
$TH^{PB}_{ShipC} = 10 * 150 * 3 = 4,500\, hours$

Warehousing
$TH^{W}_{i} = ow_i * \lambda^{W}_{i} \qquad \forall i \in I$
$TH^{W}_{ShipA} = 300 * 50 = 15,000\, hours$
$TH^{W}_{ShipC} = 500 * 50 = 25,000\, hours$

8.1.1.2 Hour distribution

Now that the total hours have been calculated, the hours need to be distributed. This is done in a similar way for all activities. In order to showcase how this is done the required steel processing hours of ship A will be distributed.

The methods used are described in Chapter 5.1.2. As mentioned in that chapter, the beta distribution uses a scale from 0 to 1. This means that the activity starts for the ships should be set to 0, and the end of the activity should be set to 1.

Below the calculations for the hour distribution of steel processing for ship A will be given. The beta distribution will be used with $\alpha = 1$ and $\beta = 2.5$.

$H^{Activity}_{i,t} = D^{Activity}_{i,t} * TH^{Activity} \qquad \forall i \in I \wedge t \in T$
$H^{Activity}_{i,t} = (P(X \leq (\frac{t+1-st^{Activity}_{i}}{dr^{Activity}_{i}})) - P(X \leq (\frac{t-st^{Activity}_{i}}{dr^{Activity}_{i}}))) * TH^{Activity} \qquad \forall i \in I \wedge t \in T$
$H^{SP}_{ShipA,t} = (P(X \leq (\frac{t+1-st^{SP}_{ShipA}}{dr^{SP}_{i}})) - P(X \leq (\frac{t-st^{SP}_{ShipA}}{dr^{SP}_{ShipA}}))) * TH^{SP} \qquad \forall t \in T$
$H^{SP}_{ShipA,0} = (P(X \leq (\frac{0+1-0}{6})) - P(X \leq (\frac{0-0}{6}))) * 60,000 = (0.366 - 0) * 60,000 = 21,964\, hours$
$H^{SP}_{ShipA,1} = (P(X \leq (\frac{1+1-0}{6})) - P(X \leq (\frac{1-0}{6}))) * 60,000 = (0.637 - 0.366) * 60,000 = 16,263\, hours$
$H^{SP}_{ShipA,2} = (P(X \leq (\frac{2+1-0}{6})) - P(X \leq (\frac{2-0}{6}))) * 60,000 = (0.823 - 0.637) * 60,000 = 11,167\, hours$
$H^{SP}_{ShipA,3} = (P(X \leq (\frac{3+1-0}{6})) - P(X \leq (\frac{3-0}{6}))) * 60,000 = (0.936 - 0.823) * 60,000 = 6,758\, hours$
$H^{SP}_{ShipA,4} = (P(X \leq (\frac{4+1-0}{6})) - P(X \leq (\frac{4-0}{6}))) * 60,000 = (0.989 - 0.936) * 60,000 = 3,168\, hours$
$H^{SP}_{ShipA,5} = (P(X \leq (\frac{5+1-0}{6})) - P(X \leq (\frac{5-0}{6}))) * 60,000 = (1 - 0.989) * 60,000 = 680\, hours$

In order to test whether the results were accurate, check whether $\sum_t H^{SP}_{ShipA,t} = TH^{SP}$, so $21,964 + 16,263 + 11,167 + 6,758 + 3,168 + 680 = 60,000$ which is the same as $60,000 = 60,000$. This means that the distributions sum to one, which means the calculations were done correctly.

8.1.1.3 Facility requirements

The facility requirements also need to be calculated. The formulations used are given in Chapter 5.2. Once again, ships A and C are used in the calculations.

Steel processing area
The steel processing area distribution formulation is similar to the activity hour calculations. For an in depth calculation see Chapter 8.1.1.2.

$TSPA_i = ap * (w_i/p) \qquad \forall i \in I$
$TSPA_{ShipA} = 5 * (600/0.1) = 30,000\, m^2$

$TSPA_{ShipC} = 5 * (1000/0.1) = 50,000\, m^2$

Building frames

The building frames distribution formulation is similar to the activity hour calculations. For an in depth calculation see Chapter 8.1.1.2.

$$TBf_i = nb_i * drb_i^{Bf} \qquad \forall i \in I$$
$$TBf_{ShipA} = 30 * 3 = 90$$
$$TBf_{ShipC} = 50 * 3 = 150$$

Hull assembly area

The hull assembly area distribution formulation is similar to the activity hour calculations. For an in depth calculation see Chapter 8.1.1.2. This time however the beta distribution for hull assembly is used instead of an activity distribution.

$$TA_i = TL_i * TW_i \qquad \forall i \in I$$
$$TA_{ShipA} = 70 * 10 = 700\, m^2$$
$$TA_{ShipC} = 100 * 15 = 1,500 m^2$$

Launching and Quay area

The launching and quay area do not utilize a particular distribution. This is due to the fact that the areas will either be completely in use, or completely not in use. When a ship is launched, the entire area of the ship will be added to the launching area. This number can never be less than the ship area. The launching and quay area will be demonstrated using ship A. During all times not calculated, the utilized area will be 0.

$$TA_i = TL_i * TW_i \qquad \forall i \in I$$
$$TA_{ShipA} = 70 * 10 = 700\, m^2$$

$$LA_{i,t} = TA_i * d_{i,t}^{L} \qquad \forall i \in I \wedge t \in T$$
$$LA_{ShipA,17} = 700 * 0 = 0\, m^2$$
$$LA_{ShipA,18} = 700 * 1 = 700\, m^2$$
$$LA_{ShipA,29} = 700 * 0 = 0\, m^2$$

$$QA_{i,t} = TA_i * d_{i,t}^{Q} \qquad \forall i \in I \wedge t \in T$$
$$QA_{ShipA,18} = 700 * 0 = 0\, m^2$$
$$QA_{ShipA,19} = 700 * 1 = 700\, m^2$$
$$QA_{ShipA,20} = 700 * 1 = 700\, m^2$$
$$QA_{ShipA,21} = 700 * 1 = 700\, m^2$$
$$QA_{ShipA,22} = 700 * 0 = 0\, m^2$$

Painting & blasting hall

The painting & blasting hall utilizes a similar logic as launching & quay area used. This is due to the whole ship level model not allowing the painting & blasting activity to be calculated with many details. In order to show the calculations the painting & blasting area necessary for ship A during the months 4 and 5 will be calculated below.

$$PBA_{i,t} \geq nb_i / dr_i^{PB} * Abb_i * d_{i,t}^{PB} \qquad \forall i \in I \wedge t \in T$$

$PBA_{i,t} \geq Abb_i * d_{i,t}^{PB}$ $\forall i \in I \wedge t \in T$
$TPBA_{ShipA,4} \geq (30/9 * 40 * 0 =)0\, m^2$
$TPBA_{ShipA,4} \geq (40 * 0 =)0\, m^2$
$TPBA_{ShipA,5} \geq (30/9 * 40 * 1 =)133\, m^2$
$TPBA_{ShipA,5} \geq (40 * 1 =)40\, m^2$

Employee facilities
The required employee facilities depend on the required working hours for the ships. These are calculated in Chapter 8.1.1.2. Below, the required employee facilities are calculated for Ship A during month 1, under the assumption that steel processing is the only activity.
$WCA_{i,t} = \sum_{a \in A} RWCA^a * H_{i,t}^a / FTE$ $\forall i \in I \wedge t \in T$
$WCA_{ShipA,1} = 2 * 16,263/150 = 217\, m^2$

$CA_{i,t} = \sum_{a \in A} RCA^a * H_{i,t}^a / FTE$ $\forall i \in I \wedge t \in T$
$CA_{ShipA,1} = 2 * 16,263/150 = 217\, m^2$

$OA_{i,t} = \sum_{a \in A} ROA^a * H_{i,t}^a / FTE$ $\forall i \in I \wedge t \in T$
$WCA_{ShipA,1} = 2 * 16,263/150 = 217\, m^2$

Steel cutting and piping fabrication
The requirements on steel cutting and piping fabrication are both related to the steel processing and piping fabrication activities. Because of this, the distributions used for those activities will be used.

For steel cutting the amount of steel cut for ship A at month 1 will be calculated. This will be the second month of steel processing for ship A. The amount of pipe spools fabricated during month 5 for ship A is also calculated below. This is the second month of piping fabrication.

$SC_{i,t} = w_i * D_{i,t}^{SP}$ $\forall i \in I \wedge t \in T$
$SC_{ShipA,1} = 600 * (0.637 - 0.366) = 163\, tons$

$PP_{i,t} = s_i * D_{i,t}^{PF}$ $\forall i \in I \wedge t \in T$
$PP_{ShipA,5} = 60 * (0.286 - 0.143) = 15\, spools$

Warehouse storage
The warehouse storage distribution formulation is similar to the activity hour calculations. For an in depth calculation see Chapter 8.1.1.2.

$TWA_i = ow_i * wta * T_i^W$ $\forall i \in I$
$TWA_{ShipA} = 300 * 2 * 3 = 1,800\, m^2$
$TWA_{ShipC} = 500 * 2 * 3 = 3,000\, m^2$

Steel storage
To calculate the area required for steel storage no distributions will be used. The calculations for ship A are given below. For each month that is not calculated below, the required steel storage area for ship A is 0.

$SSA_{i,t} = npt_i * pa * d_{i,t}^{SSA} \quad \forall i \in I \wedge t \in T$
$SSA_{ShipA,0} = 6 * 6 * 1 = 36\, m^2$
$SSA_{ShipA,1} = 6 * 6 * 1 = 36\, m^2$
$SSA_{ShipA,2} = 6 * 6 * 1 = 36\, m^2$
$SSA_{ShipA,3} = 6 * 6 * 1 = 36\, m^2$
$SSA_{ShipA,4} = 6 * 6 * 1 = 36\, m^2$
$SSA_{ShipA,5} = 6 * 6 * 1 = 36\, m^2$
$SSA_{ShipA,6} = 6 * 6 * 0 = 0\, m^2$

8.1.2 Model results

Using the input values given in Chapter D, the model can be run. In the previous sections some calculations that the model performs are already showcased. This chapter will concern itself with how the capacity model will run. In order to showcase this five scenarios will be discussed.

For these scenarios the activity showcased will be the steel processing activity. The requirements for other activities and facilities will follow a similar logic. For the calculations in following sections, the assumption will be that the steel processing area and the amount of steel cut per month will be adequate. Therefor, the only limited capacity will be the available steel processing hours.

The results are gathered by implementing the model in Python. By writing a GUI for visualisation purposes graphs can be constructed.

In order to create a scenario some extra input information is necessary. First, the yard were the scenario will be MAEe needs to be given. Secondly, the ships of the scenario must be given. These ships can also be given an extra start date. It could for example be the case that a ship only starts construction two months after the start of another ship.

Furthermore, the decision variables must all be given values. The first of these is the maximum flexibility. This is the maximum value $EP_i^{Activity}$ may take. Additionally, expansion options must be given. The costs and size of these expansions is required. This is normally dependant on the particular yard, but in order to showcase different scenarios in this chapter it is assumed to be scenario specific. Lastly, the costs for outsourcing must also be given. Again, these would be yard specific variables, but will now be discussed on a scenario level.

The used scenarios will be given below. The values of each scenario are chosen to highlight certain parts of the model. The purposes of each scenario will be given with each scenario title.

- Scenario 1: no capacity shortage
  - Yard: Yard Q (steel processing capacity of 250 FTE)
  - Ships: Ship A starting at month 0, Ship C starting at month 3
  - Maximum flexibility: 10%
  - Available expansion: Onetime expansion of 50 FTE's for a cost of 10,000
  - Outsourcing: Cost of 150 per FTE outsourced per month
- Scenario 2: extra percentage required
  - Yard: Yard X (steel processing capacity of 200 FTE)

- Ships: Ship A starting at month 0, Ship C starting at month 3
- Maximum flexibility: 10%
- Available expansion: Onetime expansion of 50 FTE's for a cost of 10,000
- Outsourcing: Cost of 150 per FTE outsourced per month

- Scenario 3: extra percentage and outsourcing required
  - Yard: Yard Y (steel processing capacity of 150 FTE)
  - Ships: Ship A starting at month 0, Ship C starting at month 3
  - Maximum flexibility: 10%
  - Available expansion: Onetime expansion of 50 FTE's for a cost of 10,000
  - Outsourcing: Cost of 150 per FTE outsourced per month
- Scenario 4: extra percentage and capacity required
  - Yard: Yard Y (steel processing capacity of 150 FTE)
  - Ships: Ship A starting at month 0, Ship C starting at month 3
  - Maximum flexibility: 10%
  - Available expansion: Onetime expansion of 50 FTE's for a cost of 5,000
  - Outsourcing: Cost of 150 per FTE outsourced per month
- Scenario 5: extra percentage, capacity and outsourcing required
  - Yard: Yard Z (steel processing capacity of 100 FTE)
  - Ships: Ship A starting at month 0, Ship C starting at month 3
  - Maximum flexibility: 10%
  - Available expansion: Onetime expansion of 50 FTE's for a cost of 10,000
  - Outsourcing: Cost of 150 per FTE outsourced per month

8.1.2.1 Scenario 1: no capacity shortage

In the first scenario ships A and C are being constructed on yard Q. This yard has a steel processing capacity of 250 FTE's. The required steel processing FTE's, as calculated by the model, are given in Table 8.1.

Month	0	1	2	3	4	5	6	7	8	9	10
Required FTE	147	109	75	216	154	103	68	41	20	5	0

Table 8.1: Steel processing requirements for scenario 1 using whole ship level input, given in hours and FTE's

As can be seen in Table 8.1 the required amount of FTE's necessary never exceed 250. This means that the capacity is feasible, even without running the model. This is shown in Figure 8.1.

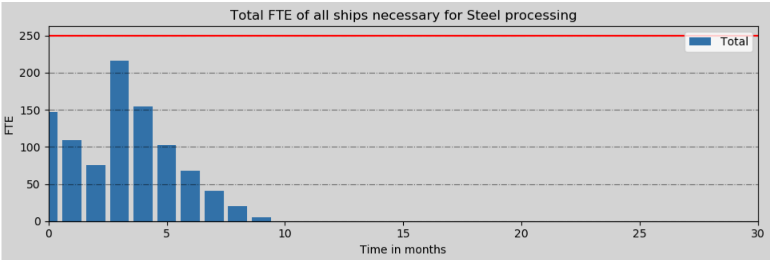

Figure 8.1: Whole ship level scenario 1; capacity is adequate

8.1.2.2 Scenario 2: extra percentage required

Scenario 2 is similar to the first scenario as it concerns the same ships. Therefor, the base requirements are the same as shown in Table 8.1. However, the steel processing FTE capacity is lowered from 250 to 200. This means that the capacity during month 3 will exceed this capacity, as 216 is greater than 200. This is also shown in Figure 8.2.

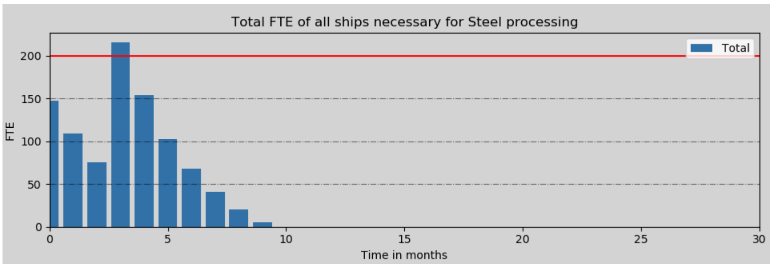

Figure 8.2: Whole ship level scenario 2; capacity is exceeded

If the capacity is exceeded three options are proposed: allow more flexibility to distribute the hours better, acquire extra capacity or outsource some requirements. If more flexibility is allowed this options should be used first, as it does not incur costs.

The allowed flexibility for scenario 2 is 10%. This means that $0.9 \leq EP_i^{Activity} \leq 1.1$. This means that the peak can be reduced by 10%, if the hours can be distributed over the other months. The only month were the requirements exceed the capacity is month 3, where the requirements are 216 FTE's needed. If the requirements are lowered by 10% the new requirement becomes 195 (216 * 0.9, rounded up). Because 195 is less than 200 no extra capacity or outsourcing is needed. This does mean however that the remaining 21 FTE's (216 - 195) should be distributed over the other months.

Month	0	1	2	3	4	5	6	7	8	9	10
Required FTE (before running model)	147	109	75	216	154	103	68	41	20	5	0
Required FTE (after running model)	147	109	75	200	160	108	71	43	20	5	0

Table 8.2: Steel processing requirements for scenario 2 using whole ship level input, before and after running the linear programming model

Table 8.2 shows the difference in required FTE's before and after running the model. As can be seen, before the model is run, the capacity will be exceeded (216 is more than 200). After the model is utilized the capacity will not be exceeded, as the required FTE's during any month never exceed 200. Secondly, the total amount of required FTE's stayed the same, as 147 + 109 + 75 + 216 + 154 + 103 + 68 + 41 + 20 + 5 = 147 + 109 + 75 + 200 + 160 + 108 + 71 + 43 + 20 + 5 + 0 = 938 FTE.

The final graph is shown in Figure 8.3. Shown in this graph is that the capacity will not be exceeded, as the model allowed flexibility. Because no extra capacity or outsourcing is necessary, no extra costs will be made.

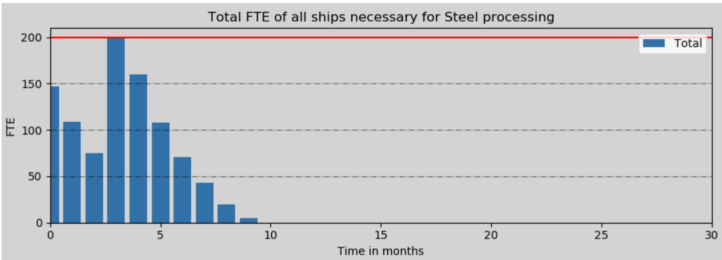

Figure 8.3: Whole ship level scenario 2; capacity is adequate

8.1.2.3 Scenario 3: extra percentage and outsourcing required

Scenario 3 concerns itself with the construction of the same ships as the previous two scenario's, but on a different yard. This yard has a lower capacity of steel processing FTE's, only 150 available FTE's. This causes the capacity to become inadequate, as both 216 and 154 are more than 150. This can be seen in Figure 8.4

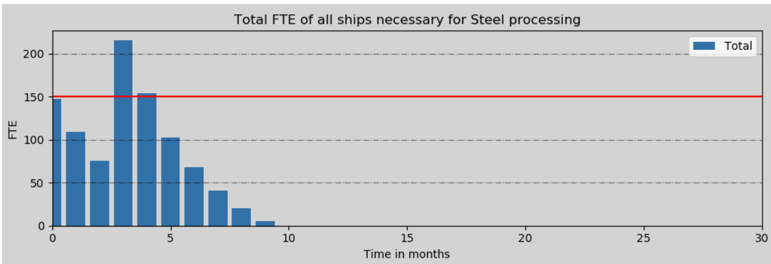

Figure 8.4: Whole ship level scenario 3; capacity is exceeded

The first thing that will be done is utilize the flexibility. The allowed flexibility for this scenario is 10%. A more in depth analysis on flexibility is given in Chapter 8.1.2.2. The added flexibility is enough for month 4, as 139 (154 * 0.9, rounded up) is less than 150. However, during month 3 the capacity will still be exceeded, as 195 (216 * 0.9, rounded up) is more than 150. Which means that even with utilizing the extra flexibility, the capacity will still be exceeded by 45 FTE's in month 3.

In order to solve the capacity problem there are two options left. The capacity can either be increased, or some FTE's should be outsourced. Increasing the capacity incurs a cost of 10,000 in this scenario. Outsourcing the FTE's cost 150 per FTE outsourced, which amounts to a cost of 6,750 (150 * 45). As outsourcing will be cheaper than acquiring extra capacity (as 6,750 is cheaper than 10,000), the extra FTE's will be outsourced.

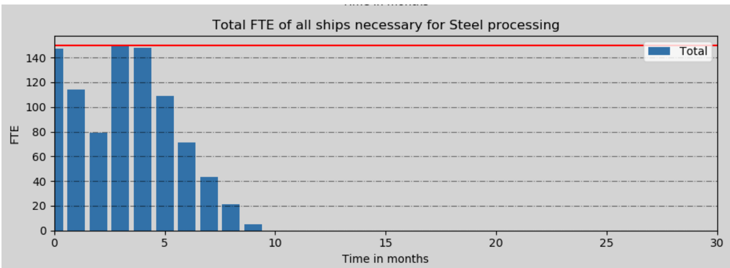

Figure 8.5: Whole ship level scenario 3; capacity is adequate

Figure 8.5 shows that after outsourcing the capacity will be adequate. The amount of hours outsourced can be seen in Figure 8.6.

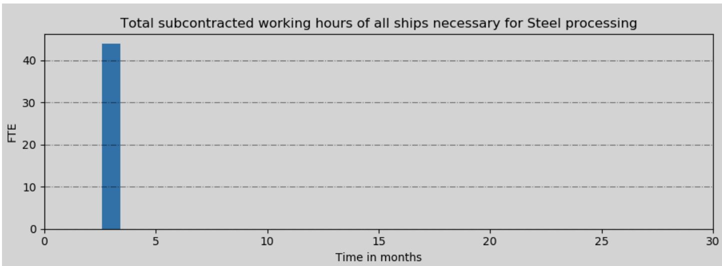

Figure 8.6: Whole ship level scenario 3; amount outsourced

The associated costs with this scenario will be 6,750. This is due to 45 FTE's being outsourced, with each a cost of 150.

8.1.2.4 Scenario 4: extra percentage and capacity required

The fourth scenario is extremely similar to the third scenario, discussed in Chapter 8.1.2.3, with one crucial difference. In scenario 4 extra capacity costs only 5,000 as opposed to the cost of 10,000 in scenario 3. Even so, the situation before the model is used is similar to scenario 3 and can be seen in Figure 8.4.

As with the previous scenario, the capacity during month 3 is still exceeded by 45 FTE. If these FTE's are outsourced the associated costs would be 6,750 (150 * 45). However, in this scenario extra capacity only costs 5,000. Because the extra capacity will be adequate in order to make the capacity adequate, this will now be the cheapest option. This means that instead of the requirements being outsourced, the capacity will be expanded.

The extra expansion is shown in Figure 8.7. The associated costs with this scenario will be 5,000. These costs are due to an extra expansion of 50 FTE's.

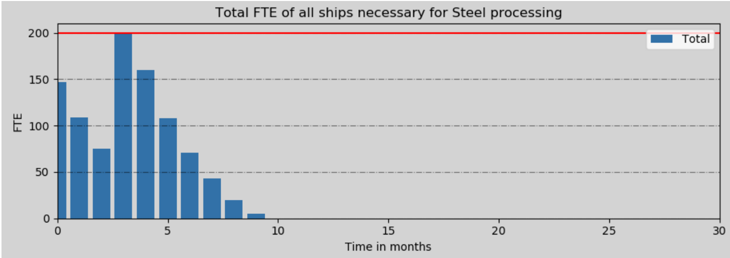

Figure 8.7: Whole ship level scenario 4; capacity is adequate

8.1.2.5 Scenario 5: extra percentage, capacity and outsourcing required

The fifth scenario utilizes the same ships as the previous scenarios, ships A and C. However, this time they are constructed on yard Z. This yard only has a steel processing capacity of 100 FTE's. This situation is visualised in Figure 8.8.

As can be seen in Table 8.1, if the capacity is only 100 FTE's the capacity will be exceeded in months 0, 1, 3, 4, 5. Furthermore, it is impossible to solely use flexibility to solve the capacity shortage. One way to show this is calculating the amount of extra FTE's the months without much requirements can be increased. This is calculated by (75 + 68 + 41 + 20 + 5) * 0.1 and amounts to 21 FTE's. The total amount of FTE's that exceed capacity is 229 (47 + 9 + 116 + 54 + 3). So it's impossible to solve the issue by only using flexibility.

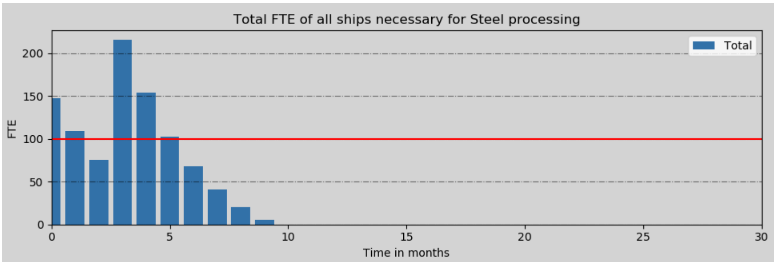

Figure 8.8: Whole ship level scenario 5; capacity is exceeded

First, the capacity will be extended by 50 FTE to 150 FTE. This is because the costs of expanding the capacity is cheaper than outsourcing. The extention costs 5,000 for the first 50 FTE's. Calculating the costs for outsourcing will be a little difficult, as the model determines the precise flexibility. However, the months with lower requirements can only see a total increase of 21 FTE's (as each month can only see a 10% increase in requirements). So if first 50 FTE's that exceed the capacity will be outsourced the minimum cost would be calculated with (47 + 9 + 50 + 50 + 3 - 21) * 150 = 20,700. As can be seen first extending the capacity is desirable, as 10,000 is lower than 20,700.

After the capacity is extended to 150 FTE's the scenario becomes the same as scenario 3, which is discussed in Chapter 8.1.2.3. Without the possibility of an extension the remaining 45 FTE's will be outsourced for an extra cost of 6,750 (45 * 150).

The final situation is given in Figure 8.9. As can be seen the final capacity will be 150 and the capacity will be adequate. There will be 45 FTE's outsourced during month 3. The final extra costs are 16,750. This is due to extra capacity costs of 10,000 and outsourcing costs of 6,750.

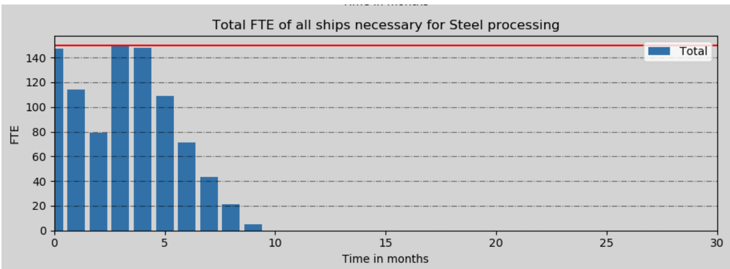

Figure 8.9: Whole ship level scenario 5; capacity is adequate

8.2 Results of the block level model

Now that a block level model has been created it can be used to model ships on a yard. In this chapter the model will be used and the results will be analysed.

8.2.1 Model requirement formulations

The model calculates the requirements of ship construction. These requirement calculations will be shown below.

Some activity and facility requirements are calculated using the same method as the whole ship level model. These calculations are shown in Chapter 8.1.1. Only the new formulations will be explained below.

The same input data used for Chapter 8.1.1 will be used. This input data can be found in Chapters D (for ship input data) & C (for yard input data). However, for the block level model more input data regarding blocks is necessary. This block level input data can be found in Chapter E. The block level data is only given for Ship A, as providing more input data would decrease clarity. Furthermore, the amount of blocks in Ship A has been decreased from 30 to 10, this is also only done for clarity purposes, as the model is capable of handling 30 blocks easily.

8.2.1.1 Activity labour requirements

First the required hours per activity will be calculated. The block level model proposes new formulations for calculating these requirements for certain activities and facilities. The other activities and facilities will be calculated using the methods proposed in the whole ship level model. The requirement calculations for these activities and facilities are discussed in Chapter 8.1.1

The calculations will only be done for ship A. Furthermore, for ship A the calculations for only 3 blocks are done. This is done to increase clarity. The other blocks will use identical formulations.

Looking at the input data given in Chapter E it can be seen that some input data is dependant on block type. The block types proposed are not equivalent to actual block types, but are purely used for showcasing purposes.

Steel processing
The first activity that will be calculated on a block level is steel processing. First the total hours

a block requires for steel processing will need to be calculated. Afterwards the required hours for steel processing will be calculated on a month by month basis. As can be seen below, it is possible to require steel processing hours for multiple blocks during the same month.

$TH_{i,k}^{SP} = c_k^{SP} * n_k + v_k * n_k * y_k^{SP} \qquad \forall i \in I \wedge k \in K_i$
$TH_{ShipA,Block1}^{SP} = 50 * 12 + 0.3 * 12 * 1500 = 6000\, hours$
$TH_{ShipA,Block2}^{SP} = 50 * 14 + 0.3 * 14 * 1500 = 7000\, hours$
$TH_{ShipA,Block5}^{SP} = 50 * 17 + 0.2 * 17 * 1700 = 4930\, hours$

$H_{i,t}^{SP} = \sum_{k \in K_i} \frac{TH_{i,t,k}^{SP}}{dr_k^{SP}} * x_{t,k}^{SP} \qquad \forall i \in I \wedge t \in T$
$H_{ShipA,0}^{SP} = (\frac{6000}{3} * 1) + (\frac{7000}{4} * 1)(\frac{4930}{4} * 0) = 3,750\, hours$
$H_{ShipA,1}^{SP} = (\frac{6000}{3} * 1) + (\frac{7000}{4} * 1)(\frac{4930}{4} * 1) = 4,982.5\, hours$
$H_{ShipA,2}^{SP} = (\frac{6000}{3} * 1) + (\frac{7000}{4} * 1)(\frac{4930}{4} * 1) = 4,982.5\, hours$
$H_{ShipA,3}^{SP} = (\frac{6000}{3} * 0) + (\frac{7000}{4} * 1)(\frac{4930}{4} * 1) = 2,982.5\, hours$
$H_{ShipA,4}^{SP} = (\frac{6000}{3} * 0) + (\frac{7000}{4} * 0)(\frac{4930}{4} * 1) = 1,232.5\, hours$
$H_{ShipA,5}^{SP} = (\frac{6000}{3} * 0) + (\frac{7000}{4} * 0)(\frac{4930}{4} * 0) = 0\, hours$

Steel building
The second block level activity is steel building. On a block level steel building will be divided into block construction and hull assembly. In order to calculate the required steel building hours the required block construction hours will be calculated on a block basis. Afterwards, it will be calculated whether block construction and/or hull assembly takes place on a block in a specific month.

$TH_{i,k}^{SB,BC} = n_k * y_k^{BC} + c_k^{SB} \qquad \forall i \in I \wedge k \in K_i$
$TH_{ShipA,Block1}^{SB,BC} = 12 * 70 + 70 = 890\, hours$
$TH_{ShipA,Block2}^{SB,BC} = 14 * 70 + 70 = 1030\, hours$
$TH_{ShipA,Block5}^{SB,BC} = 12 * 90 + 90 = 1170\, hours$

$H_{i,t}^{SB} = \sum_{k \in K_i} \frac{TH_{i,t,k}^{SB,BC}}{dr_{i,k}^{BC}} * x_{t,k}^{BC} + y_k^{HA} * x_{t,k}^{HA} \qquad \forall i \in I \wedge t \in T$
$H_{ShipA,3}^{SB} = (\frac{890}{3} * 1 + 700 * 0) + (\frac{1030}{2} * 0 + 700 * 0) + (\frac{1170}{2} * 0 + 700 * 0) = 297.7\, hours$
$H_{ShipA,4}^{SB} = (\frac{890}{3} * 1 + 700 * 0) + (\frac{1030}{2} * 0 + 700 * 0) + (\frac{1170}{2} * 0 + 700 * 0) = 297.7\, hours$
$H_{ShipA,5}^{SB} = (\frac{890}{3} * 1 + 700 * 0) + (\frac{1030}{2} * 1 + 700 * 0) + (\frac{1170}{2} * 0 + 700 * 0) = 811.7\, hours$
$H_{ShipA,6}^{SB} = (\frac{890}{3} * 0 + 700 * 0) + (\frac{1030}{2} * 1 + 700 * 0) + (\frac{1170}{2} * 1 + 700 * 0) = 1100\, hours$
$H_{ShipA,7}^{SB} = (\frac{890}{3} * 0 + 700 * 1) + (\frac{1030}{2} * 0 + 700 * 0) + (\frac{1170}{2} * 1 + 700 * 0) = 1285\, hours$
$H_{ShipA,8}^{SB} = (\frac{890}{3} * 0 + 700 * 0) + (\frac{1030}{2} * 0 + 700 * 1) + (\frac{1170}{2} * 0 + 700 * 0) = 700\, hours$
$H_{ShipA,9}^{SB} = (\frac{890}{3} * 0 + 700 * 0) + (\frac{1030}{2} * 0 + 700 * 0) + (\frac{1170}{2} * 0 + 700 * 1) = 700\, hours$
$H_{ShipA,10}^{SB} = (\frac{890}{3} * 0 + 700 * 0) + (\frac{1030}{2} * 0 + 700 * 0) + (\frac{1170}{2} * 0 + 700 * 0) = 0\, hours$

Outfitting
Outfitting is the third activity were the requirements will be calculated on a block level. The method is similar to steel processing. First, the total hours necessary for each block will be calculated. Afterwards, these hours will be distributed over the months where outfitting will take place on that block.

$TH_{i,k}^{O} = ov_k * y_k^{O} + c_k^{O} \qquad \forall i \in I \wedge k \in K_i$

$TH^O_{ShipA,Block1} = 15 * 400 + 840 = 6,840\, hours$
$TH^O_{ShipA,Block2} = 30 * 400 + 840 = 12,840\, hours$
$TH^O_{ShipA,Block5} = 45 * 800 + 875 = 36,875\, hours$

$H^{SP}_{i,t} = \sum_{k \in K_i} \frac{TH^O_{i,t,k}}{d^O_{i,k}} * x^O_{t,k}$ $\forall i \in I \wedge t \in T$
$H^{SP}_{ShipA,8} = (\frac{6,840}{4} * 1) + (\frac{12,840}{3} * 0) + (\frac{36,875}{5} * 0) = 1,710\, hours$
$H^{SP}_{ShipA,9} = (\frac{6,840}{4} * 1) + (\frac{12,840}{3} * 1) + (\frac{36,875}{5} * 0) = 5,990\, hours$
$H^{SP}_{ShipA,10} = (\frac{6,840}{4} * 1) + (\frac{12,840}{3} * 1) + (\frac{36,875}{5} * 1) = 13,365\, hours$
$H^{SP}_{ShipA,11} = (\frac{6,840}{4} * 1) + (\frac{12,840}{3} * 1) + (\frac{36,875}{5} * 1) = 13,365\, hours$
$H^{SP}_{ShipA,12} = (\frac{6,840}{4} * 0) + (\frac{12,840}{3} * 0) + (\frac{36,875}{5} * 1) = 7,375\, hours$
$H^{SP}_{ShipA,13} = (\frac{6,840}{4} * 0) + (\frac{12,840}{3} * 0) + (\frac{36,875}{5} * 1) = 7,375\, hours$
$H^{SP}_{ShipA,14} = (\frac{6,840}{4} * 0) + (\frac{12,840}{3} * 0) + (\frac{36,875}{5} * 1) = 7,375\, hours$
$H^{SP}_{ShipA,15} = (\frac{6,840}{4} * 0) + (\frac{12,840}{3} * 0) + (\frac{36,875}{5} * 0) = 0\, hours$

Painting & Blasting
Lastly, the activity requirements for painting & blasting will also be calculated on an individual block level. As painting & blasting on a block always takes a full month, only two things need to be determined. First, whether or not painting and blasting occurs on a block and secondly how long this will take. This is shown in the calculations below.
$H^{PB}_{i,t} = \sum_{k \in K_i} x^O_{t,k} * hpb$ $\forall i \in I \wedge t \in T$
$H^{PB}_{ShipA,7} = (1 * 450) + (0 * 450) + (0 * 450) = 450\, hours$
$H^{PB}_{ShipA,8} = (0 * 450) + (1 * 450) + (0 * 450) = 450\, hours$
$H^{PB}_{ShipA,9} = (0 * 450) + (0 * 450) + (1 * 450) = 450\, hours$
$H^{PB}_{ShipA,10} = (0 * 450) + (0 * 450) + (0 * 450) = 0\, hours$

8.2.1.2 Facility requirements

In the block level model the facilities will be calculated using a similar method to the activity requirements.

Steel processing/building area
The first facility that will be calculated using a block level approach is the required steel processing area. First the total area needed per block is calculated. Afterwards these hours are divided over the months.
$TSPA_{i,k} = \sum_{l \in L_k} (l_l + ml) * (w_l * mw) * np_{l,k}$ $\forall i \in I \wedge k \in K_i$
$TSPA_{ShipA,Block1} = ((3+1)*(5+1)*6)+((3+1)*(5+1)*0)+((2+1)*(4+1)*6)+((2+1)*(4+1)*0) = 234\, m^2$
$TSPA_{ShipA,Block2} = ((3+1)*(5+1)*6)+((3+1)*(5+1)*0)+((2+1)*(4+1)*8)+((2+1)*(4+1)*0) = 264\, m^2$
$TSPA_{ShipA,Block3} = ((3+1)*(5+1)*6)+((3+1)*(5+1)*4)+((2+1)*(4+1)*6)+((2+1)*(4+1)*1) = 354\, m^2$

$SPA_{i,t} = \sum_{k \in K_i} \frac{TA_{i,k}}{dr^{SP}_k} * x^{SP}_{t,k}$ $\forall i \in I \wedge t \in T$
$SPA_{ShipA,0} = (\frac{234}{3} * 1) + (\frac{264}{4} * 1) + (\frac{354}{4} * 0) = 144\, m^2$
$SPA_{ShipA,1} = (\frac{234}{3} * 1) + (\frac{264}{4} * 1) + (\frac{354}{4} * 1) = 232.5\, m^2$
$SPA_{ShipA,2} = (\frac{234}{3} * 1) + (\frac{264}{4} * 1) + (\frac{354}{4} * 1) = 232.5\, m^2$

$SPA_{ShipA,3} = (\frac{234}{3} * 0) + (\frac{264}{4} * 1) + (\frac{354}{4} * 1) = 154.5\, m^2$
$SPA_{ShipA,4} = (\frac{234}{3} * 0) + (\frac{264}{4} * 0) + (\frac{354}{4} * 1) = 88.5\, m^2$
$SPA_{ShipA,5} = (\frac{234}{3} * 0) + (\frac{264}{4} * 0) + (\frac{354}{4} * 0) = 0\, m^2$

Building frames
The required building frames will be calculated using two input variables, the amount of building frames necessary for a block, and whether or not that block requires building frames during that month. Summing over all blocks will give the required building frames that month.
$Bf_{i,t} = \sum_{k \in K_i} nbf_k * x^{BC}_{t,k}$ $\quad \forall i \in I \wedge t \in T$
$Bf_{ShipA,3} = (2 * 1) + (2 * 0) + (1 * 0) = 2$
$Bf_{ShipA,4} = (2 * 1) + (2 * 0) + (1 * 0) = 2$
$Bf_{ShipA,5} = (2 * 1) + (2 * 1) + (1 * 0) = 4$
$Bf_{ShipA,6} = (2 * 0) + (2 * 1) + (1 * 1) = 3$
$Bf_{ShipA,7} = (2 * 0) + (2 * 0) + (1 * 1) = 1$
$Bf_{ShipA,8} = (2 * 0) + (2 * 0) + (1 * 0) = 0$

Hull assembly area
The hull assembly area is a value that keeps increasing each time a new bottom block is added. After outfitting is entirely done and the ship is launched, this area will no longer be used for the ship, meaning the area becomes 0 m^2. As block 1 and 2 are bottom blocks, they add area. However, block 5 is not a bottom block and therefor does not increase the hull assembly area.
$HA_{i,t} = \sum_{k \in K_i} aa_k * x^{HAA}_{t,k}$ $\quad \forall i \in I \wedge t \in T$
$HA_{ShipA,7} = (200 * 1) + (250 * 0) + (0 * 0) = 200\, m^2$
$HA_{ShipA,8} = (200 * 1) + (250 * 1) + (0 * 0) = 450\, m^2$
$HA_{ShipA,9} = (200 * 1) + (250 * 1) + (0 * 1) = 450\, m^2$
$HA_{ShipA,10} = (200 * 1) + (250 * 1) + (0 * 1) = 450\, m^2$
$HA_{ShipA,15} = (200 * 1) + (250 * 1) + (0 * 1) = 450\, m^2$
$HA_{ShipA,16} = (200 * 1) + (250 * 1) + (0 * 1) = 450\, m^2$
$HA_{ShipA,17} = (200 * 0) + (250 * 0) + (0 * 0) = 0\, m^2$

Painting and blasting hall
The painting and blasting hall gets used when a block undergoes the painting & blasting activity. The entire block will be present in the hall. So each block that performs the painting & blasting activity during a particular month increases the required area, but only during that month.
$PBA_{i,t} = \sum_{k \in K_i} a_k * x^{O}_{t,k}$ $\quad \forall i \in I \wedge t \in T$
$PBA_{ShipA,7} = (200 * 1) + (250 * 0) + (250 * 0) = 200\, m^2$
$PBA_{ShipA,8} = (200 * 0) + (250 * 1) + (250 * 0) = 250\, m^2$
$PBA_{ShipA,9} = (200 * 0) + (250 * 0) + (250 * 1) = 250\, m^2$
$PBA_{ShipA,10} = (200 * 0) + (250 * 0) + (250 * 0) = 0\, m^2$

Limits on steel cutting
The limits of steel cutting are calculated by the weight of the steel plates that are being cut. First the total weight for each block is calculated. Then these values are distributed according to the steel processing months of each block.
$TSC_{i,k} = \sum_{l \in L_k} wg_l * np_{l,k}$ $\quad \forall i \in I \wedge k \in K_i$
$TSC_{ShipA,Block1} = (60 * 6) + (30 * 6) = 540\, kg$

$TSC_{ShipA,Block2} = (60 * 6) + (30 * 8) = 600\,kg$
$TSC_{ShipA,Block5} = (60 * 6) + (100 * 4) + (30 * 6) + (60 * 1) = 1,000\,kg$

$SC_{i,t} = \sum_{k \in K_i} \frac{SC_{i,k}}{dr_k^{SP}} * x_{t,k}^{SP} \qquad \forall i \in I \wedge t \in T$
$SC_{ShipA,0} = (\frac{540}{3} * 1) + (\frac{600}{4} * 1) + (\frac{1000}{4} * 0) = 330\,kg$
$SC_{ShipA,1} = (\frac{540}{3} * 1) + (\frac{600}{4} * 1) + (\frac{1000}{4} * 1) = 550\,kg$
$SC_{ShipA,2} = (\frac{540}{3} * 1) + (\frac{600}{4} * 1) + (\frac{1000}{4} * 1) = 550\,kg$
$SC_{ShipA,3} = (\frac{540}{3} * 0) + (\frac{600}{4} * 1) + (\frac{1000}{4} * 1) = 350\,kg$
$SC_{ShipA,4} = (\frac{540}{3} * 0) + (\frac{600}{4} * 0) + (\frac{1000}{4} * 1) = 200\,kg$
$SC_{ShipA,5} = (\frac{540}{3} * 0) + (\frac{600}{4} * 0) + (\frac{1000}{4} * 0) = 0\,kg$

Warehouse storage
The warehousing storage calculations will be performed using the first method. This means that no individual item information is used. This is done because this item information is currently not readily available even in the later proposal phase.

First, the required area for each block during each month will be calculated. This is shown below for block 1. Afterwards, these requirements are summed during during each month to get the warehousing storage required during that month.
$BWA_{k,t} = (1 - \frac{t - s_k^O}{dr_k^O}) * ov_k * x_{t,k}^O + ov_k * x_{t,k}^{WO} \qquad \forall t \in T_k^O \wedge k \in K$
$BWA_{Block1,7} = (1 - \frac{8-8}{4}) * 20 * 0 + 20 * 1 = 20\,m^3$
$BWA_{Block1,8} = (1 - \frac{8-8}{4}) * 20 * 1 + 20 * 0 = 20\,m^3$
$BWA_{Block1,9} = (1 - \frac{9-8}{4}) * 20 * 1 + 20 * 0 = 15\,m^3$
$BWA_{Block1,10} = (1 - \frac{10-8}{4}) * 20 * 1 + 20 * 0 = 10\,m^3$
$BWA_{Block1,11} = (1 - \frac{11-8}{4}) * 20 * 1 + 20 * 0 = 5\,m^3$
$BWA_{Block1,12} = (1 - \frac{11-8}{4}) * 20 * 0 + 20 * 0 = 5\,m^3$

$WA_t = \sum_{k \in K} BWA_{k,t} \qquad \forall t \in T$
$WA_7 = (20) + (0) + (0) = 20\,m^3$
$WA_8 = (20) + (30) + (0) = 20\,m^3$
$WA_9 = (15) + (30) + (40) = 85\,m^3$
$WA_{10} = (10) + (20) + (40) = 70\,m^3$
$WA_{11} = (5) + (10) + (32) = 47\,m^3$
$WA_{12} = (0) + (0) + (24) = 24\,m^3$
$WA_{13} = (0) + (0) + (16) = 16\,m^3$
$WA_{14} = (0) + (0) + (8) = 8\,m^3$
$WA_{15} = (0) + (0) + (0) = 0\,m^3$

Steel storage
The required steel storage area is the last area that still needs to be calculated. The required area formulation utilizes the months that a certain plate type is used in a block. So if a plate type is used at all in a block, a storage pile should be available for that type.

In order to calculate whether the area is available the two inequalities are added. It is important for these inequalities to be true. As can be seen, in this case they are true. For example, $x_{typea,2}^{SS}$ has to be one, because $(6 * 1) + (6 * 1) + (6 * 1) \leq 1000000 * 0$, becoming $18 \leq 0$ is not valid. Furthermore, $x_{typea,5}^{SS}$ has to be zero. This is because $(6 * 0) + (6 * 0) + (6 * 0) \geq 0.01 - 1000000 * (1 - 1)$, becoming

$0 \geq 0.01$ is not valid.
$SSA_t = \sum_{l \in L} x^{SS}_{l,t} * A_l \qquad \forall t \in T$
$SSA_0 = (1*24) + (0*24) + (1*12) + (0*12) = 36\,m^2$
$SSA_1 = (1*24) + (1*24) + (1*12) + (1*12) = 72\,m^2$
$SSA_2 = (1*24) + (1*24) + (1*12) + (1*12) = 72\,m^2$
$SSA_3 = (1*24) + (1*24) + (1*12) + (1*12) = 72\,m^2$
$SSA_4 = (1*24) + (1*24) + (1*12) + (1*12) = 72\,m^2$
$SSA_5 = (0*24) + (1*24) + (0*12) + (1*12) = 36\,m^2$
$SSA_6 = (0*24) + (0*24) + (0*12) + (0*12) = 0\,m^2$

$\sum_{i \in I} \sum_{k \in K_i} np_{l,k} * x^{SP}_{t,k} \geq 0.01 - M * (1 - x^{SS}_{l,t}) \qquad \forall l \in L \wedge t \in T$
$(np_{typea,Block1} * x^{SP}_{t,Block1}) + (np_{typea,Block2} * x^{SP}_{t,Block2}) + (np_{typea,Block5} * x^{SP}_{t,Block5}) \geq M * (1 - x^{SS}_{typea,t})$
$(6*1) + (6*1) + (6*0) \geq 0.01 - 1000000 * (1-1)$
$(6*1) + (6*1) + (6*1) \geq 0.01 - 1000000 * (1-1)$
$(6*1) + (6*1) + (6*1) \geq 0.01 - 1000000 * (1-1)$
$(6*0) + (6*1) + (6*1) \geq 0.01 - 1000000 * (1-1)$
$(6*0) + (6*0) + (6*1) \geq 0.01 - 1000000 * (1-1)$
$(6*0) + (6*0) + (6*0) \geq 0.01 - 1000000 * (1-0)$

$\sum_{i \in I} \sum_{k \in K_i} np_{l,k} * x^{SP}_{t,k} \leq M * x^{SS}_{l,t} \qquad \forall l \in L \wedge t \in T$
$(np_{typea,Block1} * x^{SP}_{t,Block1}) + (np_{typea,Block2} * x^{SP}_{t,Block2}) + (np_{typea,Block5} * x^{SP}_{t,Block5}) \leq M * x^{SS}_{typea,t}$
$(6*1) + (6*1) + (6*0) \leq 1000000 * 1$
$(6*1) + (6*1) + (6*1) \leq 1000000 * 1$
$(6*1) + (6*1) + (6*1) \leq 1000000 * 1$
$(6*0) + (6*1) + (6*1) \leq 1000000 * 1$
$(6*0) + (6*0) + (6*1) \leq 1000000 * 1$
$(6*0) + (6*0) + (6*0) \leq 1000000 * 0$

8.2.2 Model results

Using the ship input values of Chapter D and the block input values of Chapter E, a block level model can made. This model will showcase whether or not the capacity on the yard will be adequate, and what the extra costs will be if it is not. This is done by running three scenarios.

Just like in Chapter 8.1.2 the steel processing activity will be used to show how the model behaves. Other activities and facilities will use a similar logic. Furthermore, it will be once again assumed that the only limited capacity will be the available FTE's for steel processing.

Three scenarios are discussed to showcase the new capabilities of the model. For more information about expansion of the capacity Chapter 8.1.2 can be used.

The used scenarios are as following. Notice how the costs for outsourcing are constant for each block. This is done for clarity purposes, but would not be realistic.

- Scenario 1: no capacity shortage
  - Yard: Yard K (steel processing capacity of 100 FTE)
  - Ships: Ship A starting at month 0

- Maximum flexibility: 10%
- Outsourcing: Cost of 20,000 per block outsourced

- Scenario 2: extra percentage required
  - Yard: Yard L (steel processing capacity of 85 FTE)
  - Ships: Ship A starting at month 0
  - Maximum flexibility: 10%
  - Outsourcing: Cost of 20,000 per block outsourced
- Scenario 3: extra percentage and outsourcing required
  - Yard: Yard M (steel processing capacity of 60 FTE)
  - Ships: Ship A starting at month 0
  - Maximum flexibility: 10%
  - Outsourcing: Cost of 20,000 per block outsourced

8.2.2.1 Scenario 1: no capacity shortage

The first scenario describes the construction of ship A on yard K. Yard K has a steel processing capacity of 100 FTE's. Using the model calculations, the required FTE's for steel processing of ship A can be found in Table 8.3.

Month	0	1	2	3	4	5	6
Required hours	5,179	11,569	13,577	9,410	3,240	686	0
Required FTE	40	78	91	63	22	5	0

Table 8.3: Steel processing requirements for scenario 1 using block level input, given in hours and FTE's

As the table above shows, the requirements never exceed 100 FTE. This means that the capacity will be adequate. Figure 8.10 further confirms this.

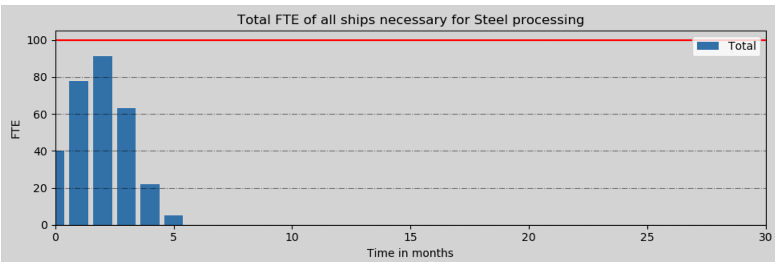

Figure 8.10: Block level scenario 1; capacity is adequate

8.2.2.2 Scenario 2: extra percentage required

In the second scenario ship A is constructed on yard L. This yard only has a capacity of 85 steel processing FTE's, lower than yard K.

As can be seen in Table 8.3 in the previous Chapter the required FTE's during month 2 is 91. This means that during this month the capacity would be exceeded. Figure 8.11 shows that the capacity is indeed exceeded.

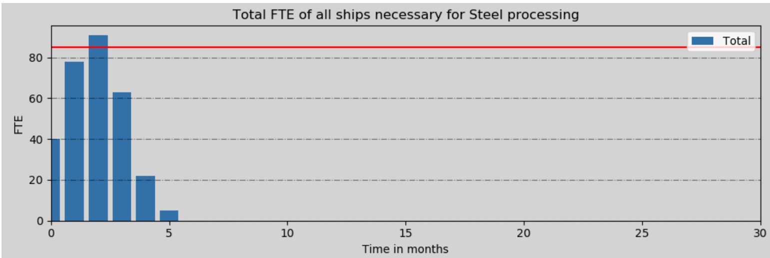

Figure 8.11: Block level scenario 2; capacity is exceeded

If the capacity is exceeded the most cost effective solution would be to allow flexibility. The maximum flexibility in this scenario is 10%. This means that within each block the hours required each month can be raised or lowered by 10%. If it is possible for all blocks that use required hours during month 3 to require 10% less than the new requirement would be 91 * 0.9 = 82 FTE. This would not exceed the total capacity.

Using extra flexibility, the capacity would be feasible. This can be seen in Figure 8.12.

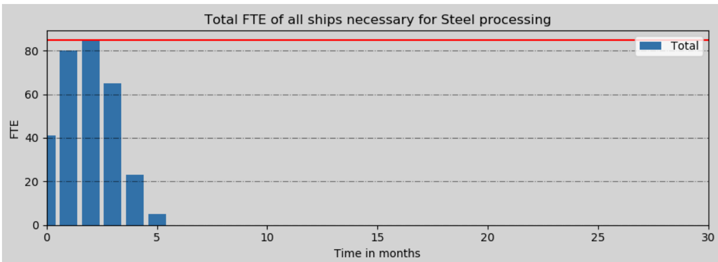

Figure 8.12: Block level scenario 2; capacity is adequate

Table 8.4 shows the new requirements after running the model. As can be seen the FTE requirement in month 3 is now 85 FTE, which does not exceed the capacity. Furthermore, the total required FTE's stayed the same, as 40 + 78 + 91 + 63 + 22 + 5 = 41 + 80 + 85 + 65 + 23 + 5 = 299 FTE's.

Month	0	1	2	3	4	5	6
Required FTE (before running model)	40	78	91	63	22	5	0
Required FTE (after running model)	41	80	85	65	23	5	0

Table 8.4: Steel processing requirements for scenario 2 using block level input, before and after running the linear programming model

8.2.2.3 Scenario 3: extra percentage and outsourcing required

In the last scenario ship A will be constructed on yard M. This yard has a steel processing capacity of only 60 FTE.

As Table 8.3 shows, if the capacity is only 60 FTE's, the capacity will be exceeded. This can also be seen in Figure 8.13. This excess of requirements cannot be solved purely by flexibility. Because extra capacity is not available in this scenario, blocks will need to be outsourced.

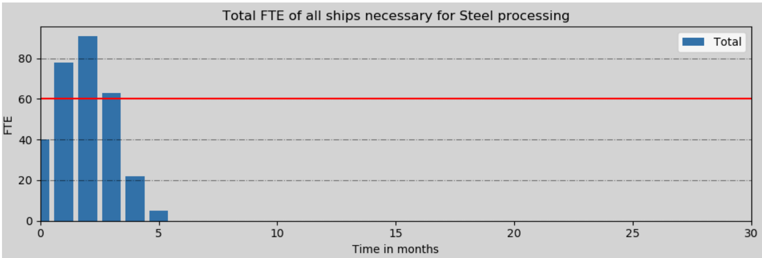

Figure 8.13: Block level scenario 3; capacity is exceeded

Outsourcing in the block level model works slightly different as opposed to the whole ship level model. For the block level activities outsourcing will happen on a block level. If for a block level activity a part of the block needs to be outsourced, the entire block will be outsourced.

In scenario 3 each block costs has the same outsourcing costs. Therefor, outsourcing blocks that require a lot of hours will be more beneficial. Table 8.6 shows the hour requirements per block.

Block	Total hours	Hours per month	Starting month	Duration
Block 1	6,000	2,000	0	3
Block 2	7,000	1,750	0	4
Block 3	6,500	2,167	0	3
Block 4	6,240	2,080	1	3
Block 5	4,930	1,233	1	4
Block 6	7,020	2,340	1	3
Block 7	1,830	610	2	3
Block 8	2,745	686	2	4
Block 9	2,135	712	2	3
Block 10	4,160	1,387	3	3

Table 8.5: Steel processing requirements per individual block in scenario 3

First the peak during month 2 needs to be lowered. It is most efficient to outsource block 3 first, as that block requires the most hours in month 2, and it costs the same to outsource as the other blocks. After outsourcing block 3 the required hours will be 13,577 - 2,167 = 11,410 hours = 77 FTE's. This still exceeds the capacity of 60 FTE's, so more outsourcing will be necessary

Additionally, because block 3 will be outsourced the required hours for month 1 will also be lower. The new required hours for month 1 will be 11,569 - 2,167 = 9402 = 63 FTE's.

The second block that is a candidate for outsourcing is block 4, following the same reasoning as block 3. This block requires 2,080 hours in month 2. If block 4 will be outsourced the required hours will be 11,410 - 2,080 = 9,330 hours = 63 FTE's. Furthermore, the required hours for month 1 will also be lowered to 9402 - 2080 = 7322 = 49 FTE's. This means that the capacity for month 1 is adequate. Moreover, because blocks 3 and 4 are outsourced the capacity for month 3 will also be adequate.

The last month were the capacity is still inadequate is month 3, where the required FTE's are 63. However, this can be solved using the extra flexibility, as 63 * 0.9 = 57, which is lower than 60. So outsourcing blocks 3 and 4 and using extra flexibility allows the ship construction to be completed on the yard.

The final situation can be seen in Figure 8.14. As can be seen, when blocks 3 and 4 are outsourced and some of the added flexibility is used, the capacity will be adequate.

Figure 8.14: Block level scenario 3; capacity is adequate

The requirements can be found in Table 8.6. As can be seen the total FTE's required after running the model are slightly more than before. This is due to how FTE's are always rounded up. Furthermore, it can be seen that flexibility is applied during month 2.

Month	0	1	2	3	4	5	6
Required FTE (before running model)	40	78	91	63	22	5	0
Required FTE (after running model)	26	50	60	50	22	5	0
Outsourced FTE (after running model)	15	29	29	14	0	0	0

Table 8.6: Steel processing requirements for scenario 3 using block level input, before and after running the linear programming model

The hours outsourced can be found in Figure 8.15. The total extra costs in this scenario would be 40,000 due to the two outsourced blocks.

Figure 8.15: Block level scenario 3; outsourcing of blocks 3 & 4

8.3 Accuracy & completeness

8.3.1 Completeness

The current model DSNS utilizes to make a planning includes 8 activities and their facilities. However, analysis of the shipbuilding process shows that not all elements are currently taken into account. The current model proposed adds two activities to this total, warehousing and painting & blasting.

The largest activity currently not included in the planning was warehousing. First of all, warehousing requires quite a lot of hours during a project, mostly because of the constant need of warehousing. Figure 8.16 shows that around 5% of the total hours during the project is because of warehousing. As can be seen, if warehousing would be included in the planning, only around 5% of the total hours will not be planned for. Furthermore, warehousing requires quite a lot of space on the shipyards, especially on foreign yards where space might need to be shared between different shipbuilding companies. Interviews with employees conclude that warehousing space has caused issues in the past.

The second activity that used to not be included in the SYM was painting & blasting. This activity does not require a lot of personnel in order to function. However, because of limited space this is an important bottleneck. This is because of the limited capacity of the painting & blasting facilities. Blocks need to stay in this facility for quite a while in order to preserve the quality. Hiring more employees will not speed this activity up much, mainly because of the drying time. Including this activity will give a better overview where potential bottlenecks and delays in the proposal might lie.

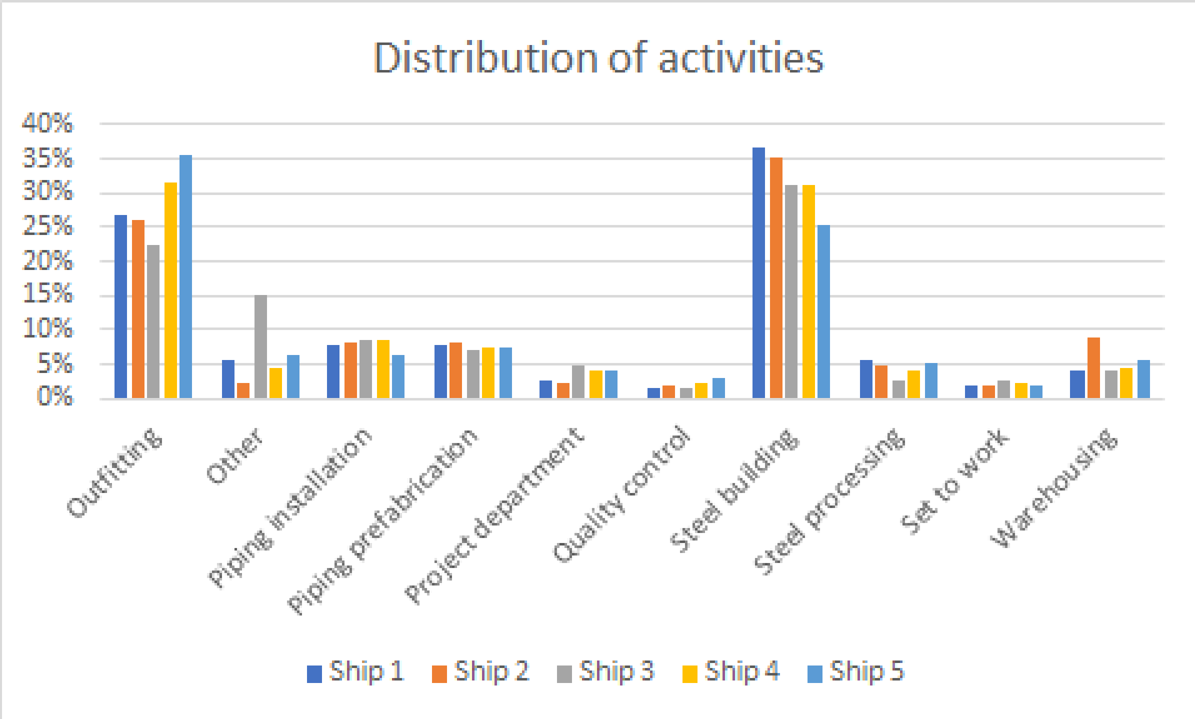

Figure 8.16: Percentage of total working hours of activities

As can be seen in Figure 8.16 the new whole ship level model and block level model are about 95 % complete in terms of activity hour requirements, with 5% of the not modelled hours being in the "other" category. This "other" category chiefly consists of: managerial activities not related to the other activities, foreign yard support, outsourcing support and painting & blasting.

Calculating the completeness of the facility requirements is more difficult to calculate with quantitative data, due to the lack of available information. However, after reviewing multiple shipyards and conducting interviews with professionals in the field almost all yard facilities are included in the model. Like mentioned earlier, the greatest addition here is the painting & blasting hall. Small gains could still be made by modelling more employee facilities, e.g. parking spots. Due to the relatively small amount of added insight these facilities give they are not included in the model.

8.3.2 Accuracy

For the purposes of creating a strategic planning model assessing whether feasibility will be adequate, two models were created. One model utilizes only low detail whole ship level information, the other utilizing more detailed block level information.

As mentioned in Chapter 5.1.2 real data from ships has been used to calculate the calculations & distributions. Some of this data has been used to determine input values. However, some ships have been put aside to test the accuracy of the model.

In order to assess the increase in accuracy the old model is compared to the new models. This is done by comparing the requirements each month using three methods to determine the improvement in accuracy.

The Mean Squared Error (MSE) technique has also been used in Chapter 5.1.2 to determine the best alpha and beta values. The MSE has been widely used due to its theoretical relevance in statistical modeling (Hyndman & Koehler, 2006). It squares the difference between the calculated requirements and the real requirements each month and sums them all up. This method penalises large errors more severely that minor errors. Imagine there are only two errors in two distinct prediction models. The first model has an error of 30 and an error of 20, the second model has an error of 45 and an error of 5. The MSE will be $\frac{30^2+20^2}{2} = 650$ for the first model and $\frac{45^2+5^2}{2} = 1025$ for the second model, meaning the first model will be deemed more accurate. The more severe punishment for larger error values can be positive, but has also been criticized (Armstrong, 2001).

The second method used is the Mean Absolute Error (MAE). This method calculates the absolute difference between the calculated requirements and the real data. An advantage to calculating the MAE is that it is easily understood, as opposed to techniques like the MSE (Hyndman & Athanasopoulos, n.d.). Both the MSE and MAE values are not useful on their own. However, the values of the new model can be compared to the value of the old model.

Activity	Percentage change MSE WSL model	Percentage change MSE BL model	Percentage change MAE WSL model	Percentage change MAE BL model
Steel processing	24.5 %	26.3 %	19.8 %	20.4 %
Steel building	31.1 %	35.5 %	21.1 %	25.0 %
Outfitting	27.8 %	32.1 %	25.0 %	31.3 %
Piping fabrication	23.0 %	23.0 %	20.5 %	20.5
Piping installation	16.1 %	16.1 %	11.3 %	11.3 %
Quality control	17.1 %	17.1 %	8.6 %	8.6 %
Project department	16.2 %	16.2 %	15.9 %	15.9 %
Set to work	17.5 %	17.5 %	14.9 %	14.9 %

Table 8.7: Accuracy increase of the whole ship level model and the block level model in comparison with the old model

Table 8.7 shows the increases in MSE and MAE for the activities that were included in the old model. As painting & blasting and warehousing were not included in this model, their relative increase can not be shown. The calculated MSE and MAE values are based on the real model outputs of the analysed ships.

The first thing to notice is that all the percentages are positive numbers. This is due to the fact that the table shows the relative accuracy increase. This means however that the MSE and MAE have both decreased, which in turn means that the error terms have decreased. So a decrease in the MSE and MAE leads to an increase in accuracy.

The second aspect to notice is that the new total hour calculations only account for a small increase of accuracy. Quality control, project department and set to work kept the same total hour calculations. Yet their accuracy increase is only slightly lower than the other activities. This means that the better fitted distributions play a bigger role in the increase of accuracy of the model than the total hour calculations.

Furthermore, it can be seen that the decrease in MSE is always higher than the increase in MAE.

This means that the model is especially more accurate in removing large error values. A high MSE might be caused by a few large errors in the data. This means that even a single data point might cause a high MSE.

Another method for assessing accuracy will also be utilized, the Mean Absolute Percentage Error (MAPE). Like the MSE, this is a primary metric that is useful in determining accuracy in time series (Makridakis et al., 1982). This value is calculated by calculating the percentage of the error terms. For example, if the calculated requirement is 1100 hours and the real requirement is 1000 hours, than the MAPE for that month is 100 / 1000 = 10 %. There are however drawbacks to using the MAPE. A major drawback is that an error larger than the actual data point results in a larger MAPE compared to an equally large error that occurs below the actual data point (Makridakis et al., 1993).

Activity	MAPE old model	MAPE WSL model	MAPE BL model
Steel processing	10.5 %	8.5 %	8.4 %
Steel building	13.1 %	10.3 %	9.8 %
Outfitting	12.4 %	9.3 %	8.5 %
Piping fabrication	11.5 %	9.1 %	9.1
Piping installation	9.9 %	8.8 %	8.8 %
Quality control	9.1 %	8.3 %	8.3 %
Project department	9.6 %	8.1 %	8.1 %
Set to work	15.8 %	13.5 %	10.9 %
Warehousing	N/A	11.1 %	11.1 %
Painting & blasting	N/A	8.1 %	6.1 %

Table 8.8: Comparison of the MAPE of the old model, the whole ship level model & the block level model

Table 8.8 shows the Mean Absolute Percentage Error for the old model, whole ship level model and the block level model. These are again based on the real ship data discussed in earlier chapters. As can be seen the WSL and BL models have a lower MAPE, which means that on average, the deviation will be smaller. This was already expected, as the MAE of the models were also lower than the old model.

9 Conclusion

For the purpose of gaining tactical and strategic insights into the shipbuilding process during the proposal phase, two models have been created. These models show whether or not the capacity of chosen yards will be feasible for the construction of particular ships.

The first model can be used in very early stages of the proposal stage. It uses fairly rough ship estimates as input data and uses this to determine whether constructing a ship on a yard is feasible. It does this by dividing the entire shipbuilding process into ten activities and calculating the labour and physical requirements of these activities. If these requirements are exceeded the model will also calculate the appropriate extra capacity and outsourcing costs.

A second model has also been constructed. This model can be used in later stages of the proposal phase where more detailed information about the ship is available. This model uses this more detailed information to gain more detailed insights about the required capacity. It does so by dividing the ship into blocks and planning those blocks over the entire shipbuilding process.

9.1 Research questions

Sub question 1

How can a substantiated estimation of the requirements of selected ships throughout a project be calculated?

This thesis proposes two methods for the calculation of the requirements. First, a whole ship level approach has been used. Secondly a block level approach has been used. This block level approach will be discussed in sub question 3.

For the whole ship level approach, formulations for the total required amount of working hours are discussed in Chapter 5.1.1. In Chapter 5.1.2 these total requirements are distributed. Chapter 5.2 calculates and distributes the facility requirements.

Sub question 2

How can the completeness of the yard planning model be improved with the inclusion of additional activities & facilities?

After analysis of the ship constructing process two new activities have been added to the model. These activities are warehousing and painting & blasting. Furthermore, their appropriate facilities, the warehouse and the painting & blasting hall, are also included. The increase of completeness of the SYM by the addition of these two new activities is discussed in Chapter 8.3.1. The current model is about 95 % complete in terms of working hour requirements. The completeness of facility requirements is also deemed to be extremely high.

The required hours for these two activities are discussed in Chapter 5.1.1 and distributed in Chapter 5.1.2, like the other activities. The required facilities for painting & blasting are calculated in Chapter 5.2.5. The facility requirements appropriate to warehousing are discussed in Chapters 5.2.8 for the outfitting items, and Chapter 5.2.9 for steel storage.

Sub question 3

How can subdividing a ship into smaller units increase the accuracy of the yard planning model?

As mentioned earlier two models are made, a whole ship level model and a block level model. The block level model utilizes a subdivision of the ship, namely the blocks. Blocks are small building units that make up the total ship. This block level model is discussed in Chapter 6. The accuracy of this addition is discussed in Chapter 8.3.2. As can be seen the block level model has a higher accuracy for all block level activities relative to both the old model and the whole ship model.

Sub question 4

How can a realistic model be created by taking into account activity correlations and shipyard capacities by making use of subcontracting?

Previous sub-questions address the calculation of requirements. However, this does not give insight in the feasibility of constructing ships on a yard. In total two models have been created to see whether certain scenarios are feasible. The whole ship level model can be found in Chapter 5, and the block level model in Chapter 6.

As can be seen both models utilize three decision variables that can be used to make the capacity feasible. More flexibility can be allowed, more capacity can be added and parts of the project can be subcontracted / outsourced. As can be seen there are correlations between activities and facilities. For example, if steel processing is outsourced, the required amount of steel processing area necessary also decreases.

Sub question 5

How can visualisation and interactivity be used to clearly communicate the planning?

In Chapter 7 a GUI (Graphic User Interface) has been created for the model. It is possible to easily change input data in this program, and slightly tweak scenarios for analysis purposes. Furthermore, the outcome of the model is presented in a clear way to effectively communicate the planning to others.

Main research question

How can a complete and accurate high level strategic planning model that analyses the capacity feasibility of a proposed project be created, with limited current information?

During this thesis two planning models have been created. Both are strategic planning models that assess the feasibility of constructing proposed ships on a particular yard. The first model uses only very low detailed input, that will be available early in the proposal phase. The second model allows for more detailed input. Because two separate models are created it is possible to always create a planning using the most up-to-date information. If information is limited the model will be less accurate, but still available.

As can be seen in Chapter 8.3 the accuracy and completeness of the capacity feasibility model have both been increased. Less than 5% of the total hour requirements are not included in the model, and the accuracy has been increased by more than 15%.

9.2 Limitations

Some aspects of the model can be looked at in more detail if this is desired. These could be made as later additions to the model. If more information is gathered about the relation between blocks and warehousing tasks a more detailed analysis is possible. Due to a limited amount of data available on specific items that will be installed in the ship this might be a difficult addition.

Furthermore, splitting steel building into two activities can also potentially give more accurate insights. Currently in the block level model steel building is already split into block construction and hull assembly. However, block construction could also be split further into welding and steel working. However, due to limited data availability this was currently not possible.

In order to increase the completeness, higher level managerial activities could also be added. As mentioned earlier, about 95 % of the total hour requirements are modelled. Adding managerial activities and foreign yard support will increase this number even further.

Moreover, transport has been purposefully left out of the model. This was done due to limited known information. However, adding a transport activity will increase the completeness of the model. Transport could even be added on a block level. This would require a more operational planning in order to determine when large items will arrive.

Additionally, the input values used for DSNS have been based on a very limited amount of available data. Because DSNS only constructs a small number of ships this data was in short supply. However, the values for ship type input, like the tons of steel cut per hour, could be made more accurate by using a larger amount of data.

Lastly, the current created model will be utilized as a decision support model. Due to large customer input, the model can only suggest a particular course of action. DSNS and the customer will utilize this model in order to help in their decision making, and not let the model make decisions for them. If it is desirable to create a decision making model, transport and managerial tasks should be added. Furthermore, data on more shipyards should be available. Currently, the only shipyard data that will be utilized is given before the use of the model. However, in order to make the model decide where a ship will be constructed more yards need to be added. Construction on particular yards should therefor also be added as a decision variable.

9.3 Discussion

In total two models have been created in order to support the decision making in the proposal phase. The model encompasses large parts of the ship construction process, but as mentioned in Chapter 9.2 will not be used to directly make decisions. A plan to transform the decision support model into a decision making model has been discussed. However, in order to perform this task more input data on shipyards has to be known. Unfortunately DSNS does not have this large amount of data on various shipyards, as they are often owned by customers or other ship construction companies. Therefor, it was chosen to keep the model as a decision support model.

Furthermore, the input values used for the model, e.g. the distributions, are based on a limited set of historical data. This is due to DSNS constructing only a limited number of ships. In order to increase the accuracy of the model, the accuracy of the input data should also be increased. It is recommended for DSNS to collect more data of the ships that will be constructed, in order to be utilized for more accurate models.

9.4 Future research

First of all, this research has focused on creating a capacity planning model on a strategic level. However, including some tactical and maybe even operational planning aspects could also give increased insights. For example, with more available information individual machines could be modelled. This was currently not done due to the limited amount of information available during the proposal phase. However, if the model continues being used during the construction phase, these could be helpful additions.

Secondly, the activities quality control, project department and set to work can be looked at in more detail. Currently DSNS utilizes a different tool to schedule individual employees for these activities.

However, including these total hour calculation in the model could make the building strategy more cohesive.

Additionally, randomness is not included into the model. Randomness could be added to aspects like the total requirements, or even the duration of the activities. Using randomness, a simulation model could be made that could simulate the ship constructing process.

Furthermore, the effect of delays has not been looked at. Currently the activity for the blocks can be delayed using the input values. However, delays are not an option for the whole ship level model. This could be combined with including randomness in order to simulate the ship constructing process on the yard.

Machine learning can also be utilized to determine calculations required to calculate the total requirements. The type of machine learning that can be utilized are neural networks. If neural networks are used, than physical input values of a ship can lead to the total requirements. This would mean that the conversion factors, and therefor the type dependant variables, would not have to be calculated.

Neural networks require data of historic ships in order to operate. There are two data types that are required. First ship information is needed. The more information is available, the better. This ship information includes common information like bare ship weight, length and speed. However, it would also be desirable if more data is available, like deck area, amount of rooms or material types used.

The second type of data necessary are the total requirements needed for historic ships. These requirements include the activities and if possible also the facilities.

What neural networks will try to accomplish is determining a formulation that uses the ship information given to determine the total hour calculations. The machine learning program will go through many options of using the input values to deliver the output values. It does this by applying weights to certain data values. These weights are determined by the neural network itself.

Machine learning is not utilized for DSNS for two major reasons. The first reason is that the formulations obtained by machine learning are not explainable. The machine learning algorithm will apply the best weights to each variable. This could mean that the engine type might influence the required hours of steel processing, a relation that would be difficult to explain. A large part of this research is that the calculations should be substantiated, as it should be communicated clearly to the customer. It is entirely possible that the customer desires to know how the total requirements are calculated. The logic behind the calculations is very important in that case.

Secondly, machine learning requires a large amount of data in order to be used. This large amount of data is not available to DSNS. First of all, not a lot of ship input data will be available in the early proposal phase. Even later on in the proposal phase, a lot of variables are yet to be finalized. Secondly, a fair amount of total requirement information should be available. This is also not the case. Requirement information of only 17 ships are available. This is far too little data in order to use machine learning to gain accurate calculations.

Bibliography

Armstrong, J. (2001). *Principles of forecasting; a handbook for researchers and practitioners.* New York.
70

Bao, J., Zheng, X., Zhang, J., Ji, X., & Zhang, J. (2018). Data-driven process planning for shipbuilding. *Artificial Intelligence for Engineering Design, Analysis and Manufacturing*, *32*, 122-130.
4

Chan, W. K. V., A. D'Ambrogio, G. Z., Mustafee, N., Wainer, G., & Page, E. (2017). Application of a multi-level simulation model for aggregate and detailed planning in shipbuilding. *Proceedings of the 2017 Winter Simulation Conference*, 3864–3875.
4

Duclos, L., Vokurka, R., & Lummus, R. (2003). A conceptual model of supply chain flexibility. *Industrial Management & Data Systems*, *103*(6), 446-456.
3

Gribskov, J. (1988). A group technology approach to master scheduling of shipbuilding projects. *Proceedings of the NSAP ship production symposium*, 24-26.
3

Hyndman, R., & Athanasopoulos, G. (n.d.). *Forecasting: principles and practice (2nd edition).* Melbourne, Australia.
70

Hyndman, R., & Koehler, A. (2006). Another look at measures of forecast accuracy. *International Journal of Forecasting*, *22*(4), 679-688.
70

Jong, M. L., Jeong, Y., & Woo, J. H. (2018). Development of an evaluation framework of production planning for the shipbuilding industry. *International Journal of Computer Integrated Manufacturing*, *31*(9), 831-847.
3, 4

Kiran, A. S., Cetinkaya, T., & Cabrera, J. (2001). Hierarchical modeling of a shipyard integrated with an external scheduling application. *Proceedings of the 2001 Winter Simulation Conference*, 877–881.
4

Lamb, T., H. Chung, M. S., Shin, J. G., Woo, J. H., & Koenig, P. (2006). Simulation-based performance improvement for shipbuilding processes. *Journal of Ship Production*, *22*(2), 49–65.
3

Lee, J., Lee, K., J.S. Hong, W. K., E.Y. Kim, S. C., Kim, H., Yang, O., & Choi, H. (1995). Das: Intelligent scheduling systems for shipbuilding. *The AI Magazine*, *16*, 78-94.
4

Makridakis, S., Andersen, A., Carbone, R., Fildes, R., Hibon, M., Lewandowski, R., ... Winkler, R. (1982). The accuracy of extrapolation (time series) methods: Results of a forecasting competition. *Journal of Forecasting*, *1*(2), 111-153.

71

Makridakis, S., Chatfield, C., Hibon, M., Lawrence, M., Mills, T., Ord, K., & Simmons, L. (1993). The m2-competition: A real-time judgmentally based forecasting study. *International Journal of Forecasting*, *9*(1), 5-22.
71

Pham, D., Dimov, S., & Nguyeen, C. (2005). Selection of k in k -means clustering. *Journal of Mechanical Engineering Science*, *219*(1), 103-119.
12

Sadiku, M. O., Shadare, A. E., Musa, S., Akujuobi, C., & Perry, R. (2016). Data visualisation. *International Journal of Engineering Research And Advanced Technology*, *2*(12), 11-16.
47

Shaheen, A., Al-Sayyed, R., & Sleit, A. (2017). Improving visual analyses and communications of ontology by dynamic tree (case study: computer system). *International Journal of Advanced and Applied Sciences*, *4*(5), 62-66.
47

Storch, R., & Lim, S. (1999). Improving flow to achieve lean manufacturing in shipbuilding. *Production Planning Control*, *10*(2), 127-137.
3

Zhuo, L., Chua, D. K. H., & Yeoh, K. (2011). Aggregate production planning for shipbuilding with variation-inventory trade-offs. *International Journal of Production Research*, *49*(20), 6249–6272.
4

A Whole ship level model variables

Used sets and indices

- i = specific ship
- I = all ships in the project
- t = specific time in months
- T = all months in the project
- a = specific activity
- A = all activities
- f = specific facility
- F = all facilities

Decision variables

- $EP^a_{i,t}$ = The extra percentage of hours of an activity that can be done at month t in ship i. A maximum will need to be given.
- $ECap^a_t$ = The extra capacity that will be used at month t for the activity. A maximum will need to be given.
- O^a_t = The amount of outsourcing necessary for an activity at month t.

All activities (set A)

- SP = Steel processing
- SB = Steel building
- O = Outfitting
- PF = Piping fabrication
- PI = Piping installation
- PB = Painting & Blasting
- WP = Warehousing
- QC = Quality control
- PD = Project department
- STW = Set to work

All facilities (set F)

- SPA = Steel processing area
- BF = Building frames
- HA = Hull assembly area
- LA = Launching area

- QA = Quay area
- PBA = Painting & blasting area
- SC = Steel cut
- PP = Pipes processed
- WA = Warehousing area
- SSA = Steel storage area

Physical ship values:

- w_i = the total "bare ship weight" of ship i. This is the weight of just the ship itself, so without any provisions.
- ow_i = the total outfitting weight of ship i. This is all the weight of the outfitting items in the ship. This includes a variety of items like machines, chairs, monitors and turrets.
- s_i = The total amount of pipe spools in ship i. Pipe spools are used for a variety of systems for example for oxygen, fuel and water.
- p = weight of an average plate
- nb_i = an estimate of the number of blocks in ship i
- TA_i = total area of ship i in m^2
- TL_i = total length of ship i in m
- TW_i = total width of ship i in m
- nr_i = The total number of rings in ship i.
- TA_i = total area of ship i in m^2
- TL_i = total length of ship i in m
- TW_i = total width of ship i in m
- nb_i = an estimate of the number of blocks in ship i
- Abb_i = the area of the largest block in ship i in m^2
- npt_i = the number of steel plate types in ship i
- pa = average area required to store one pile of plates in m^2

Ship activity values & conversion terms:

- $d_{i,t}^{SSA}$ = binary value determining whether or not plates need to be stored during those months. A 1 means plate storage is necessary, a 0 means no plates are stored. When $D_{i,t}^{SP} \geq 0$ than $d_{i,t}^{SSA} = 1$
- λ_i^a = This is the constant that converts the weight or amount of spools into hours. This value will either be hours/ton or hours/spool dependant on the activity. For example, λ_i^{SP} is the hours of steel processing each ton of bare ship weight takes.
- $D_{i,t}^a$ = percentage of the total hours of the activity of ship i that happens at month t.

- $D_{i,t}^{HA}$ = distribution of the hull assembly area. This will slowly become 1, meaning 100% of the total area of the ship is in the hull assembly area. If outfitting is finished and the ship is launched this number will become 0 again.
- $d_{i,t}^{L}$ = a binary value determining whether or not the launching area will (1) or will not (0) be used for ship i at time t
- $d_{i,t}^{Q}$ = a binary value determining whether or not the quay area will (1) or will not (0) be used for ship i at time t
- $d_{i,t}^{PB}$ = binary variable indicating whether the painting & blasting activity occurs for ship i at time t. If painting & blasting work is done during that time the value will be 1, otherwise it will be 0.
- drb_{i}^{Bf} = the amount of months a block of ship i needs to reside on a building frame of ship i

Fixed input values:

- FTE = number of hours each Full Time Employee per week works (each ship needs 3 employees needing 3 weeks to complete the activity, this is not influenced by ship type as the handling is very similar from ring to ring and ship to ship)
- wta = the conversion factor of weight to area
- fl = maximum allowed flexibility, between 0 and 1

Capacity values:

- Cap_{t}^{a} = the capacity of the activity at time t.
- c^{a} = the cost of outsourcing 1 hour of an activity.
- ec^{a} = the cost of getting 1 hour of extra capacity.

Calculated values:

- $TH_{i}^{Activity}$ = The total hours necessary for the activity for ship i
- $H_{i,t}^{Activity}$ = The hours spend on an activity at month t for ship i
- $TSPA_{t}$ = total steel processing area needed for ship i in m^2
- $SPA_{i,t}$ = steel processing area needed for ship i at month t in m^2
- TBf_{t} = total building frames months needed for block i
- $Bf_{i,t}$ = total building frames needed for block i at time t
- $HA_{i,t}$ = required hull assembly area for ship i at time t in m^2
- $LA_{i,t}$ = required launching area for ship i at time t in m^2
- $QA_{i,t}$ = required quay area for ship i at time t in m^2
- $RWCA_{a}$ = the required washing and changing room area for one employee of activity a
- RCA_{a} = the required canteen area for one employee of activity a
- ROA_{a} = the required office area for one employee of activity a
- $WCA_{i,t}$ = washing and changing area needed for ship i at time t in m^2

- $CA_{i,t}$ = canteen area needed for ship i at time t in m^2
- $OA_{i,t}$ = office area needed for ship i at time t in m^2
- $SC_{i,t}$ = the amount of steel that needs to be cut for ship i at month t in tons
- $PP_{i,t}$ = the amount of piping that needs to be fabricated for ship i at month t in amount of pipe spools
- TWA_i = the total warehousing area needed for ship i in m^2
- $WA_{i,t}$ = the warehousing area needed for ship i at time t in m^2 ship i at month t in amount of pipe spools
- $SSA_{i,t}$ = the amount area needed to store steel plates of ship i at time t in m^2

B Block level model variables

Used sets and indices

- i = specific ship
- I = all ships in the project
- t = specific time in months
- T = all months in the project
- a = specific activity
- A = all activities
- f = specific facility
- F = all facilities
- k = a particular block
- K = all block in the project
- K_i = all blocks in ship i
- l = a particular plate type
- L = all plates types in the project
- L_k = all plates types in block k
- m = a particular item type
- M = all item types used in the project
- M_k = all item types in block k
- A^* = all whole ship level activities
- $A^{'}$ = all block level activities

Decision variables

- $EP^a_{i,t}$ = The extra percentage of hours of an activity that can be done at month t in ship i. A maximum will need to be given.
- $EP^a_{k,t}$ = The extra percentage of hours of an activity that can be done at month t for block k. A maximum will need to be given.
- $ECap^a_t$ = The extra capacity that will be used at month t for the activity. A maximum will need to be given.
- O^a_t = The amount of outsourcing necessary for an activity at month t.
- o^a_k = Binary variable telling whether activity a for block k is outsourced or not. A one means that the block is outsourced, a zero means that the block is produced on the yard.

All activities (set A)

- SP = Steel processing

- SB = Steel building
- O = Outfitting
- PF = Piping fabrication
- PI = Piping installation
- PB = Painting & Blasting
- WP = Warehousing
- QC = Quality control
- PD = Project department
- STW = Set to work

All whole ship level activities (set A^*)

- PF = Piping fabrication
- PI = Piping installation
- WP = Warehousing
- QC = Quality control
- PD = Project department
- STW = Set to work

All block level activities (set $A^{'}$)

- PF = Piping fabrication
- PI = Piping installation
- WP = Warehousing
- QC = Quality control
- PD = Project department
- STW = Set to work

All facilities (set F)

- SPA = Steel processing area
- BF = Building frames
- HA = Hull assembly area
- LA = Launching area
- QA = Quay area
- PBA = Painting & blasting area
- SC = Steel cut
- PP = Pipes processed

- WA = Warehousing area
- SSA = Steel storage area

Physical ship values:

- w_i = the total "bare ship weight" of ship i. This is the weight of just the ship itself, so without any provisions.
- ow_i = the total outfitting weight of ship i. This is all the weight of the outfitting items in the ship. This includes a variety of items like machines, chairs, monitors and turrets.
- s_i = The total amount of pipe spools in ship i. Pipe spools are used for a variety of systems for example for oxygen, fuel and water.
- p = weight of an average plate
- nb_i = an estimate of the number of blocks in ship i
- TA_i = total area of ship i in m^2
- TL_i = total length of ship i in m
- TW_i = total width of ship i in m
- nr_i = The total number of rings in ship i.
- TA_i = total area of ship i in m^2
- TL_i = total length of ship i in m
- TW_i = total width of ship i in m
- nb_i = an estimate of the number of blocks in ship i
- Abb_i = the area of the largest block in ship i in m^2
- npt_i = the number of steel plate types in ship i
- pa = average area required to store one pile of plates in m^2

Ship activity values & conversion terms:

- $d_{i,t}^{SSA}$ = binary value determining whether or not plates need to be stored during those months. A 1 means plate storage is necessary, a 0 means no plates are stored. When $D_{i,t}^{SP} \geq 0$ than $d_{i,t}^{SSA} = 1$
- λ_i^a = This is the constant that converts the weight or amount of spools into hours. This value will either be hours/ton or hours/spool dependant on the activity. For example, λ_i^{SP} is the hours of steel processing each ton of bare ship weight takes.
- $D_{i,t}^a$ = percentage of the total hours of the activity of ship i that happens at month t.
- $D_{i,t}^{HA}$ = distribution of the hull assembly area. This will slowly become 1, meaning 100% of the total area of the ship is in the hull assembly area. If outfitting is finished and the ship is launched this number will become 0 again.
- $d_{i,t}^{L}$ = a binary value determining whether or not the launching area will (1) or will not (0) be used for ship i at time t

- $d^{Q}_{i,t}$ = a binary value determining whether or not the quay area will (1) or will not (0) be used for ship i at time t
- $d^{PB}_{i,t}$ = binary variable indicating whether the painting & blasting activity occurs for ship i at time t. If painting & blasting work is done during that time the value will be 1, otherwise it will be 0.
- drb^{Bf}_{i} = the amount of months a block of ship i needs to reside on a building frame of ship i

Physical block/plate values:

- n_k = the number of plates in block k
- ov_k = the outfitting volume of block k in m^3
- $ni_{k,m}$ = number of items of type m in block k
- l_l = length of plate l in meters
- w_l = width of plate l in meters
- $np_{l,k}$ = number of plates of type l in block k
- nbf_k = number of building frames needed to construct block k at (often just 1)
- aa_k = area the block adds to the hull assembly area in m^2. Will be ≥ 0 for base block, but will be 0 for non-base blocks.
- a_k = the area of block k in m^2
- wg_l = weight of plate l in kg
- A_l = area necessary for a storage pile for a plate of type l

Constant and variable block times:

- y^{BC}_{k} = the welding time to weld a new plate to block k
- y^{HA}_{k} = the welding time to weld block k to the hull
- c^{SB}_{k} = the required setup time for steel building of block k
- y^{O}_{k} = the hours required to outfit one m^3 of items, dependant on the block type of block k
- c^{O}_{k} = the required setup time for outfitting of block k
- x^{O}_{k} = binary variable indicating whether outfitting on block k
- tii_m = time to install one item of type m in hours takes place at time t

Activity values for blocks:

- dr^{SP}_{k} = the duration of the block construction tasks in the steel building activity for block k
- $x^{BC}_{t,k}$ = binary variable indicating whether block construction on block k takes place at time t
- $x^{HA}_{t,k}$ = binary variable indicating whether hull assembly on block k takes place at time t
- d^{O}_{k} = the duration of the outfitting activity for block k
- dr^{SP}_{k} = the duration of the steel processing activity for block k

- $x^{SP}_{t,k}$ = binary variable indicating whether steel processing on block k takes place at time t
- x^{PB}_{k} = binary variable indicating whether painting and blasting on block k takes place at time t
- $x^{HAA}_{t,k}$ = binary variable indicating whether block k has been added to the hull assembly at time t. This will be a 1 when the block is present in the hull assembly area, will be 0 before it is added and will turn 0 again when the ship is launched.
- x^{PB}_{k} = binary variable indicating whether painting and blasting on block k takes place at time t
- dr^{SP}_{k} = the duration of the steel processing activity for block k
- $x^{SP}_{t,k}$ = binary variable indicating whether steel processing on block k takes place at time t
- $x^{SS}_{l,t}$ = binary variable indicating whether a plate of time l will be stored at time t

Fixed input values:

- FTE = number of hours each Full Time Employee per week works (each ship needs 3 employees needing 3 weeks to complete the activity, this is not influenced by ship type as the handling is very similar from ring to ring and ship to ship)
- wta = the conversion factor of weight to area
- fl = maximum allowed flexibility, between 0 and 1
- ml = extra margin (for mobility) for length in m
- mw = extra margin (for mobility) for width in m
- hpb = the hours to paint and blast one block

Capacity values:

- Cap^{a}_{t} = the capacity of the activity at time t.
- c^{a} = the cost of outsourcing 1 hour of an activity.
- ec^{a} = the cost of getting 1 hour of extra capacity.

Calculated values:

- $TH^{Activity}_{i}$ = The total hours necessary for the activity for ship i
- $H^{Activity}_{i,t}$ = The hours spend on an activity at month t for ship i
- $TH^{SB,BC}_{i,k}$ = the total required hours to finish block construction tasks of the steel building activity for block k in ship i
- $TH^{O}_{i,k}$ = the total required hours to finish outfitting for block k in ship i
- $TSPA_{i,k}$ = total steel processing area needed for block k in ship i in m^2
- $SPA_{i,t}$ = steel processing area needed for ship i at month t in m^2
- TBf_{t} = total building frames months needed for block i
- $Bf_{i,t}$ = total building frames needed for block i at time t

- $HA_{i,t}$ = required hull assembly area for ship i at time t in m^2
- $LA_{i,t}$ = required launching area for ship i at time t in m^2
- $QA_{i,t}$ = required quay area for ship i at time t in m^2
- $RWCA_a$ = the required washing and changing room area for one employee of activity a
- RCA_a = the required canteen area for one employee of activity a
- ROA_a = the required office area for one employee of activity a
- $WCA_{i,t}$ = washing and changing area needed for ship i at time t in m^2
- $CA_{i,t}$ = canteen area needed for ship i at time t in m^2
- $OA_{i,t}$ = office area needed for ship i at time t in m^2
- $SC_{i,t}$ = the amount of steel that needs to be cut for ship i at month t in tons
- $PP_{i,t}$ = the amount of piping that needs to be fabricated for ship i at month t in amount of pipe spools
- TWA_i = the total warehousing area needed for ship i in m^2
- $WA_{i,t}$ = the warehousing area needed for ship i at time t in m^2 ship i at month t in amount of pipe spools
- $SSA_{i,t}$ = the amount area needed to store steel plates of ship i at time t in m^2

C Yard input data

The values given in this scenario are not representing actual shipyard data due to confidentiality. The values will be solely used to demonstrate the model.

C.1 Outsourcing costs:

Variable	Description	Unit	Value Yard U	Value Yard V	Value Ship W
c^{SP}	Outsourcing costs of steel processing	Costs/FTE	150	200	150
c^{SB}	Outsourcing costs of steel building	Costs/FTE	250	200	200
c^{O}	Outsourcing costs of outfitting	Costs/FTE	100	130	145
c^{PF}	Outsourcing costs of piping fabrication	Costs/FTE	220	200	260
c^{PI}	Outsourcing costs of piping installation	Costs/FTE	270	200	150
c^{PB}	Outsourcing costs of painting & blasting	Costs/FTE	170	240	150
c^{W}	Outsourcing costs of warehousing	Costs/FTE	175	200	200
c^{QC}	Outsourcing costs of quality control	Costs/FTE	200	200	200
c^{PD}	Outsourcing costs of project department	Costs/FTE	200	200	200
c^{STW}	Outsourcing costs of set to work	Costs/FTE	200	200	200

C.2 Extra capacity costs:

Variable	Description	Unit	Value Yard U	Value Yard V	Value Ship W
ec^{SP}	Extra capacity costs of steel processing	Costs / 20 FTE	1500	2000	1500
ec^{SB}	Extra capacity costs of steel building	Costs / 20 FTE	2500	2000	2000
ec^{O}	Extra capacity costs of outfitting	Costs / 20 FTE	1000	1300	1450
ec^{PF}	Extra capacity costs of piping fabrication	Costs / 20 FTE	2200	2000	2600
ec^{PI}	Extra capacity costs of piping installation	Costs / 20 FTE	2700	2000	1500
ec^{PB}	Extra capacity costs of painting & blasting	Costs / 20 FTE	1700	2400	1500
ec^{W}	Extra capacity costs of warehousing	Costs / 20 FTE	1750	2000	2000
ec^{QC}	Extra capacity costs of quality control	Costs / 20 FTE	2000	2000	2000
ec^{PD}	Extra capacity costs of project department	Costs / 20 FTE	2000	2000	2000
ec^{STW}	Extra capacity costs of set to work	Costs / 20 FTE	2000	2000	2000
ec^{SPA}	Extra capacity costs of steel processing	Costs / 200 m^2	1500	2000	1500
ec^{BF}	Extra capacity costs of steel building	Costs / 20 frames	2500	2000	2000
ec^{HA}	Extra capacity costs of outfitting	Costs / 200 m^2	1000	1300	1450
ec^{LA}	Extra capacity costs of piping fabrication	Costs / 200 m^2	2200	2000	2600
ec^{QA}	Extra capacity costs of piping installation	Costs / 200 m^2	2700	2000	1500
ec^{PBA}	Extra capacity costs of painting & blasting	Costs / 200 m^2	1700	2400	1500
ec^{SC}	Extra capacity costs of warehousing	Costs / 200 kg	1750	2000	2000
ec^{PP}	Extra capacity costs of quality control	Costs / 200 spools	2000	2000	2000
ec^{WA}	Extra capacity costs of project department	Costs / 200 m^2	2000	2000	2000
ec^{SSA}	Extra capacity costs of set to work	Costs / 200 m^2	2000	2000	2000

C.3 Capacities

Variable	Description	Unit	Value Yard U	Value Yard V	Value Ship W
ec^{SP}	Capacity of steel processing	FTE	150	200	150
ec^{SB}	Capacity of steel building	FTE	250	200	200
ec^{O}	Capacity of outfitting	FTE	100	130	145
ec^{PF}	Capacity of piping fabrication	FTE	220	200	260
ec^{PI}	Capacity of piping installation	FTE	270	200	150
ec^{PB}	Capacity of painting & blasting	FTE	170	240	150
ec^{W}	Capacity of warehousing	FTE	175	200	200
ec^{QC}	Capacity of quality control	FTE	200	200	200
ec^{PD}	Capacity of project department	FTE	200	200	200
ec^{STW}	Capacity of set to work	FTE	200	200	200
ec^{SPA}	Capacity of steel processing	m^2	1500	2000	1500
ec^{BF}	Capacity of steel building	frames	250	200	200
ec^{HA}	Capacity of outfitting	m^2	1000	1300	1450
ec^{LA}	Capacity of piping fabrication	m^2	2200	2000	2600
ec^{QA}	Capacity of piping installation	m^2	2700	2000	1500
ec^{PBA}	Capacity of painting & blasting	m^2	1700	2400	1500
ec^{SC}	Capacity of warehousing	kg	1750	2000	2000
ec^{PP}	Capacity of quality control	spools	2000	2000	2000
ec^{WA}	Capacity of project department	m^2	2000	2000	2000
ec^{SSA}	Capacity of set to work	m^2	2000	2000	2000

D Whole ship level input

The values given in this scenario are not representing actual ship data due to confidentiality. The values will be solely used to demonstrate the model.

D.1 Ship dependant variables

Variable	Description	Unit	Value Ship A	Value Ship B	Value Ship C	Value Ship D	Value Ship E
$type_i$	Ship type	Type	Type I	Type I	Type II	Type II	Type II
w_i	Bare ship weight	(t) tons (1000kg)	600	650	1000	1050	1100
ow_i	Outfitting weight	(t) tons (1000kg)	300	325	500	525	550
s_i	Number of spools	Amount	60	65	100	105	110
TL_i	Ship length	m	70	70	100	100	110
TW_i	Ship width	m	10	10	15	15	15
nr_i	Number of rings	Amount	6	6	10	10	11
nb_i	Number of blocks	Amount	30	30	50	50	55
npt_i	Number of plate types	Amount	6	7	10	10	11
drb_i^{Bf}	Duration frame	hours	3	3	3	3	3
Abb_i	Area largest block	m^2	40	40	50	50	50
T_i^W	Item storage time	months	3	3	3	3	3
λ_i^{SP}	Steel Processing	hours/ton	100	100	80	80	80
λ_i^{SB}	Steel Building	hours/ton	150	150	120	120	120
λ_i^{O}	Steel Building	hours/ton	150	150	120	120	120
λ_i^{PF}	Steel Building	hours/spool	80	80	75	75	75
λ_i^{PI}	Steel Building	hours/spool	80	80	70	70	70
λ_i^{W}	Warehousing	hours/ton	50	50	50	50	50

D.2 Scenario variables

Variable	Description	Unit	Value
FTE	FTE length	hours	150
ap	Area average plate	m^2	5
pa	Storage area average plate	m^2	6
p	Weight average plate	tons (1000kg)	0.1
wta	Area of one ton of outfitting weight	m^2/ton	2

D.3 Distribution variables

Abbreviation	Activity/facility	alpha (α)	beta (β)
SP	Steel processing	1.0	2.5
SB	Steel processing	1.0	2.0
O	Steel processing	1.0	1.5
PF	Steel processing	1.0	1.0
PI	Steel processing	1.5	1.0
PB	Steel processing	2.0	1.0
WA	Steel processing	2.5	1.0
HA	Hull assembly area	1.0	1.0

D.4 Activity & facility starts and durations

Variable	Description	Unit	Value Ship A	Value Ship B	Value Ship C	Value Ship D	Value Ship E
st_i^{SP}	Start steel processing	Month	0	0	0	0	0
dr_i^{SP}	Duration steel processing	Months	6	7	7	9	8
st_i^{SB}	Start steel building	Month	3	5	4	5	6
dr_i^{SB}	Duration steel building	Months	9	8	12	13	14
st_i^{O}	Start outfitting	Month	8	10	7	12	13
dr_i^{O}	Duration outfitting	Months	10	9	14	13	14
st_i^{PF}	Start piping fabrication	Month	4	2	5	5	4
dr_i^{PF}	Duration piping fabrication	Months	7	8	12	11	10
st_i^{PI}	Start piping installation	Month	8	10	7	12	13
dr_i^{PI}	Duration piping installation	Months	4	3	7	6	8
st_i^{PB}	Start painting & blasting	Month	5	7	6	7	8
dr_i^{PB}	Duration painting & blasting	Months	9	7	11	12	13
st_i^{W}	Start warehousing	Month	6	8	5	10	11
dr_i^{W}	Duration warehousing	Months	13	12	17	16	17
st_i^{HA}	Start hull assembly	Month	5	7	6	7	8
dr_i^{HA}	Duration hull assembly	Months	13	12	15	18	19
st_i^{L}	Start launching	Month	18	19	21	25	27
dr_i^{L}	Duration launching	Months	1	1	1	1	1
st_i^{Q}	Start quay	Month	19	20	22	26	28
dr_i^{Q}	Duration quay	Months	3	4	3	5	7

D.5 Employee facility variables

Variable	Description	Unit	SP	SB	O	PF	PI	PB	W
$RWCA^a$	Required washing/changing area per FTE	m^2	2	2	2	2	2	2	2
RCA_a	Required canteen area per FTE	m^2	2	2	2	2	2	2	2
ROA_a	Required office area per FTE	m^2	2	2	2	4	2	2	4

E Block level input

The values given in this scenario are not representing actual ship data due to confidentiality. The values will be solely used to demonstrate the model. Furthermore, the block type names are also not representative of actual ship block types.

E.1 Block physical variables of ship A table 1

Block	Type	Number of plates n_k	Plate volume v_k (m^3)	Outfitting weight ow_k (tons)	Outfitting volume ov_k (m^3)
Block 1	Bottom	12	0.3	15	20
Block 2	Bottom	14	0.3	30	30
Block 3	Bottom	13	0.3	25	25
Block 4	Middle	16	0.2	35	35
Block 5	Middle	17	0.2	45	40
Block 6	Middle	18	0.2	40	40
Block 7	Top	6	0.15	20	25
Block 8	Top	9	0.15	25	25
Block 9	Top	7	0.15	15	20
Block 10	Other	8	0.2	50	55

E.2 Block physical variables of ship A table 2

Block	Type	Building frames nbf_k	Added HA area aa_k (m^2)	Block area a_k (m^2)
Block 1	Bottom	2	200	200
Block 2	Bottom	2	250	250
Block 3	Bottom	2	250	250
Block 4	Middle	1	0	200
Block 5	Middle	1	0	250
Block 6	Middle	1	0	250
Block 7	Top	1	0	200
Block 8	Top	1	0	250
Block 9	Top	1	0	250
Block 10	Other	1	0	150

E.3 Plate types in ship A

Plate type	Length plate l_l (m)	Width plate w_l (m)	Weight plate wg_l (kg)	Storage area A_l (m^2)
Type a	3	5	60	24
Type b	3	5	100	24
Type c	2	4	30	12
Type d	2	4	50	12

E.4 Plates in blocks of ship A

Block	Type	Amount of type a	Amount of type b	Amount of type c	Amount of type d
Block 1	Bottom	6	0	6	0
Block 2	Bottom	6	0	8	0
Block 3	Bottom	6	0	7	0
Block 4	Middle	6	4	6	0
Block 5	Middle	6	4	6	1
Block 6	Middle	6	4	6	2
Block 7	Top	0	4	0	2
Block 8	Top	0	4	0	5
Block 9	Top	0	4	6	3
Block 10	Other	0	6	0	2

E.5 Set-up times of ship A

Block	Type	Set-up time SP c_k^{SP} (hrs)	Set-up time SB c_k^{SB} (hrs)	Set-up time O c_k^{O} (hrs)
Block 1	Bottom	50	70	840
Block 2	Bottom	50	70	840
Block 3	Bottom	50	70	840
Block 4	Middle	50	90	875
Block 5	Middle	50	90	875
Block 6	Middle	50	90	875
Block 7	Top	65	100	870
Block 8	Top	65	100	870
Block 9	Top	65	100	870
Block 10	Other	100	110	920

E.6 Variable times of ship A

Block	Type	Variable time SP y_k^{SP}	Welding time BC y_k^{BC}	Welding time HA y_k^{HA}	Variable time O y_k^{O}
Block 1	Bottom	1500	70	700	400
Block 2	Bottom	1500	70	700	400
Block 3	Bottom	1500	70	700	400
Block 4	Middle	1700	90	700	800
Block 5	Middle	1700	90	700	800
Block 6	Middle	1700	90	700	800
Block 7	Top	1600	100	700	700
Block 8	Top	1600	100	700	700
Block 9	Top	1600	100	700	700
Block 10	Other	2100	110	700	1200

E.7 Fixed variables

Variable	Description	Unit	Value
hpv	Time P&B one block	hours	450
ml	Margin length	m	1
mw	Margin width	m	1
M	Large number	N/A	1,000,000

E.8 Start of activities/facilities of blocks in ship A

Variable	Block 1 value	Block 2 value	Block 3 value	Block 4 value	Block 5 value	Block 6 value	Block 7 value	Block 8 value	Block 9 value	Block 10 value
st_k^{SP}	0	0	0	1	1	1	2	2	2	3
dr_k^{SP}	3	4	3	3	4	3	3	4	3	3
st_k^{BC}	3	5	4	4	6	5	5	7	6	8
dr_k^{BC}	3	2	2	3	2	2	3	2	2	2
st_k^{O}	8	9	8	9	10	9	10	11	10	12
dr_k^{O}	4	3	4	6	5	7	5	4	6	5
st_k^{PB}	7	8	7	8	9	8	9	10	9	11
dr_k^{PB}	1	1	1	1	1	1	1	1	1	1
st_k^{HA}	7	8	7	8	9	8	9	10	9	11
dr_k^{HA}	1	1	1	1	1	1	1	1	1	1