Identifying and improving the internal and external information exchange for shipbuilding processes

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THECLA BODEWES
SHIPYARDS

BARKMEIJER
SHIPYARDS
Since 2019 part of Thecla Bodewes Shipyards

TU Delft

Thesis for the degree of MSc in Marine Technology in the specialization of Ship Design,
Production & Operation (SDPO)

Identifying and improving the internal and external information exchange for shipbuilding processes

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Performed at:

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Preface

As a first impression, I have chosen an impressive picture of the bow of the Anchorage for the front page of this report. For Barkmeijer Shipyards, the Anchorage marks an important transition. When the yard suffered bankruptcy in 2018, 165 years of shipbuilding history was threatened to disappear. Fortunately, Thecla Bodewes offered to buy the shipyard and found a client who was interested in finishing the casco of the Anchorage.

Transitions or changes are never-ending. *πάντα ρεῖ* (panta rhei), everything flows. Whether we focus on the very volatile shipbuilding market or personal life. During this graduation process, I also went through a transition phase. Both intellectual, as I learned so much about simulation and communication during a ship production process, and characteristically, as I learned so much about my capacities and strengths and weaknesses.

The ever-changing world changed even slightly more in the year 2020 because of the corona crisis. This was an extra challenge during the graduation process, as the solid base of the daily life structure disappeared. Another change, which eventually made me stronger and more adaptive.

Now, after 6 years of studying, another big change awaits me and I am looking forward to it. The things I have learned during my master's and my graduation will always influence my vision and way of thinking. I noticed that when in a textbook I read the sentence: "collecting information that you do not use will only cost you money". With all I have learned during my graduation process, I find this a very interesting point of view and with all knowledge that I gained, I will be able to develop a founded opinion or maybe be able to lead a discussion on this statement once.

I could not have finished this thesis without the help of many. First of all, I would like to thank Jeroen Pruijn, my university supervisor, for his valuable advice and guidance. Furthermore, I would like to thank Hans Veraart and Jos de Groot, my company supervisors, for their practical insights and support. Of course, all other employees at TB Shipyards/Barkmeijer Shipyards also deserve my thanks for their input and of making me feel at home in the company. Finally, I would like to thank my parents, who always support me, and Wouter, my true love who supported me both mentally and intellectually by giving me hugs and tips and helping me regain my confidence whenever I lost it.

May this thesis report expand your knowledge on modelling information in shipbuilding processes and may it help many maritime companies improve their processes!

Esther Douma,

Grou, 15th of June 2020

Executive Summary

A ship production process is extremely complex and throughout any complex (ship) construction process, communication is key. Many companies including TB Shipyards acknowledge the importance of effective communication, as it leads to successful project execution in terms of quality, cost, and time and improved employee motivation. Therefore, from the industry, there is a demand to gain an overview of the internal and external information flows throughout a ship production process. From literature, it is observed that it is possible to model and simulate complex information creation and sharing, but that this has not been applied to a ship production process yet. Therefore, from the scientific field, there is a demand to fill this knowledge gap.

In this report, both practical and scientific demands are met and an approach is provided to identify and improve the information flow for ship production processes using simulation techniques. The corresponding main question is "Which measures are effective for improving the information handling in a general ship production process for TB Shipyards?".

A modelling approach is defined through a literature review. By combining practical requirements with literature, it becomes clear that simulation techniques are indeed a good choice for modelling information flow for a ship production process, and more specifically, that Discrete Event Simulation combined with Petri Net techniques is deemed suitable for the problem. Furthermore, the model is further scoped to focus on the timing of the information.

By performing a stakeholder analysis and making use of the Stage-Gate model, a conceptual model is established. A distinction is made between information objects, which are visualized as circles, and information processing activities, which are visualized as rectangles. By specifying PERT-distributions for the information processing activities and assigning responsible stakeholders, the total throughput time and stakeholder waiting times or bottlenecks can be calculated. This is calculated using a mathematical model in Python programming language.

After full establishment of the model, verification and validation tests are performed and experiments are executed. The experiments are performed for a specific case-study, being a pusher tug built at TB Shipyards, which can be considered relatively small, but relatively complex. The first experiment that is executed focuses on identification and optimization of the bottlenecks. The second experiment focuses on pre-mature release of information objects and the effects on total throughput time and stakeholder waiting times. Next to the experiments applied to the full model, two additional, more specific experiments are executed focusing on elimination of delivery times and delay of a construction plan.

From these experiments, the measures which are effective for improving information handling can be defined, i.e. the main question can be answered. For a highly complex small ship, it became clear that to improve the total throughput time of information in a ship production project, TB Shipyards should focus on ways to reduce duration of the activity "weld sections together", for example by stocking standardized cascos, making use of welding robots or night shifts and that TB

Shipyards should make sure that the specification of the primary construction in the basic engineering phase does not suffer from any delays.

For future projects enhancing the accuracy of the approach, additional case studies and/or experiments should be performed. Also, the focus of the model could be shifted from information timing towards other causes of ineffective communication, being information deficiency, information instability, information discrepancy, information mutation or wrong information. For this, a roadmap had been created.

Samenvatting

Een scheepsproductieproces is zeer complex en voor ieder complex (scheeps)constructie proces geldt; communicatie is de sleutel tot succes. Veel bedrijven inclusief TB Shipyards erkennen het belang van effectieve communicatie, aangezien het leidt tot succesvolle projectuitvoering op het gebied van kwaliteit, kost en tijd en bovendien verbeterde werknemersmotivatie. Hieruit volgt dat er vanuit de industrie een vraag is om overzicht te verkrijgen van de interne en externe informatiestromen van een scheepsproductieproces. Vanuit de literatuur is duidelijk geworden dat het mogelijk is om complexe informatiecreatie en -deling gemodelleerd en gesimuleerd kan worden, maar dat dit nog niet gedaan is voor een scheepsproductieproces. Hieruit volgt dat er vanuit de wetenschap behoefte is om deze kennis aan te vullen.

Dit rapport zal zowel aan de praktische/industriële als wetenschappelijke vraag voldaan worden en er wordt een aanpak verschaft om de informatiestromen van een scheepsproductieproces te identificeren en optimaliseren met behulp van simulatietechnieken. De bijbehorende hoofdvraag is "Welke maatregelen zijn effectief voor het verbeteren van de omgang met informatie in een algemeen scheepsproductieprocess voor TB Shipyards?

Een modelleeraanpak is gedefinieerd met behulp van een literatuuronderzoek. Door praktische eisen te combineren met de literatuur wordt duidelijk dat simulatietechnieken inderdaad een goede keus zijn voor het modelleren van de communicatie in een scheepsproductieproces. Specifieker; dat Discrete Event Simulation gecombineerd met Petri Net technieken wordt gezien als geschikt voor het probleem. Hiernaast is het model verder gescopet zodat het focust op de timing van informatie.

Door het uitvoeren van een stakeholder analyse en gebruik te maken van het Stage Gate model wordt een conceptueel model opgesteld. Onderscheid wordt hierbij gemaakt tussen informatie objecten, welke gevisualiseerd worden als cirkels, en informatie verwerkingsactiviteiten, welke gevisualiseerd worden als rechthoeken. Met behulp van PERT-distributies voor de informatie verwerkingsactiviteiten en het toewijzen van verantwoordelijke stakeholders kunnen de totale doorlooptijd en stakeholder wachttijden berekend worden. Dit wordt gedaan door middel van een mathematisch model in Python programmeertaal.

Na het volledig uitwerken van het model zijn verificatie- en validatietesten uitgevoerd en vervolgens zijn experimenten uitgevoerd. De experimenten zijn opgesteld voor een specifieke case-study, een duwboot, gebouwd bij TB Shipyards, welke relatief klein en relatief complex is bevonden. Het eerste uitgevoerde experiment focust op identificatie en optimalisatie van bottlenecks. Het tweede experiment focust op vroegtijdig beschikbaar maken van informatieobjecten en de effecten hiervan op de totale doorlooptijd en stakeholder wachttijden. Naast deze twee experimenten welke betrekking hebben op het volledige model zijn er twee meer specifieke experimenten uitgevoerd, welke focussen op eliminatie van levertijden en de vertraging van een constructieplan.

Van deze experimenten kunnen de maatregelen welke effectief zijn voor het verbeteren van de informatieomgang gedefinieerd worden, oftewel de hoofdvraag kan beantwoord worden. Voor een complex, klein schip werd duidelijk dat om de totale doorlooptijd van informatie in een scheepsproductieproces te verbeteren, TB Shipyards zou moeten focussen op manieren om de activiteit "las secties samen" te verkorten. Bijvoorbeeld, door gebruik te maken van de opslag van gestandaardiseerde casco's, gebruik maken van lasrobots of nachtdiensten. Verder moet TB Shipyards ervoor zorgen dat het specificeren van de primaire constructie in de basic engineering fase geen vertragingen ondervindt.

Voor toekomstige projecten om de nauwkeurigheid van de aanpak te vergroten, zouden extra case-studies of experimenten uitgevoerd kunnen worden. Ook zou de focus van het model van informatie timing geschoven kunnen worden naar de andere aspecten van ineffectieve communicatie, zoals informatietekort, informatie instabiliteit, informatie discrepantie, informatie mutatie of verkeerde informatie. Voor verdere implementatie van het model is een roadmap gecreëerd.

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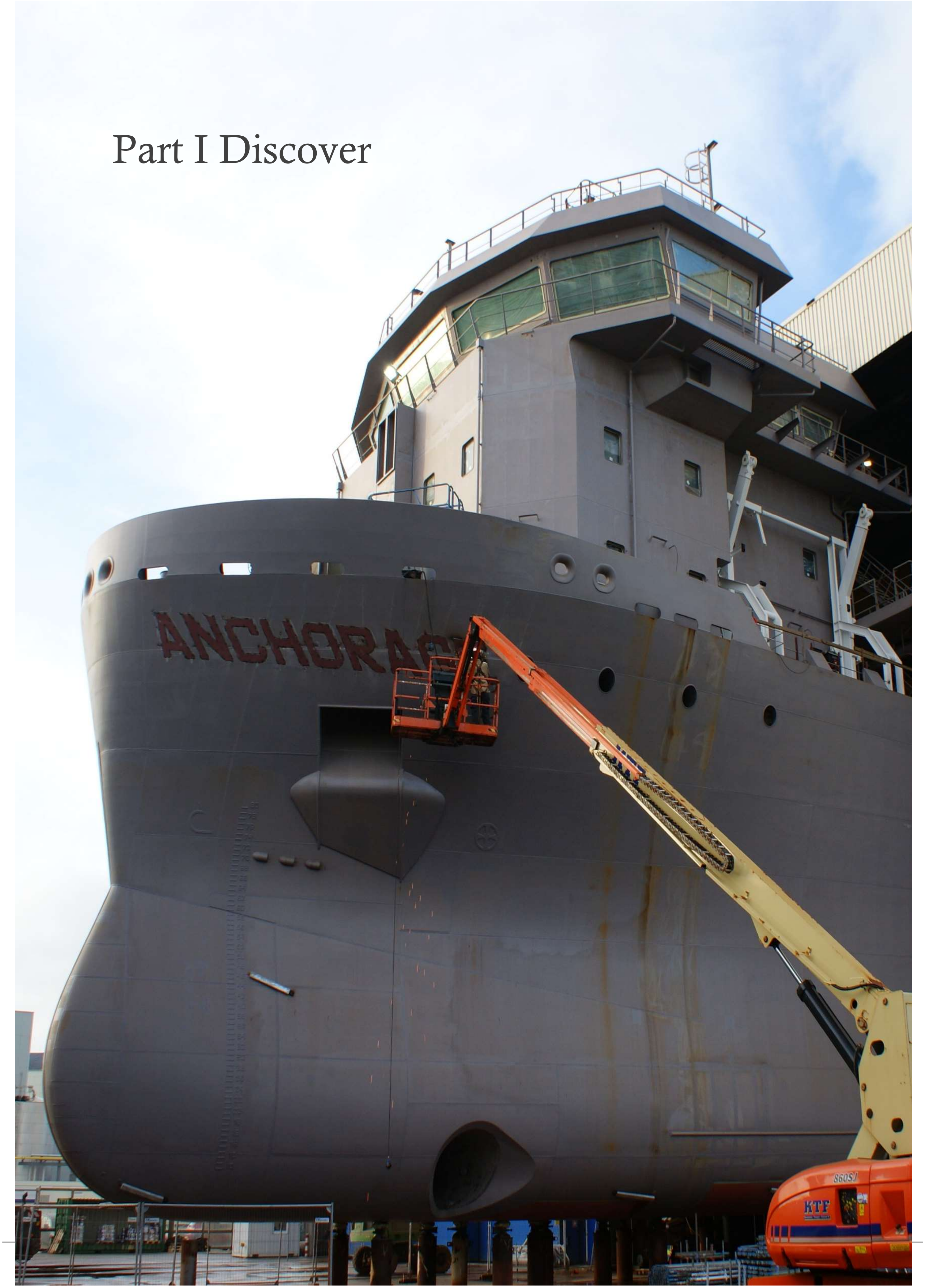
Nomenclature

ABM	Agent Based Modelling
ABS	Agent Based Simulation
AHP	Analytic Hierarchy Process
CPA	Critical Path Analysis
CPM	Critical Path Method
DEMO	Dynamic Essential Modelling of Organisations
DES	Discrete Event Simulation
D&E	Design and Engineering
ER	Engine Room
FTE	Full-time Equivalent, a unit to indicate the workload of an employed person.
GBS	Goal Breakdown Structure
GHP	Goal Hierarchy Plot
IMO	International Maritime Organization
ISO	International Organization of Standardization
MCS	Monte Carlo Simulation
MIT	Massachusetts Institute of Technology
NPD	New Product Development
PDF	Probability Density Function
PERT	Project Evaluation and Review Technique
PI	Production Information
QHSE	Quality, Health, Safety & Environment
SD	System Dynamics

Part I Discover



1. Introduction

As Albert Einstein once said: "*The formulation of a problem is often more essential than its solution, which may merely be a matter of mathematical or experimental skills.*" (Einstein & Infeld, 1938). This chapter is all about understanding and formulating the problem and its scientific, practical and social relevance. Please note that throughout the report, some endnotes have been added, which are discussed at the end of each chapter.

1.1 Problem understanding

A ship production process is extremely complex. Not only does a ship contain many unique parts, but it also has to be built according to a strict schedule and it involves many stakeholders from different disciplines, different companies on different locations (Emblemsvåg, 2014; Fafandjel, Pavletić, & Hadjina, 2005; Liker & Lamb, 2002). For every step in the process, several types of information are transferred from one person to another. Throughout any complex (ship) construction process with multiple parties involved, **communication is key** (Kamalirad, Kermanshachi, Shane, & Anderson, 2017).

According to the Cambridge Academic Content Dictionary, communication is defined as "*1. The process by which messages or information is sent from one place or person to another, or the message itself; 2. Communication is also the exchange of information and the expression of feeling that can result in understanding.*" (Cambridge University Press, 2009). Throughout the report, the notions "communication" and "information flow" are used interchangeably[1].

Recently, TB Shipyards expanded their business with four former independent shipyards being the previously called "Volharding Shipyards" in Harlingen, "De Kaap" in Meppel, "Peters Shipyards" in Kampen and "Barkmeijer Shipyards" in Stroobos. These shipyards all had their different working methods, means of communicating and transferring information, company culture and interpretation of responsibilities. As a result of this merge, **there is no overview of how both internal and external information flows through the company.** This problem is not only relevant for the TB Shipyard case where independent shipyards merge into one. There are many other examples in the ship production industry of problems regarding a lack of overview of the information flow. One of them is described by Levering et al. (2016):

> *"A typical example of the lack of alignment between Dutch shipbuilding practices and industry demands can be found in a shipbuilding project in which the client interacted with a shipyard, changing the technical specifications frequently. To implement the changes demanded, the shipyard, as lead organization, informed the subcontractors about the changes on an individual basis. However, the tasks of the subcontractors were highly interdependent, and due to a lack of (needed) communication between them, the activities for implementing the changes were insufficiently coordinated. As a result, the project needed more time and was more costly than initially budgeted."*

This is one of many examples with serious consequences of problems with the *external* communication, which often occur as sometimes up to 70 percent of the ship construction is delivered from outside the shipyard (Levering et al., 2016).

A case, where *internal* communication is not optimal, is described in an example given by a project engineer in the report of Wesselman (2017):

> *"The ship always had a certain type of engines and these engines fit perfectly, but then we had Caterpillar engines which were much bigger, so the cooling water pipes did not fit anymore. That was really a thing, in the end it was okay but it took a lot of time to find out how to make it possible. It took me two days to look for the right person who could tell me why we had different engines now".*

In this example, responsibilities were unclear and the interviewee had no overview of the *internal* communication hierarchy of the company. Next to these, there are many other examples of internal and external communication problems within a ship production process, such as one having to dig through a large report to find one value (information overflow), mutations in the transfer of information due to the use of different software or one assuming that the person receiving this information has enough knowledge to understand it (Al-Rawas & Easterbrook, 1996; Conrad, 2014; Eppler, 2007).

Effective communication leads to successful project execution performance in terms of time, cost and quality targets (Murray, Tookey, Langford, & Hardcastle, 2000), and improved employee motivation (Armstrong, 2006). Ineffective communication leads to a chance of major reworks, poor end-product quality or conflicts between project parties (Kamalirad et al., 2017). Problems with the information flow may result in delays or even failure to complete projects, added employee stress, low company morale and sometimes loss of sales (The Economist Intelligent Unit, 2018). Among 400 surveyed companies, an average loss of 62.4 million dollars per year due to poor communication is reported (Grossman, 2011). Information is as much important to the existence of organisations as it is as oxygen for human life (Hakim, 2008) and organisations widely recognize the challenge of how to better understand and manage the capturing, storing and retrieving of information (Lo Storto, D'Avino, Dondo, & Zezza, 2008).

Companies acknowledge the value of improving their information flows and try to solve their issues by adopting novel project- and/or information management methods. Currently, **companies often implement communication improvement measures in a "trial-and-error" way instead of examining their potential beforehand**. With an average implementation failure rate of 73% (or some even reporting failure rates of 93%) it has become a standard that attempts for organizational change remain unrewarded, which often leads to employees being reluctant to adopt yet another new improvement measure (Decker et al., 2012).

In summary, many companies acknowledge the importance of understanding, managing and improving their information flow and for shipbuilding processes, there is a demand for a way to gain an overview of the internal and external information flow and a way to examine measures for improving the information flow.

1.2 A wicked problem

The problem as described above cannot be compared to a standard technical problem and is an example of a so-called "wicked problem". From the fields of policy-making and ethics, the theory on wicked problems is studied and reproduced widely. From a technical perspective, however, the theory is less used, whilst it provides a good framework for higher-level problem understanding. By approaching this problem as a wicked problem instead of a standard technical problem, technocratic pitfalls can be avoided, where a clear-cut solution to a problem is expected and often a so-called "complexity neglect" occurs (Roeser, 2017). A "wicked problem" approach encourages to adopt a holistic viewpoint and critically reflect results and put them in perspective. Rittel & Webber (1973) describe the characteristics of a wicked problem. These fit our case as discussed below.

A first important characteristic of a wicked problem is that problem and solution are very closely related[2]. In order to be able to describe the problem, already some kind of solution must be known. A problem cannot be defined until the solution has been (partly) found. This is illustrated with an example of mental health services. "*If we recognize deficient mental health services as a part of the problem, then -trivially enough- "improvement of mental health services" is a specification of the solution. If, as the next step, we declare the lack of community centers one deficiency of the mental health services system, then "procurement of community centers" is the next specification of the solution."* (Rittel & Webber, 1973). In our case, having no overview of the information flow or method to examine improvement possibilities are identified as problems and subsequently imply that the solution should be closely related.

This brings us to a second important characteristic, being that wicked problems can be considered a symptom of another, higher-level problem. As an example, a problem might be that employees in the manufacturing industry are unmotivated to change their working methods. This can be considered a symptom of the higher-level problem, being that many attempts to change working methods have low success rates. This can be considered a symptom of a higher-level problem, being that there is insufficient knowledge about the structure of the company and how it would react to organizational changes. This example shows that the observed problems as stated in Section 1.1 are closely related and might be symptoms of each other. According to Rittel & Webber (1973) "*The level at which a problem is settled, depends upon the self-confidence of the analyst and cannot be decided on logical grounds. There is nothing like a natural level of a wicked problem. Of course, the higher the level of a problem's formulation, the broader and more general it becomes: and the more difficult it becomes to do something about it. On the other hand, one should not try to cure symptoms: and therefore one should try to settle the problem on as high a level as possible."*[3]

Other characteristics of wicked problems relate to its solutions, being that solutions to wicked problems are not true-or-false, but rather good-or-bad. The solution of a freeboard calculation for a ship and whether it is able to meet its freeboard requirements as specified by the International Load Line Convention is a true-or-false solution whereas having an overview of the information flow within a company could be a good solution to communication problems according to a manager who often consults the overview, but a bad solution for a welder who thinks the overview is too general. Furthermore, wicked problems do not have an enumerable set of potential solutions, nor is there a well-described set of permissible operations that may be incorporated into the plan. There are for example many different project management tools and combinations of them in order to solve communication problems, but one could never define them all, let alone be able to test them.

A final characteristic is that every solution to a wicked problem is a "one-shot operation": because there is no opportunity to learn by trial-and-error, every attempt counts significantly. For standard mathematical problems, new solutions can be implemented as often as desired as these will not influence the initial problem. For wicked problems, implemented solutions greatly influence the initial state. The observed case of workers being reluctant to adopt new solutions due to already having tried many is an example of this.

In summary, many of the characteristics of wicked problems fit the problem as described in this report and by approaching it in an equal manner, a critical attitude towards potential solutions can be adopted. By understanding the type of problem on a higher level, also the type of solution can be understood better. We cannot solve our problems with the same level of thinking that created them (Prensky & Einstein, n.d.). This theory will play a significant role in the discussion of the results.

1.3 Literature review & knowledge gap

Before diving into potential solutions for the problem, it is important to get an overview of the current knowledge in the field. Therefore, a literature study has been performed. This section describes the results. In Appendix 12.1, a more elaborate description of the approach can be found.

First, some general sources were sought to provide a fundamental view of corporate communication by means of the searching tags "information flow" or "communication". Much general information on communication and information flow was given by 2 Dutch information experts, Prof. dr. ir. Jan Leonardus Gerardus Dietz and Prof. dr. Theo Maria Aloysius Bemelmans. They wrote several documents on information management for organizations (Bemelmans, 1994; J L G Dietz, 1987; Jan L. G. Dietz, 2006; Jan L.G. Dietz, 2001; Jean Leonardus Gerardus Dietz, 1996). From these documents, it becomes clear that communication is a very rich topic which can be approached in many different ways. Furthermore, Murray et. al. (2000), Armstrong (2006), Kamalirad et. al. (2017) and Grossman (2011) focus more on the corporate aspect of understanding and managing information flow.

Second, to find whether simulation or modelling techniques are used successfully to gain an understanding of communication networks, the searching tags "information flow/communication" and "simulation/modelling" were combined., Many sources were found which consider or make use of a simulation model (Durugbo, 2011; Jakieła, Olech, & Litwin, 2016; Kyriy, Sheiko, & Petrova, 2019; Leventsov, Nikolaevskiy, & Radaev, 2017; Thiede et al., 2019).[4] However, all these State-of-the-Art researches are focused on organizations delivering microsystems technology (Durugbo, 2011), mass production companies (Jakieła et al., 2016) or electricity companies (Kyriy et al., 2019), which are very distinct from ship production enterprises.

Therefore, ship production-specific sources were searched using the combination of searching tags "information flow /communication", "simulation /modelling" and "ship (production) /shipbuilding". One important, ship-specific source attempting to gain an overview of communication within a shipbuilding process and subsequently proposing improvement measures by simulation techniques is the doctoral thesis of Coenen (2008). In this thesis, the creation of a simulation model for engineering processes in the shipbuilding industry is described, which can be used to evaluate strategic choices for organizational changes and to improve the current engineering planning. This is done according to a so-called Modelling-to-Order principle, which in this case means that every company can model their specific structure with the help of standard, pre-defined building blocks. Furthermore, she has been able to model information by assigning two characteristics to it, a confidence level and an instability level. However, Coenen focused on the full process for the engineering part only, whilst this project focuses on communication/information flow only for the full ship production process. This was the only relevant source that could be found matching all searching tags.

To get inspired on how others handled ship production specific information flow problems, the searching tags "communication/information flow" and "ship production/ship building" were used. One important source resulting from this is the master's thesis of Wesselman (2017). Here, the bottlenecks of the information flow were explored by conducting interviews, in order to develop a new (physical) communication support tool[5]. In this report, investigation of the bottlenecks in the information flow is relevant as well, but the goal of this research is not to build a physical tool. The interviews and conclusions from Wesselman, however, do provide a solid base and potentially a possibility to qualitatively check results for this report.

To see how others applied simulation and modelling techniques for ship (production) related problems, the searching tags "simulation/modelling" and "ship (production)/ship building" were combined. This lead to the master's thesis of Wijma (2018), who has described a way of modelling ships entering the harbour of Rotterdam and the corresponding information flow. He subsequently investigated using discrete event simulation whether data sharing would improve the port call process. In the report of Wijma, very elaborate stakeholder analyses, sensitivity analyses and verification and validation analyses have been performed, which are very useful for this research.

Next to the thesis of Wijma, many papers were found using simulation/modelling techniques in maritime applications. First, there is the paper of Song, Woo & Shin (2009). This paper explores several methods to create a simulation-based ship production support system for middle-sized shipbuilding companies and briefly explains its potential applications. The paper, however, is focusing on the actual building (material supply, available space, block geometry etc.) rather than the communication/information flow during the process. Second, there is the paper of Whitfield et al. (2003), which provides a general overview on ship product modelling techniques and describes the current state of the art, especially for the engineering/design part, but also focuses more on product modelling rather than process modelling. Third, the paper of Zhang et al. (2010)

describes a modelling approach for a ship repair company but focuses very specifically on the improvement of resource utilization.

Taking all the sources as described above into account, a knowledge gap is observed as there are no documents available that tick all the boxes in Table 1. In summary, **from the literature study it has become clear that it is possible to model and simulate complex information creation and sharing, but that this has not been applied to a full ship production process yet.**

	Contribution		
Author:	**Covers information flow/ communication**	**Covers simulation/ modelling**	**Covers ship (production)/ shipbuilding**
Bemelmans (1994)	x		
Dietz (1987, 1996, 2001, 2006)	x		
Murray et. al. (2000)	x		
Armstrong (2006)	x		
Kamalirad et. al. (2017)	x		
Grossman (2011)	x		
C. Durugbo (2011)	x	x	
Kyriy et. al. (2019)	x	x	
Leventsov et. al. (2017)	x	x	
Jakiela et. al. (2016)	x	x	
Thiede et. al. (2019)	x	x	
Wesselman (2017)	x		x
Wijma (2018)		x	x
Y. Song et. al. (2009)		x	x
Whitfield et. al. (2003)		x	x
Zhang et. al. (2010)		x	x
Coenen (2008)	focused on also other aspects	x	focused on engineering part
This thesis:	**x**	**x**	**x**

Table 1 Summary of reviewed literature and its contribution to the field

1.4 Research objectives

From the problem definition, it became clear that many ship production companies acknowledge the importance of improving their information flow and that there is a demand for a way to gain an overview of the internal and external information flow and a way to examine measures for improving the information flow. Subsequently, the main objective of the research can be formulated, which is as specified in Section 1.2 closely related to the problem definition, but somewhat generalized to settle the problem on as high a level as possible.

The main goal of the research is to identify and improve the professional communication exchange of shipyards and the companies it exchanges information with.

By reaching this objective, this research will contribute to several higher-level scientific, practical and societal goals. These overarching goals are described below.

The overarching scientific goals are:

- To provide a clear basis on the information flow and its stakeholders in shipbuilding companies, which can be used to explore further communication digitalization or -automation possibilities;
- To fill the gap on modelling and simulating communication/information flow for a ship production process;
- To elaborate on the report of Coenen (2008) by modelling the full production process including all stakeholders rather than the engineering part alone;
- To apply the State-of-the-Art simulation knowledge as described by Durugbo (2011), Jakiela et al. (2016) and Thiede et al. (2019) to a ship production process;
- To complement the work of Wijma (2018), Whitfield (2003), Zhang et al. (2010) and Song (2009) in its road to stimulate and expand knowledge on simulation applications for the maritime industry.

The overarching practical goals are:

- To support TB Shipyards and other ship design or -production companies and their stakeholders in their way to prevent communication errors and improve their information exchange;
- To help shipbuilding companies find their way through the maze of management tools, philosophies and theories and to provide the ability to examine measures before implementing it;
- To provide TB Shipyards with a clear overview of the communication barriers currently experienced;
- To stimulate a culture of measurement within TB Shipyards and others involved;

The overarching societal goals are:

- To minimize defects and rework due to communication errors in order to increase efficiency and minimize production waste (Kamalirad et al., 2017);
- To enhance the success rate of information improvement measures, which results in more clarity for the company and its employees while going through corporate changes (Decker et al., 2012);
- To reduce the work stress of employees caused by communication errors (The Economist Intelligent Unit, 2018).

1.5 Approach & research questions

The main objective can be subdivided into two main parts, identification or modelling of the information flow and testing measures or experimenting to improve the information flow (See also Figure 1 Goal Breakdown Structure of the project). The following main research question will be asked to reach the objective:

Which measures are effective for improving the information handling in a general ship production process for TB Shipyards?

In order to identify/model the information flow, first it should be defined what the model should look like. Three things are important for this. First, it is important to look at literature and see which techniques and theories are applicable, second is important to scope the model to make it manageable, as it is difficult if not impossible to take all kinds of characteristics and influences into account, and third, it is important to take into account which experiments are to be conducted with it as this might influence the formation of the model.

After defining what the model should look like, the actual model can be developed. Here, it should be clear which stakeholders should be included and afterwards, it should be clear whether the model coincides with the real-world situation.

To test measures for improving the information flow, it should first be defined which experiments are interesting to be executed. Then, a case-study is performed and afterwards again a check will be performed to see whether the results of the experiment are trustworthy and reliable. Finally, the results of the experiments can be interpreted and the main objective can be reached

The objectives and sub-objectives are visualized by means of a Goal Hierarchy Plot (GHP) (Saaty, 1990) or Goal Breakdown Structure (GBS) (Attrup & Olsson, 2015) in Figure 1. A GHP helps to clarify the *why* and *how* of this research and is of great value when managing the project (Attrup & Olsson, 2015). Below each sub-goal, a clear task is defined which will be executed to reach the goal. For every sub-goal, a corresponding sub research question can be defined. This results in the following sub research questions:

1. How can the information flow for a general ship production process be modelled?
2. What will be the focus of the model and how will this influence the formation of the model?
3. Which potential improvement measures are interesting to test and how will the corresponding experiments look like?
4. Which stakeholders/actors are important in the information flow?
5. Does the general model coincide with the real-world situation sufficiently?
6. For which case should the experiments be executed?
7. Are the results of the case study reliable? Does the case-specific model coincide with the real-world situation sufficiently?

After answering these sub-questions, the main question can be answered.

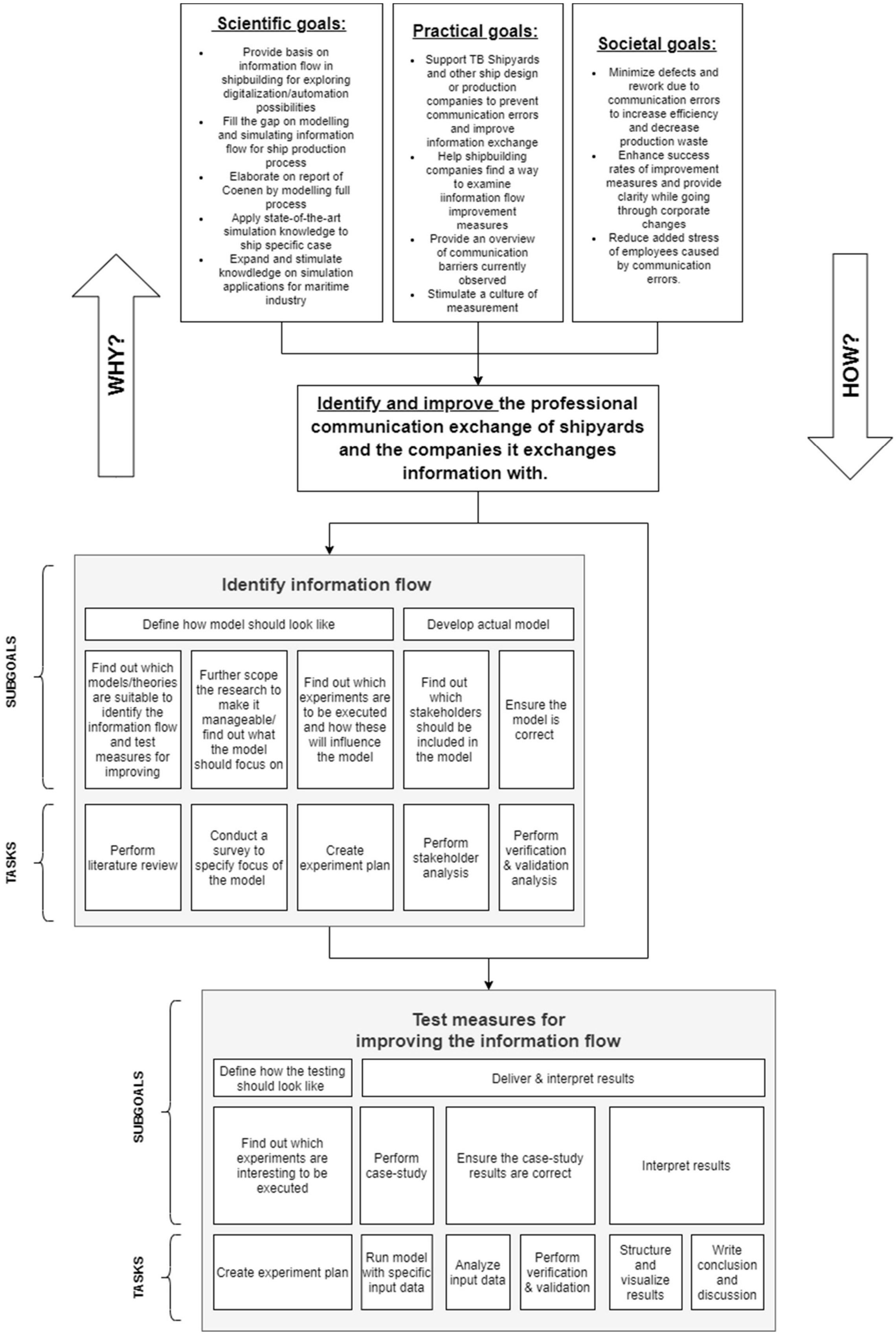


Figure 1 Goal Breakdown Structure of the project

1.6 Thesis outline

This report will be structured according to the double diamond model. The double diamond model or 4D model visualizes the divergent and convergent stages of a (solution) design process. The 4D's stand for the names of each stage; Discover, Define, Develop and Deliver (Tschimmel, 2012).

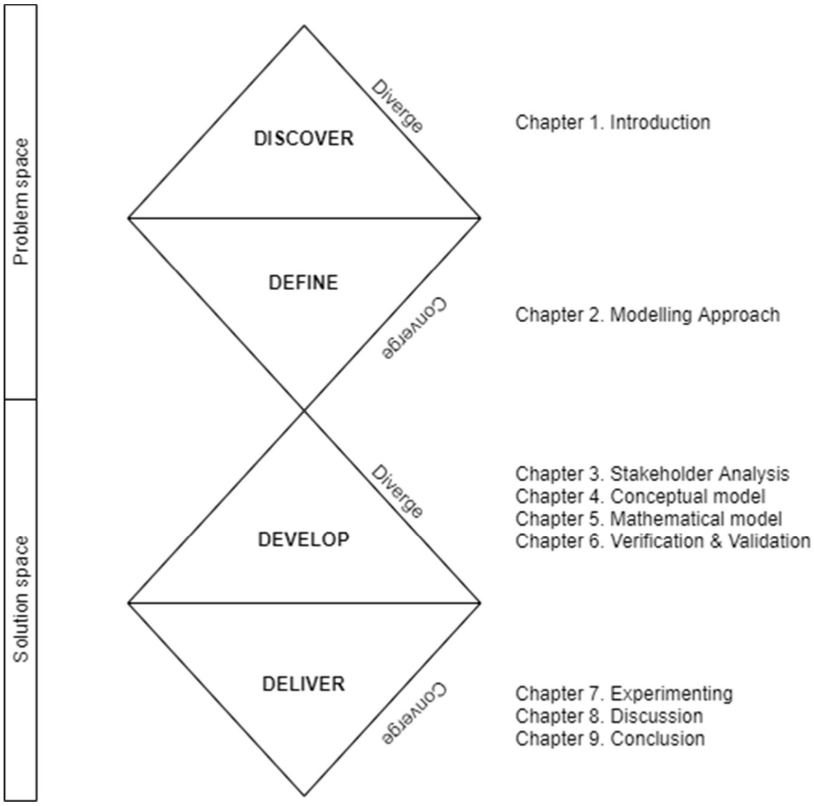


Figure 2 Double diamond model

In this chapter, the problem has been discovered in a diverging manner. It started with a few examples of specific problems in Section 1.1, broadened our horizon by executing a literature study and ended with a general, high-level objective and its scientific, practical and social contribution. Next, Chapter 2 will start broadly and continue the literature research and look for theories and models which apply to the problem. This phase will converge by scoping the research and state which experiments will be executed. In this chapter, the first 3 sub research questions will be answered.

The next chapters will again be diverging as here the development of the actual general model will be described. The phase will end with a verification/validation chapter in which it will be investigated whether the model is coinciding with the real-world situation and also applicable for multiple cases. Here, sub research questions 4 and 5 will be answered.

After this, again a converging phase will occur when the model will be applied to a specific case-study. The pre-defined experiments will be applied to this case-study and the results will be interpreted. In the corresponding chapters 7, 8 and 9, the sub research questions 6 and 7 and the main question will be answered.

Notes

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[1] According to Coenen (2008), information flow should not be used as a metaphor for information exchange, but as the term is widely used throughout literature and offers a certain familiarity, the view of Coenen (2008) has not been adopted. See also Section 3.1.

[2] This is a free interpretation of the first characteristic described by Rittel & Webber (1973). Originally the characteristic is summarized as "*There is no definitive formulation of a wicked problem".*

[3] To structure these higher and lower level problems which result in higher and lower level objectives, use is made of Goal hierarchy plots. A graphical method which is part of AHP (Analytic Hierarchy Process)-theory. This can be found in Section 2.5.

[4] Further reasons to make use of a simulation model for this problem are substantiated in Chapter 3.

[5] The thesis of Wesselman (2017) has been executed in order to obtain a MSc. in Strategic Product Design and Science Communication, hence the necessity to create a physical product.

Part II Define

2. Modelling Approach

As psychologist Abraham Maslow once said: "*I suppose it is tempting, if the only tool you have is a hammer, to treat everything as if it were a nail"* (Maslow, 1966). The quote implies that it is important to create a broad overview of the available tools for a problem. This will be done in this chapter. After having created a broad overview, the research will be further scoped. The final goal of the chapter is to define how the model is going to look like.

In Section 2.1, the terminology and abstractedness of communication will be discussed and the first sub research question will be answered. "How can the information flow for a general ship production process be modelled?". In Section 2.2, it is time to move from theory to practice and answer the second sub research question. "What will be the focus of the model and how will this influence the formation of the model?". Then in Section 2.3, the basic layout of the model will be presented. In the final section, Section 2.4 it will be made fully clear how the model and experiments are going to look like and sub research question 3 will be answered: "Which potential improvement measures are interesting to test and how will the corresponding experiments look like?"

2.1 Theoretical framework information flow

In this section, the terminology and abstractedness of communication will be discussed. Unlike physical flows like cooling water with specific characteristics as viscosity, temperature and flow speed, "information flow" is more abstract. An exploration of the subject will benefit further understanding of the rest of the report. Next, by reviewing the literature, it will be investigated which techniques and theories are suitable for identifying the information flow. By the end of the section, sub research question 1 can be answered: "How can the information flow for a general ship production process be modelled?".

2.1.1 Information flow terminology

As specified in Chapter 1.1, "communication is defined as "*The process by which messages or information is sent from one place or person to another, or the message itself;"* (Cambridge University Press, 2009). Information flow can be defined as "*a particular view that focuses on the path followed by information entities*" (Hainaut, Brogneaux, & Cleve, 2013). Both definitions are very similar and therefore, the notions are used interchangeably. For some, the notion "flow" implies a fluid that should be transferred in a steady, continuous way, which is not the case for information. However, as the term is widely used throughout literature and offers a certain familiarity, the term "information flow" will not be rejected.

Sometimes, the notions "information", "data" and "knowledge" are used interchangeably, but these are three very different concepts. The difference between information, data and knowledge can be illustrated with the example of a ship motion sensor aboard of a ship carrying project cargo. The sensor measures accelerations at certain frequencies, which can be seen as *data*. This data will only become *information* when it gets a certain purpose, for example when an (average) acceleration value is reported to the captain so that he will be able to check it. Subsequently, the captain will need a certain *knowledge* to be able to judge whether the reported acceleration value does not exceed the limits of his cargo.

2.1.2 Information flow de-abstraction

Information flow is a very broad concept as it contains many characteristics. "*The more compound an entity is, the more abstract it is because a greater amount of detail has to be ignored when the entity is analysed as a whole"* (Hazzan & Zazkis, 2005). Therefore, to reduce its abstraction level, the concept is split up into some relevant characteristics together with examples to clarify it.

Information (flow) can be expressed in terms of:

- Quantity: A stability booklet from one engineering company could be providing more information than the stability booklet from another company.
- Clarity: The specifications of one engine could be clearer than the specifications of another.
- Reliability: Information from an expert can be considered more reliable than information from an intern.
- Accuracy: The results of a CFD resistance calculation can be considered more accurate than those of a Holtrop & Mennen estimation.[1]
- Stability: Construction information for a mid-ship section can be more stable than construction information for an often-changing accommodation section
- Frequency: The number of (direct) information exchanges between a CEO and a welder can be less than the number of information exchanges between a production manager and a welder.

Furthermore, some additional useful characteristics of the concept "information (flow)" are found throughout the literature:

- Coenen (2008) defines higher- and lower-level information objects. For example, the information objects "length, breadth and draught" are considered lower level than its parent object called "main dimensions", which is subsequently a lower level information object than a "general arrangement".
- Yazici (2002) defines three types of information flow forms in organizations being verbal, written or in electronic form.
- Henczel (2001) defines four types of information moves, 1. between individuals in an organisation or organisations, 2. between organisational departments, 3. between multiple organisations, and 4. between an organisation and its environment.
- Coenen (2008) specifies two strategies of publishing information, 1. an iterative strategy in which information is released early in a process with relatively low stability and a high risk of rework, but relatively small throughput times or 2. a set-based strategy in which only "certain" information is released, which results in a low risk of rework but relatively long throughput times.

- Loshin (2013) lists several discrete processing stages for information flow, being: supply of external data, acquisition of existing data instances, transformation of data, creation of new data, processing of data, storing of data, packaging of data, routing of data, decision points, delivery of data and consuming of data. Coenen (2008) distinguished next to the generation or processing of information also evaluation stages.

2.1.3 Information flow modelling

Information is as much important to the existence of organisations as it is as oxygen for human life (Hakim, 2008) and organisations widely recognize the challenge of how to better understand and manage the capturing, storing and retrieving of information (Lo Storto et al., 2008). Problems with the information flow may result in delays or even failure to complete projects, added employee stress, low company morale and sometimes loss of sales (The Economist Intelligent Unit, 2018). Among 400 surveyed companies, an average loss of 62.4 million dollars per year due to poor communication is reported (Grossman, 2011). In other words, there is much to gain for companies if they are able to understand and improve their information flow processes.

Modelling is a classic approach to gain a deeper understanding of complex problems (Durugbo, Tiwari, & Alcock, 2013). By representing a real-world system at a certain level of detail, a model can help visualize things that cannot be actually seen. A model is useful both as an explanatory tool in order to better understand a process and as a predictive tool in order to test ideas and make predictions (Chittleborough & Treagust, 2009), which perfectly fits the objective of the research: to identify and improve the professional communication exchange of shipyards and the companies it exchanges information with. Subsequently, models are very useful as decision-making support tools (Pidd, 2010).

There are countless types of modelling approaches, some suitable for many topics other than information flow, but Durugbo et al. (2013) reviewed 118 articles on modelling information flow specifically. 47 of those articles were categorized as “general” articles, but the remaining articles could be classified into two main approaches:

1. Approaches for diagrammatical (qualitative) modelling of information flow
2. Approaches for mathematical (quantitative) modelling of information flow.

Below, each type of approach will be briefly explained.

2.1.3.1 Diagrammatical

Diagrammatic approaches serve as a means of communication and presentation and are of great help for visualizing qualitative information. Diagrammatic models can be further classified into:

- Pictorial representations (e.g. rich picture diagrams)
- Graph representations
    - Structured analysis tools (e.g. Petri Net diagrams, entity relationship diagrams, swimming lane diagrams)
    - Network analysis tools (e.g. network analysis diagrams)
- Matrix representations (e.g. design structure matrix diagrams)

Some practical examples of these approaches are further explained in Appendix 12.2. The appendix can be consulted when there is low to zero experience with these kinds of tools and more understanding is desired.

2.1.3.2 Mathematical

As mentioned before, information flow can also be modelled mathematically. Mathematical models are often classified based on the following opposed properties (Andreski, 1972):

- Linear versus nonlinear
- Static versus dynamic
- Explicit versus implicit
- Continuous versus discrete
- Deterministic versus probabilistic/stochastic
- Deductive versus inductive[2]

The property "linearity" means that mathematical relationships can be represented as a straight line whereas with nonlinearity this is not the case. A static model implies that the model acts constantly over time, which is not the case for dynamic models. Explicitness means that the current state at every timestep is not included in the results, whilst for implicit methods, the current state of the system is involved. A continuous model can have infinitely many values and visually, time-dependent graphs are uninterrupted. A model is discrete when it is non-continuous and has for example, integer values or specific ranges. Deterministic models do not have a random aspect in the model, whilst stochastic models do. Finally, deductivity means that the model is based on theory, whilst inductive models are more data-driven.

2.1.3.3 Combining diagrammatical & mathematical methods: simulation

Combining both quantitative and qualitative methods is considered beneficial, as this combination compensates the mutual and overlapping weaknesses of both types of approaches (Johnson & Onwuegbuzie, 2007; Kelle, 2006). Furthermore, the combination ensures a holistic view (Kelle, 2006) which is considered important for this research.

One specific modelling type that typically combines qualitative and quantitative (or diagrammatic and mathematical) approaches is **simulation** (Aoyama, Ratick, & Schwarz, 2005; Durugbo et al., 2013). The next chapter will further elaborate on the simulation methodology and why simulation might be a good choice for modelling information flow.

2.1.4 Simulation modelling approach

Simulation as a discipline can be seen like mathematics; as a field that has its own tools and theories and something that can be applied in many different areas (Niazi, 2019).

Simulations are important for many different types of cases with respect to the "real world", for example when experimentation on a real system is dangerous (e.g. testing the fire integrity of a ship), non-existing (e.g. testing sea-keeping of a vessel that has not been built yet), taking too long (e.g. testing decay of material used for wind farms), or defined as one-shot operations (e.g. implementing information flow improvement possibilities)

2.1.4.1 Simulation terminology

One definitive definition of the word "simulation" is difficult to give, as there are more than 100 different definitions (Ören, 2011), but Ingalls (2008) gives a description which is considered appropriate in this set-up:

> *"Simulation is the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behaviour of the system or of evaluation of various strategies (within the limits imposed by a criterion or set of criteria) for the operation of the system."*

The words "modelling" and "simulation" are often used interchangeably, but they are not fully equal. Every simulation requires modelling, but not every model is for simulation as every ship requires an engine but not all engines are for ships.

2.1.4.2 Types of simulation models

Niazi (2019) lists more than 750 different types of simulation, from "ab initio simulation" to "zero-variance simulation". Durugbo et al. (2013)'s "*Modelling information flow for organisations: A review of approaches and future challenges*" helps distinguishing three main techniques for simulation of information flow specifically being:

1. Discrete-event simulation (DES): a DES is based on a discrete sequence of events in time. It is widely used in decision support tools for logistics and supply chain management (Holm-Nielsen & Ehimen, 2016). It can estimate the performance of nonlinear and implicit systems (Hirschi, 2019). Coenen (2008) and Wijma (2018) both made use of this technique.
2. System-dynamics (SD): a technique that has been developed in the late 1950s by researchers of MIT. It builds on information-feedback theory and shows how the organization structure and time delays relate to the success of the company (Lai, Lee, & Ip, 2003). An SD model is always time-oriented and often based on differential equations. Important parts of a system dynamics model are the flow, which is a function of inflow and outflow, the stock and a feedback element.
3. Agent-based simulations (ABS): ABS offers the ability to model complexity from individual actions and interactions (P. O. Siebers, MacAl, Garnett, Buxton, & Pidd, 2010). The agents in the model are autonomous, individual elements with properties and behaviour characteristics. These can be human but can also be companies or for example trees in modelling spread of forest fire.

2.1.4.3 Simulation: a good choice for modelling information flow

First of all, as mentioned in Section 3.3.3, simulation combines qualitative and quantitative data, which is considered beneficial and helpful when taking a holistic view of the problem.

As previously mentioned in Section 2.3, the second reason to consider simulation techniques for the problem is that this has already been done before, so it has already proven to be successful, but nevertheless, still, a knowledge gap exists as some applications of simulation models in the maritime field have not been explored yet.

Next to this, in order to design a simulation framework, a thorough system investigation should be executed, which is already very useful in its own right (Coenen, 2008).[3] The thorough system investigation complies with the first part of the research objective (to identify the internal and external professional communication exchange). The fact that simulation is defined as "*the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behaviour of the system or of evaluation of various strategies*" very well fits the second part of the objective (to improve the internal and external professional communication exchange). Therefore, the third reason to make use of simulation is because it fits the objective of the research.

Fourth, simulation model characteristics suit the characteristics of the case: a ship production process and its communication generally contain complex interdependencies and are of a stochastic nature (Coenen, 2008). Simulation models are appropriate to model these kinds of difficulties, where other techniques might be less suitable as simulation models, in general, have less restrictive assumptions, offer visualisation of the subject, can be used as means of communication, offer some kind of transparency and create knowledge and understanding (P.-O. Siebers, 2012). All of these are characteristics that are considered very valuable for this research.

The final reason is based on the fact that Coenen (2008) mentions that simulation models encourage a culture of measurement which subsequently provides a basis for continuous process improvement. As shipbuilding is a very tough and competitive business, continuous process improvement is necessary in order to survive. Thus, adopting this "culture of measurement" is encouraged by many, including the European Commission and renowned shipyard owners (European Commission, 2015).

2.1.5 Summary

With the theoretical framework as described in this chapter, it is possible to answer the first sub research question:

"How can the information flow for a general ship production process be modelled?"

From literature, it has become clear that information flow can be modelled in three ways: diagrammatically (qualitative), mathematically (quantitative) or a combination of both. Diagrammatic approaches can be further classified into pictorial, graph or matrix representations. Mathematic approaches can be further classified into linear/nonlinear, static/dynamic, explicit/implicit, discrete/continuous, deterministic/stochastic and deductive/inductive characteristics.

It is beneficial to combine both qualitative and quantitative approaches (which is the case for simulation models) to compensate the mutual and overlapping weaknesses of both types of approaches and keeping a holistic viewpoint. Additional reasons to make use of a simulation model are that simulation models are proven to be successful but still worth studying, fitting the objective, fitting the characteristics of the case and encouraging a culture of measurement. Therefore, simulation modelling is considered a suitable tool for this research.

When simulating information flow specifically, three main types of simulation models have been found in literature: System Dynamics, Discrete Event Simulation and Agent-Based Simulation.

Which simulation technique suits best is dependent on the focus of the model and will be described in Section 2.2.3.

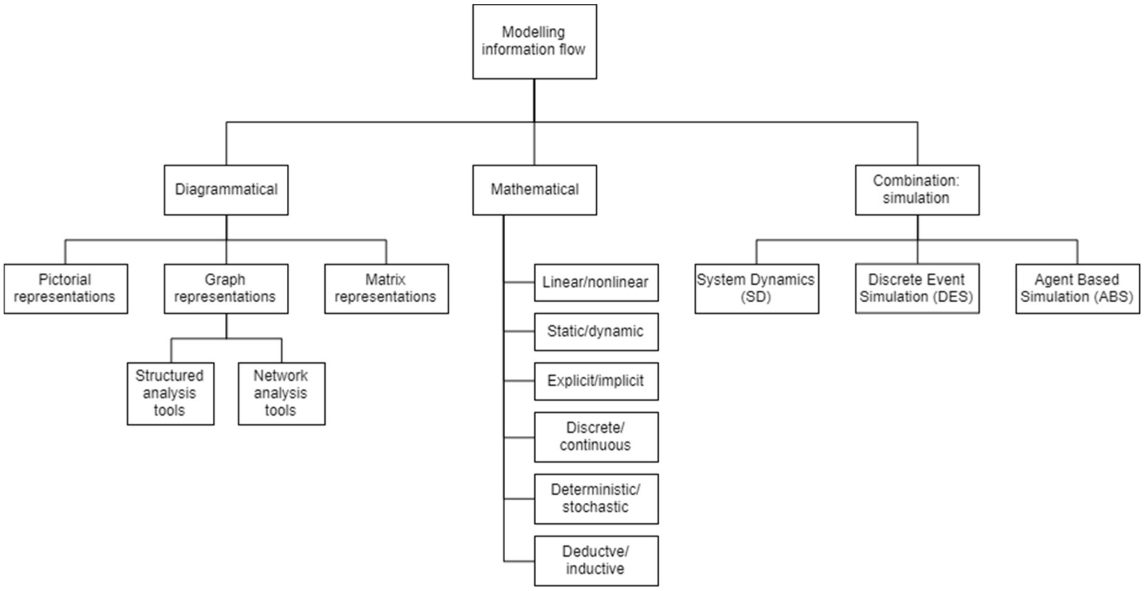

Figure 3 Overview modelling of information flow

2.2 Model demarcation & choice of simulation technique

Now that it is known how the information flow for a general ship production process *can* be modelled, it should be investigated how the information flow for a general ship production process *should* be modelled and converge towards a specific approach. The sub research question "What will be the focus of the model and how will this influence the formation of the model?" will be answered. Based on this, a definite choice of the simulation technique can be made.

2.2.1 Focus of the model

Modellers often can be subdivided into two camps: those who think the real world can never be modelled in detail and those who do think it is possible to build detailed models of the real world and make predictions based on it. The first type of modeller produces abstract models with educated guesses and assumptions, whether the second type of modeller produces so-called "kitchen-sink" models, which has as much as possible of the real world represented inside it (Andy Evans, 2014). As communication in a process is very complex, much input data is unavailable and there is limited time-availability, information flow with all its characteristics and properties cannot be modelled in full detail. Also from expert conversations, it became clear that it is important to specify a clear direction for the model to prevent it from being too superficial and therefore non-contributing to improving the situation. Therefore, a specific "focus" of the model should be chosen. To do so, 14 common information flow problems have been listed to choose the most relevant to focus on. The options are based on expert conversations, confirmed by literature (Al-Rawas & Easterbrook, 1996; Conrad, 2014; Eppler, 2007) and are as follows:

- **Information damaging:** by using different software or communication channels, information gets lost or damaged;
- **Information mutation**: because of misinterpretations or different viewpoints, information changes;
- **Information overflow:** the essence of information gets lost because too much information is given;
- **Information deficiency:** because of too little information, assumptions are made and communication problems arise;
- **Information discrepancy:** what a receiver needs and what a sender thinks a receiver needs does not coincide;
- **Information timing:** when one has to wait too long for the necessary information;
- **Information instability:** when information changes too often during a project;
- **Information inaccuracy**: because of working with information that is often based on rough estimations;
- **Untargeted information:** when it is unclear who the information is intended for;
- **Wrong information:** when information is simply incorrect or conflicting;
- **No confirmation:** because there is no confirmation whether information is received or understood;
- **Use of jargon**: incomprehension caused by use of too many specific technical terms;

- **Culture difference:** because different departments and companies speak “different languages”;
- **Language barriers:** because people literally speak different languages.

Through a survey under employees of TB Shipyards, the most important options have been defined to further specify the focus of the model. Making use of a survey is preferred over interviews or workshops, as this is more cost-effective, data is easier to process and it enables respondents to answer anonymously. The survey has only been held for employees of TB Shipyards, as the main research question is: “Which measures are effective for improving the information handling in a general ship production process **for TB Shipyards**?” and asking other stakeholders in the process might result in a different focus which might be less relevant for TB Shipyards. The survey is featured in Appendix 12.3.

From the 40 approached employees, 21 responses were collected.[4] Their functions ranged from production leaders to sales and from engineers to managers. They were asked to choose and rank 4 out of the possible causes for communication errors in the shipbuilding process as stated in the list above. 11 out of 21 marked “Information timing” as an important cause and 10 out of 21 marked “Information discrepancy” and “Information deficiency”. 9 out of 21 listed “Information instability” and “Information mutation” as important causes.

Subsequently, by ranking them from most (4 points) to least relevant (1 point), it became clear that the most important causes for communication errors in the shipbuilding process are (according to TB Shipyards employees):

1. Information timing (15%)[5]
2. Information deficiency (14%)
3. Information instability (13%), Information discrepancy (13%) & Information mutation (13%)
4. Wrong information (11%)

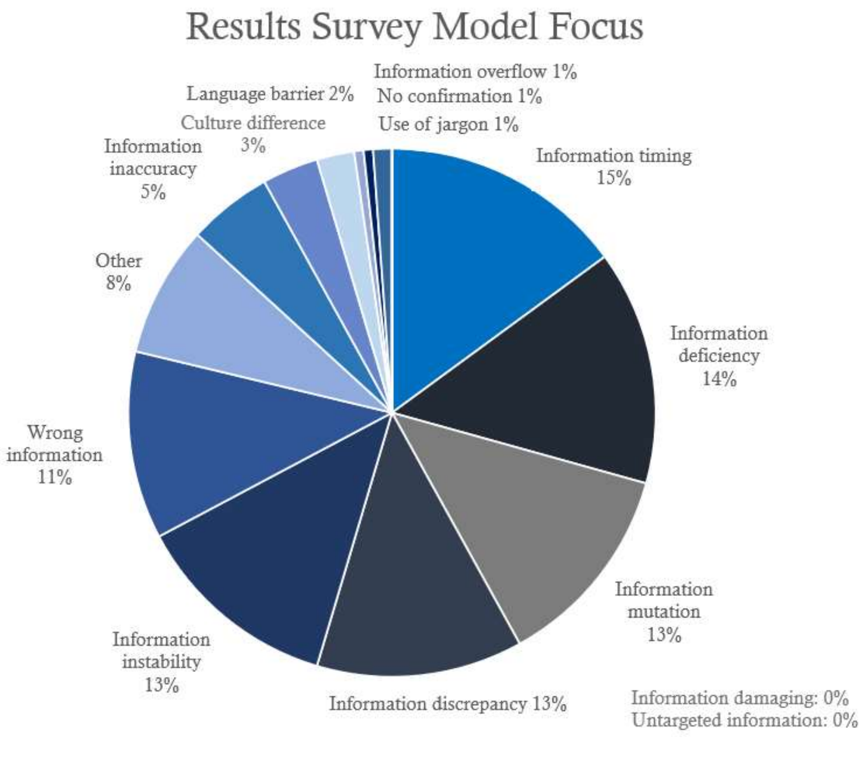

Figure 4 Results of model focus survey

This way of ranking is preferred over AHP methods, as AHP requires many comparisons and the much work that applying AHP requires, might go unrewarded when it becomes clear that the results are inconsistent (Rezaei, 2015; Saaty, 1990). The results have been visualized in Figure 4 . It can be seen that there is not one outstanding main cause, but there are multiple relevant options to focus on. Alternatively, it is chosen to focus on "Information timing" because of the following reasons:

- Many simulation models are time-dependent and have timespan as output (Coenen, 2008; Wijma, 2018).
- By thinking in time units, it is easy for others to understand the model and perform verification and validation of the model.
- It is assumed that tackling one of the top six main presumed causes of communication errors in the shipbuilding process is sufficient to reach the objective of the research and moreover considered manageable with respect to the available time and resources.

2.2.2 Scope of the model

The main purpose of the model is to comply with the objective of the research being: to identify and improve the professional communication exchange of shipyards and the companies it exchanges information with. Subsequently, it should answer the corresponding main research question: "Which measures are effective for improving the information handling in a general ship production process for TB Shipyards?" Based on the previously explained focus of the model (information timing), the purpose of the model can be further scoped. This results in the following requirements:

- The model should be able to identify the time spent waiting for information;
- The model should be able to test measures to decrease waiting times;
- The model should, based on the main objective, include both internal and external information flow;
- The model should, based on the main objective, include the full information flow of a ship production process, from inquiry to delivery.
- The model should not be too generic. It should contain sufficient specifics to be useful preferably on an operational level instead of a strategic level.

2.2.3 Choice of simulation technique

These requirements as described previously have the following consequences for the formation of the model. System Dynamics approaches are rejected, as information transfer is of a discrete and stochastic nature, whilst SD often relies on continuous and deterministic processes. Also, System Dynamics approaches are often based on differential equations and information timing cannot be easily expressed as such.

Agent-Based Simulation approaches are rejected, as here only the stakeholders are modelled and not the information objects as entities, which makes it difficult to model information transfer.

Furthermore, by modelling a net of stakeholders and no information objects, the information part must be very generic, whilst a more specific character of the model is preferred. [6]Discrete Event Simulation approaches seem most suitable for the case, as it matches the stochastic character of the case and in literature, many different DES applications can be found which provides much flexibility.

No queueing theories will be applied to the model, as this requires different information objects to be categorized which may cause the model to be too generic.

Petri Nets techniques offer both a basis for the diagrammatical part as the mathematical part (J L G Dietz, 1987) and much supportive software and literature is available. Combining Petri Nets techniques with DES is also common in much literature (Gaeta, 1996; Gribaudo & Sereno, 2000; Haas & Shedler, 1989; Holloway, Krogh, & Giua, 1997). Therefore, Petri Nets are preferred as a basis for the diagrammatical and mathematical part of the model.

2.2.4 Summary

The following sub research question can be answered:

"What will be the focus of the model and how will this influence the formation of the model?"

By means of a small survey, it became clear that the employees of TB Shipyards could not agree on one clear cause for information flow problems but instead defined six main potential causes. From these six, one has been chosen as this was considered manageable with respect to time and resources. This option can be combined into one model, is expected to improve the understandability of the model and fits the requirements of simulation models. The aspect the model will focus on is information timing.

Next to complying with the research objective and main research question, the model should be able to both identify and improve waiting time for information. Also, the model should show the internal and external part and be not too generic. With respect to the formation of the model, it is concluded that DES approaches are preferred over ABS and SD approaches to model information timing; that queueing theory causes generic results which is not preferred and that Petri Nets provide a good basis for both the mathematical as diagrammatical part of the model.

2.3 Conceptual Model Approach

Now, a set-up for the conceptual model can be developed. As previously stated, the model will be supported by Petri-Net theory. Petri Nets are invented by Carl Adam Petri in 1939 in order to describe chemical processes (Olimpo, 2011). A Petri Net consists of circles, which indicate "places[7]" and rectangles, which indicate "transitions". There can be no link between nodes of the same type (circle to circle or rectangle to rectangle). Furthermore, places may contain so-called "tokens". The tokens can "fire" transitions and are determining the dynamic aspect of the model. The information objects will be modelled as places (circles) and information processing activities as transitions (rectangle).

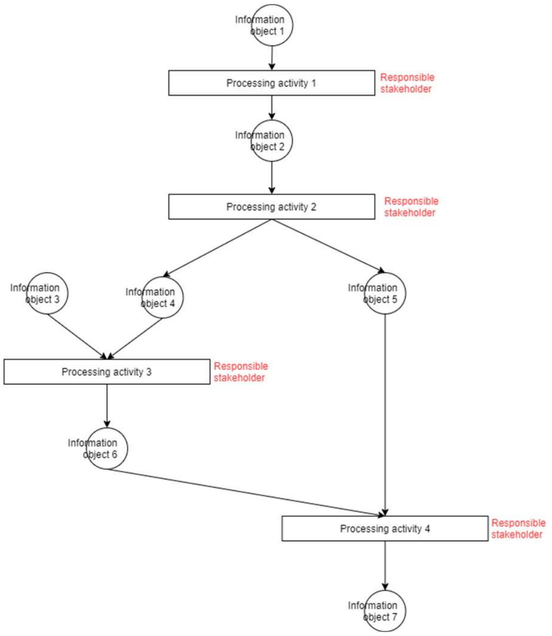

Figure 5 Set-up of conceptual model

Instead of "Information object 1" and "processing activity 1" a name will be assigned, for example "cross section drawing" or "building of cross-section". Furthermore, one or more stakeholders will be assigned to each object and processing activity.

Information timing will be modelled mainly by means of the processing activities. Based on PERT theory, a "time to complete"-distribution will be obtained by means of a value for optimistic finish, most probable finish and pessimistic finish. If a processing activity is finished, it will unleash the information objects depending on the activity, which are required for starting other processing activities. By assigning stakeholders to each object and activity, we can measure how long a stakeholder is waiting for certain information objects or activities to start. Subsequently, we can experiment with this by changing distributions or structures. It can then fulfil the objectives as specified in Section 2.2.2, "to identify the time spent waiting for information" and "test measures to decrease waiting times."

The model somewhat resembles a Critical Path Method (CPM) or Critical Path Analysis (CPA). A CPM is an algorithm which is often used in combination with PERT (Kelley & Walker, 1959).

The model indeed makes use of the basics of this algorithm, but it provides the additional ability to simulate the process multiple times, which is not necessarily the case for all CPA's. Furthermore, the often quite difficult to understand schemes belonging to CPA's (See also Figure 6) are not used in this project. Instead, the more comprehensive Petri-Net set-up is used, which enables visualizing of both information objects as information processing activities. This greatly enhances the "feeling" with the model, which could not be obtained when using traditional CPA visualizations.

Furthermore, as previously mentioned, Simulation as a discipline can be seen like mathematics; as a field which has its own tools and theories and something that can be applied in many different areas (Niazi, 2019). Whilst for mathematics, there are tools and theories like the abc-rule, trigonometry or Laplace transformations, in simulation you will find tools and theories like PERT, queueing theory, and Petri Nets. If one uses a Riemann sum to find an area instead of integration, this does not necessarily mean that his approach is good or bad, provided that they both reach the same goal. This is not any different for simulation applications. The conceptual model as presented here can be seen as a combination of several tools and techniques which reinforce each other to obtain a common goal.

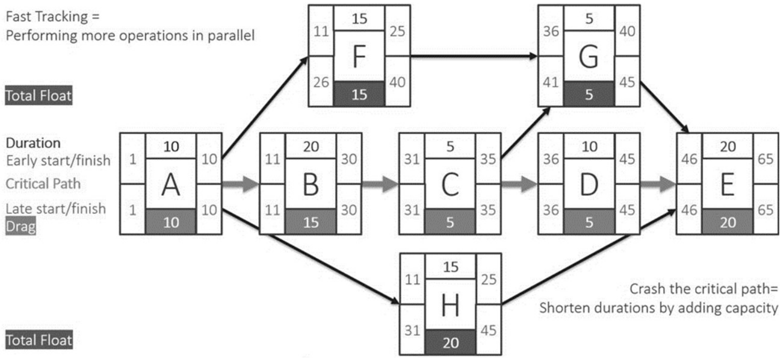

Figure 6 Example of a Critical Path Analysis schedule, obtained from (Business Central, n.d.)

In Chapter 4, the conceptual model will be further developed and the corresponding assumptions will be described.

2.4 Experimenting Approach

In this section, an approach will be described in order to predefine which questions the model will be expected to answer. The kinds of decisions the simulation model will aid should be decided upfront, as the building, verification and validation of the model is highly dependent on this (Sargent, 2011). An unplanned, "hit-or-miss" course of experimentation with a simulation model is considered inefficient and time-consuming (Kelton & Barton, 2015). This experiment plan does not include experiments for verification/validation purposes. Through this section, the sub-question "Which potential improvement measures are interesting to test and how will the corresponding experiments look like?" is answered.

The goal of the model is to answer the question "Which measures are effective for improving the information handling in a general ship production process for TB Shipyards?" and to achieve this by finding measures that reduce the total throughput time and stakeholder waiting times. In order to make these more clear, hypotheses are defined which should be confirmed or refuted by means of the experiments.

Experiment 1: Bottleneck identification and optimization

The first measure that could decrease the total throughput time is to identify the main bottlenecks and modify the input values of the preceding activities of the main bottlenecks. Focusing on bottlenecks to improve information flow is proposed in literature (Helms & Buijsrogge, 2005; Tribelsky & Sacks, 2010). For example, if from the model it becomes clear that the activity "create initial structural model" often needs to wait very long for "arrangement drawings" before it can kick-off, we could change the input values of the preceding activities. The pessimistic or most probable finishing times of the supplier providing part information to create the arrangements could be set lower, which ultimately could result in a lower total throughput time or even total elimination of the bottleneck. The corresponding hypothesis can be formulated as follows:

H1: For bottleneck X, if the input value of preceding activity Y is set to Z, the total throughput time and stakeholder waiting times will be reduced and bottleneck X may even disappear.

This hypothesis may be used for multiple bottlenecks. Which preceding activity Y and input value change Z will be set, is case-dependent and requires background knowledge of the situation. For example, the shipyard may be able to specify in supplier contracts that the maximum delivery time of part information is limited to 2 weeks quite easily, but may not be able to specify this for classification societies.

Experiment 2: Pre-mature release of information

A second measure to improve the information timing is to release information objects pre-maturely. One example is to release the tank plan when it is done for say 80 percent, so that the HVAC supplier can start creating its system diagrams earlier and he does not have to wait for the information. For every activity specifically, we can release its subsequent information objects after finishing it for 60 and 80 percent and compare it to the case when we release it after finishing it for

100 percent. It is expected that there are some main activities that lead to a significant reduction in total throughput time when released earlier. The corresponding hypothesis to test is:

H2: If information object X is released pre-maturely, a significant reduction in total throughput time and stakeholder waiting times can be obtained.

This hypothesis will be applied to all information object releasing activities. For some activities in the critical path, this hypothesis will be confirmed and for others, it will be refuted. Of course, the more pre-mature an information object is released, the more it is likely to change afterwards. If a tank plan is released when it is done for 80 percent, there is a chance that modifications occur that affect the HVAC supplier and its created system diagrams. This chance is even higher when a plan is released whilst only for 60 percent done.

Next to these 2 large experiments investigating the model as a whole, additional, more-specific experiments will be executed.

Experiment 3: Eliminate delivery times

For the third experiment, the delivery times in the model will be eliminated. It is expected that by eliminating the delivery times, the total throughput time will be reduced as well as the stakeholder waiting times. The corresponding hypothesis is as follows:

H3: If the delivery times of all suppliers in the process are set to zero, the total throughput time and stakeholder waiting times will be reduced.

Many other variants of this experiment could be applied to the model, for example instead of total elimination, the delivery times may be reduced to half the delivery times or other information processing activity durations may be set to zero.

Experiment 4: Delay of construction plan

Whilst the previous experiment focuses on reduction of durations, this experiment focuses on delays in the model. More specifically, a delay in the construction plan. This specific activity is chosen as this situation occurred real-time whilst performing this research. The corresponding hypothesis is:

H4: If the throughput time of the specification of the primary construction is increased, the total throughput time and stakeholder waiting times will increase.

Again, other variants of this experiment may be applied to the model, but for this research the focus will be on these four experiments.

Notes

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[1] Assumed that results of both types of tools are obtained by experienced users

[2] Additionally the characteristic "floating" could be added indicating that a model has not been built on neither theory (deductive) nor observation (inductive), but on expectations.

[3] TB Shipyards also acknowledges the importance of an information flow overview, so making use of a simulation model also fits the interests of the client.

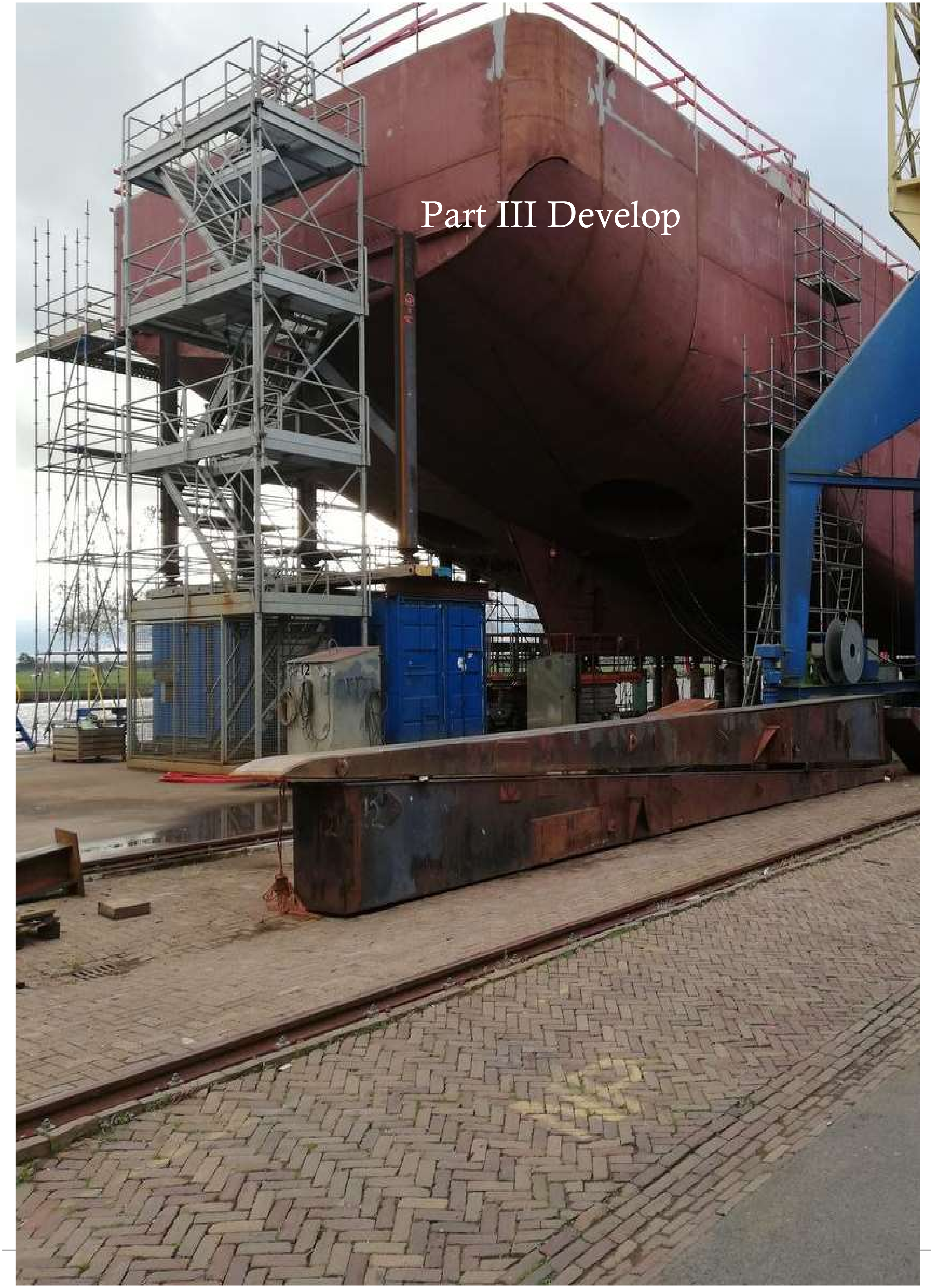
[4] Because of the (unavoidable) low response number and qualitative survey data, no statistical tests have been performed.

[5] The percentages are obtained by adding all given points of an option and subdivide it by the total points to be distributed.

[6] Please note that despite these reasons there still might be exceptional cases where SD or ABS can be used.

[7] Here, places do not have to be physical locations. Objects may also be used.

Part III Develop



3. Stakeholder analysis

In the previous chapters, an approach for the conceptual model was specified and from this it became clear that for every information object and processing activity, the responsible stakeholders should be defined. Furthermore, to collect other data for the model, stakeholders should be approached. Therefore, a stakeholder analysis is performed. This is subdivided into internal and external stakeholders.

3.1 Internal stakeholders

The internal stakeholders are based on the company's organization chart. Here, the similar roles on different locations are merged and generalized.[13] This results in the following internal stakeholders.

3.1.1 Management

The management department consists of the managing directors, the location managers and the employees that support their tasks, such as the secretary and administration and reception. The management board is able to hire, fire and compensate the top-level decision-makers and is able to ratify and monitor important decisions (Fama & Jensen, 1983). At TB Shipyards, the management department (including location managers and supporting employees) consist of approximately 4 FTE. As the ship production process is more or less managed by the separately defined project managers and the managing department is more involved with strategic decision making, this stakeholder will therefore not be included in the model.

3.1.2 Sales

The sales department consists of salespersons and financial managers. The task of the salespersons is to secure orders. To do so, they perform market research, promotional activities, enquiry screening and response and prepare first concept designs. Also, after-sales services are included, being the provision of a guarantee period and collecting operational feedback (Bruce & Garrard, 1999). At TB Shipyards, the sales department consists of approximately 3 FTE.

3.1.3 Engineering

The engineering department can be both in-house and external. It highly depends on the project whether engineering is done in-house or external. For relatively simple ships or designs that are similar to the ones previously built, most of the engineering is done in-house. For complex ships, often an external party is asked. The engineering department is further divided into concept engineering, basic engineering and detail engineering. Typical for engineering processes is that the throughput times are often highly fluctuating (Coenen, 2008).

Examples of information handling activities for the in-house engineering department are the creation of manufacturing drawings for the production floor or establishing an electric load balance diagram from the information on electrical equipment. The detailed engineering of a ship design may take tens of thousands or even hundreds of thousands man-hours, being around 10 percent of the total building price (Dokkum, 2007). At TB Shipyards, the engineering department consists of approximately 8 FTE.

3.1.4 Project Management

The project management department is one of the main pivots in the process. They manage the shipbuilding process by determining the production planning and being the spokesperson for many stakeholders in the process. A few of many examples of information handling activities for project managers are creating a planning based on the agreements as specified in the contract, thinking about the yard layout and discussing this with the production leaders. At TB Shipyards, the project management department consists of approximately 6 FTE.

3.1.5 Production

The production department is responsible for transferring the building information and materials into physical parts of the ship. They also support some of the large logistical activities, for example, hoisting an engine into the ER. At TB Shipyards, the production department consists of approximately 17 FTE per ship[14]

3.1.6 Warehousing/Logistics/Procurement

The warehousing/logistics/procurement department knows which individual parts and materials are necessary for building the ship. They transfer this kind of information into real physical objects by purchasing the components or raw materials. At TB Shipyards, the warehousing/logistics department consists of approximately 6 FTE.

3.1.7 QHSE

QHSE stand for Quality, Health, Safety and Environment. The QHSE department makes sure that these four notions are maintained during the ship production process. This is mainly focused on the environment the ship is being built rather than the ship as a product. With respect to Quality and Safety of the ship as a product, also the Class department (See 3.2.4) is responsible. As this department does not explicitly transfer information relevant for the production of the ship but is more present on the background of it, this stakeholder will not be taken into account when building the model.

3.2 External stakeholders

3.2.1 Client

The client is most often the shipowner and at the beginning of the ship production process, he submits a list of requirements as a call for tenders to several shipyards (Dokkum, 2007). These requirements vary from operational profile requirements to preferred suppliers of equipment. Throughout the production process, the client is involved when making important decisions and updated regarding the process on a regular base. The amount of involvement is very different for each different client.

3.2.2 Supplier

The supplier is responsible for providing the raw materials and subparts necessary in order to build the ship. Examples of supplier goods are steel, windows, engines, safety equipment, propellers etcetera. Sometimes, the client has preferences for specific suppliers. In a ship production process, the most common information handling activity for suppliers is finding the necessary information regarding delivery times and price after having received a tender request from the shipyard. Here, suppliers are further categorized as suppliers of main machinery parts (for example engines or switchboards), suppliers of secondary machinery parts (for example pumps or separators), suppliers of non-machinery parts (for example car cranes or navigational equipment) and specifically the steel supplier.

3.2.3 Subcontractor

The difference between a supplier and a subcontractor is that a supplier provides goods only, whilst a subcontractor provides goods and services. An example of a subcontractor is a piping company that provides both pipes as a good and also engineering of the piping system as a service or an HVAC company that supplies and fits, for example, air conditioning systems. Because of the service part, information flow structures for subcontractors are generally more complicated than for suppliers. Here, suppliers are further classified into subcontractor for accommodation installation (i.e. carpenter), subcontractor piping, subcontractor HVAC/sanitary, subcontractor electrical installations and subcontractor painting.

3.2.4 Class

During the production process, classification societies make sure that the ship is built according to the international laws and regulations of the IMO (International Maritime Organization) and the additional rules as specified class-specifically. They check the building information for approval and perform on-site surveys. Afterwards, they deliver a certificate of class, which is necessary in order to insure the ship. The types of information they handle are drawings and calculation documents. When the documents are not approved, they are sent back for revision.

3.2.5 Engineering/design bureau

Often, engineering activities are partly done in-house by the shipyard and partly outsourced to external companies. Often with drawings or documents from comparable and previously designed ships, engineers create drawings and documents for the new ship to be produced. These drawings have to comply with the client requirements, class regulations and of course other, coexisting drawings and models of the ship to avoid inconsistency.

3.2.6 Research institutes

Research institutes are involved with the ship production process when there are special wishes concerning the ship. For example, when the client indicates that he wishes the ship resistance to be as small as possible, additional research institutes can be asked to perform towing tests or CFD calculations to optimize the hull form. As we focus on a general ship production process, we assume that this stakeholder is not of importance in this model.

A list of the involved stakeholders for the project case specifically is featured in Appendix 11.7. In the model, the suppliers and subcontractors will be annotated according to their function (e.g. supplier of steel instead of "Centraalstaal B.V.").

3.3 Summary

In this chapter, a stakeholder analysis had been performed in order to identify the most important stakeholders in the process. By this chapter the fourth sub research question can be answered:

"Which stakeholders/actors are important in the information flow?"

The stakeholders could be subdivided into internal stakeholders and external stakeholders. The most relevant internal stakeholders in the process are the engineering-, sales-, project management-, production- and warehousing/logistics and procurement department. The management and QHSE department are also very important stakeholders, but do not directly contribute to the shipbuilding process. The most important external stakeholders are the client, classification society, suppliers and subcontractors.

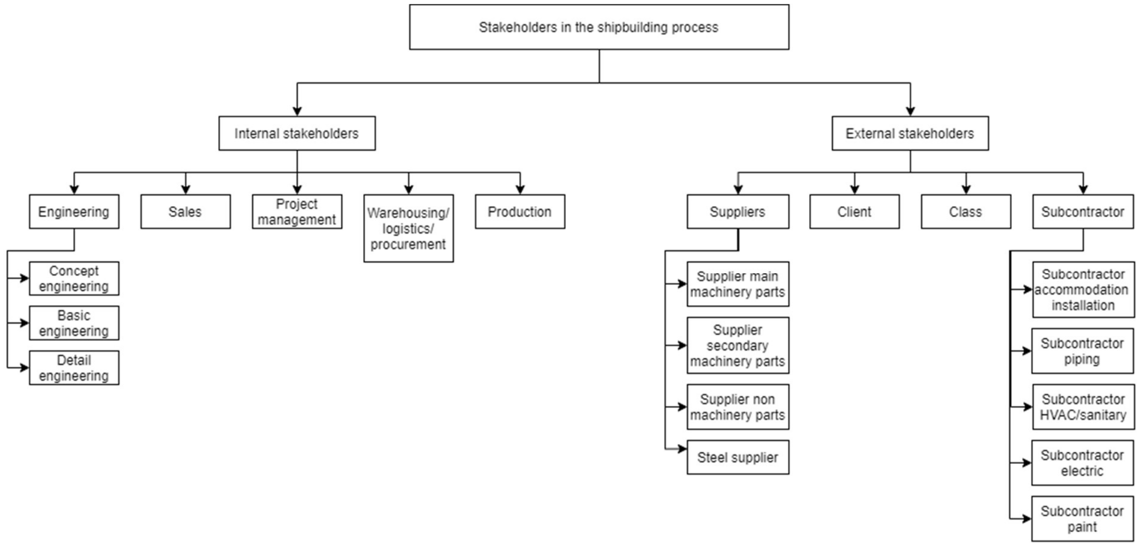


Figure 7 Overview of important stakeholders in the ship production process

Notes

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[13] The ship repair department in Meppel is left out of consideration as the research only entails the ship production process.

[14] Of course, this may fluctuate due to hiring temporary workers. This is based on a total of approximately 50 FTE for the full company and 3 ships being built concurrently.

4. Conceptual Model

In Section 2.3, already a description of the conceptual modelling approach had been given. It was argued that the model should be supported by Petri Net theory. The information objects are modelled as places (circles) and information processing activities as transitions (rectangle). In this chapter, we will further elaborate on the conceptual model. In Section 4.1, it will be explained what is used as a basis to establish the model. Next, the variables of the model will be summarized. In Section 4.3 the assumptions and constraints of the model will be discussed. Hereafter, the possibility of modifying the model will be discussed. In the final section, a brief discussion on the originality of the model is mentioned.

4.1 Establishment of the process model

The conceptual model is a process model of the ship production process, with a focus on information objects and information processing activities. Process models may be descriptive (describing what actually happens during a process), or prescriptive (describing what should happen during a process) (Finger & Dixon, 1989). This model will be of a descriptive nature.

To establish the process model, the "Stage-Gate" framework has been used. A Stage-Gate model is an approach to establish a new product from idea to launch. "*A blueprint for managing the new product process to improve effectiveness and efficiency"* (Cooper, 1990). Each stage describes essential activities which are to be carried out. Stages are complemented by so-called "gates" where activities are evaluated. The gates contain three main agreements in the form of "deliverables", "criteria" and "outputs" (Grönlund, Sjödin, & Frishammar, 2010). If these pre-defined agreements cannot be met, the stage-gate managers (called "stagekeepers") should decide whether it is safe enough to continue with the next stage or whether the current stage should first be further completed.

The reason that a Stage-Gate approach is used to establish the process model is that research has shown that the Stage-Gate process energizes and speeds up a firms New Product Development (NPD) efforts (Grönlund et al., 2010). As every (one-off) ship production cycle can be seen as a New Product Development cycle, a stage-gate model is suitable for managing this. A second reason is that the stage-gate approach is known to be used successfully at different Dutch ship production companies. This means that the deliverables, criteria and outputs have already been extensively described for a ship production process, which means time and effort savings for this project and a pre-iteration with respect to validation of the model. The basics of the Stage-Gate approach for TB Shipyards, which is used as a basis, is featured in Appendix 12.4.

The stages are further broken down in activities and information objects. First, based on experience and conversations an initial set-up was established, which subsequently was checked by an expert in the field. Some information transferring intensive stages, which turned out to be the concept- and multidisciplinary engineering stages, required multiple iterations and some less information transferring intensive stages sufficed by one iteration. Furthermore, a separate category to stage 3/4 Multidisciplinary design had been added, being the Tendering and Procurement process.

When all subparts of the different stages were completed and validated by experts, they were combined and finally validated as a total by the project management officer. The conceptual model is considered sufficiently embodying a general ship production process by its users, but please note it is not claimed that the model is 100 percent perfect. As the famous statistician George Box once said, all models are wrong, but some are useful. A model is a simplification or approximation of reality and will not reflect all of reality (Burnham & Andersom, 2002). The verification and validation process of the model is further discussed in Chapter 6.

The full conceptual model can be printed as a whole on A0 format but for this report, the model is broken down into the different stage gates to improve readability.

The first stages, "Stage 1/2 Concept design and Contract signing" kick-off with the information object O1 "incentives for fleet expansion". It then contains a few serial processing activities, being "Client submits engineering request", "Performing research & validation of client and project requirements", "determine main dimensions and ratios" and "determine ship lay-out". After these, some parallel or concurrent activities follow, e.g. "perform weight estimation", "create hull form/lines plan", "estimate scope of work & hours for production/engineering". The contributions of the concept engineering department and sales department are summarized and an offer is given to the client. The client subsequently shows interest, gives feedback and the concept engineering department processes the feedback. Assumed that the client is still interested and content with the updates, the negotiation and financing process starts. The most important stakeholders in this stage are the client, sales department and concept engineering department. The elaborate version of the Stage 1/2 Concept design and Contract signing can be found in Appendix 12.5.

After the contract has been signed, the "General Plan Contract" (O29) and "Building specification contract" (O30) are used to request tenders from suppliers and subcontractors in the "Tendering and Procurement" stage. Tenders are requested for the paint supplier and subsequently paint subcontractor, the carpenter/accommodation installation, the piping subcontractor, the electrical installation subcontractor, the HVAC/sanitary subcontractor, and the main machinery, secondary machinery and non-machinery suppliers. The subcontractors use the information from the general plan and building specification to propose paint plans, accommodation arrangements and system diagrams. These proposals are subsequently checked with the client and shipyard. The suppliers provide information about their equipment which

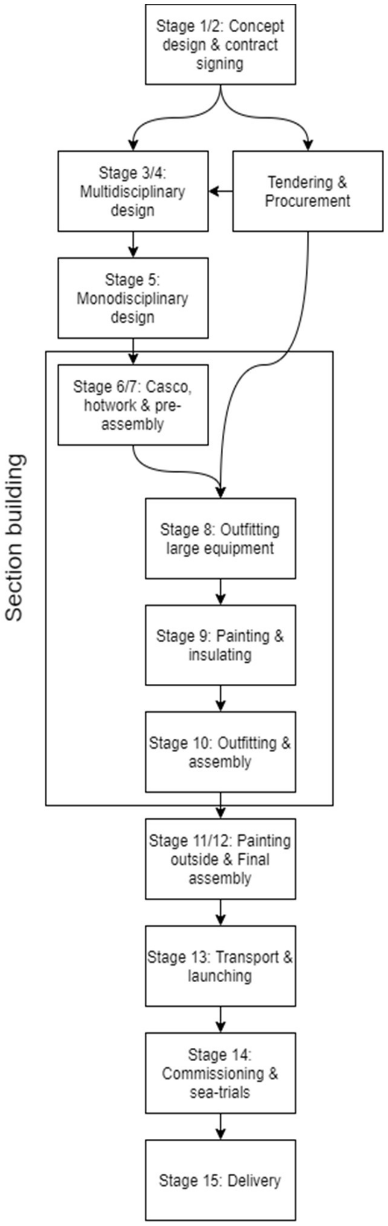


Figure 8 Stage gate structure of model

sometimes also is required as an input for the subcontractors. For example, the main machinery supplier serves information which the electrical subcontractor needs for his system diagrams. Next to the previously mentioned suppliers and subcontractors, there additionally is the steel supplier. To roughly provide a tender, the steel supplier requires a light ship weight calculation. Important stakeholders are here the previously mentioned suppliers and subcontractors, the client and the project management/procurement department. The "Tendering and Procurement" stage in detail is featured in Appendix 12.6.

Concurrently to the "Tendering and Procurement" stage, "Stage 3/4 Multidisciplinary design" is active. The information objects from the concept engineering stage are used to perform basic engineering activities such as "specify primary construction", "create installation & systems related documents" and "create ship specific documents". Sometimes, input from the suppliers and subcontractors is required for this. Some of these documents are to be approved by class or the client and subsequent remarks of client or class are then processed by the basic engineering department. Also, approval of the system diagrams and arrangements as created by the subcontractors is included in this stage. The most important stakeholders in this stage are the class, client, basic engineering department and some of the suppliers and subcontractors. A detailed overview of all information objects and activities of this stage is featured in Appendix 12.7.

After this, "Stage 5 Monodisciplinary design" is relevant. For this stage, approved structure drawings and information, routing schemes and information and outfitting and equipment information is used to create a 3D model. If this 3D model is ready, production information (PI), piping & outfitting (P&O), deck layouts, equipment alignment drawings and structure assembly drawings are extracted from the model. This information serves as input for the production department and steel supplier. The most important stakeholder here is the Detail engineering department. An overview of this stage is featured in Appendix 12.8 and furthermore in Figure 9.

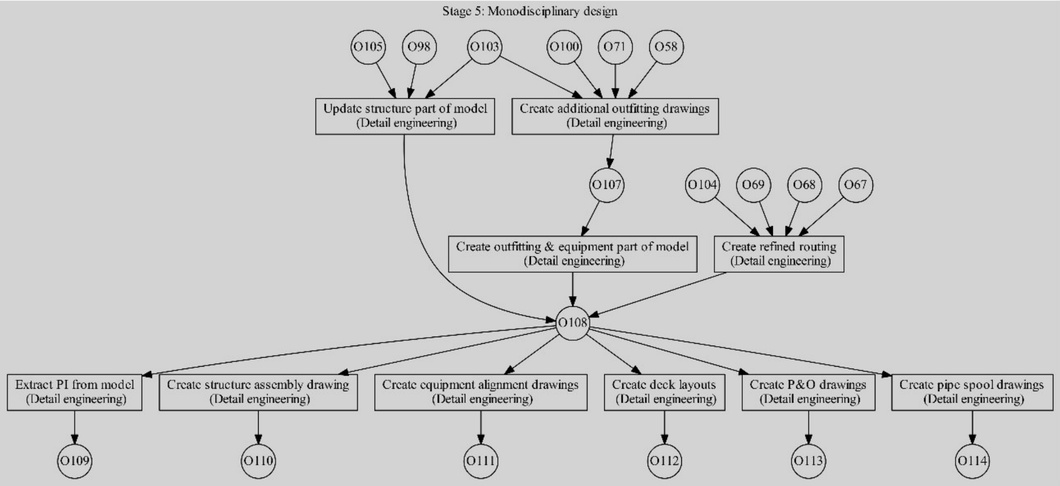


Figure 9 Example of the conceptual model for Stage 5 Monodisciplinary design

After the monodisciplinary design, the production starts. The corresponding stages are "Stage 6/7 Casco, hotwork and pre-assembly", "Stage 8 Outfitting large equipment", "Stage 9 Painting & insulating", "Stage 10 "Outfitting and assembly", "Stage 11 Painting outside", "Stage 12 Final assembly", "Stage 13 Transport and launching" , "Stage 14 Commissioning and Sea-trials" and "Stage 15 Delivery". Except for stages 11-15, most of these stages are concurrent. In these stages, the most important stakeholders are Production, Warehousing/logistics, subcontractors and suppliers, and in the final stages also the project manager and the client. As these stages are less "information intensive", and highly concurrent, these are treated in one figure. An overview of the stages can be found in Appendix 12.9.

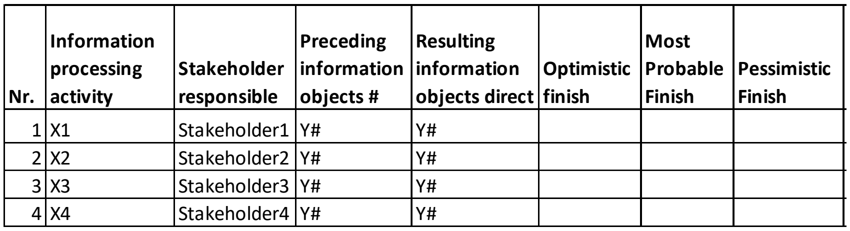
4.2 Variables

The next step is to identify the variables of the model. There are different kinds of variables. The first kind of variables is called *dependent variables* or *output variables*, which are the resulting system performance measures that are of interest. These are often easy to identify, as they highly correspond with the objectives of the study (Barton, 2010). The objective of the study is to improve the information handling by finding the bottlenecks in the process and proposing measures to reduce them. The bottlenecks can be measured in terms of the *total throughput time* and *waiting times per stakeholder.*

The next types of variables are the *independent variables* or *input variables*. These are variables that can be set to desired or case-specific values. In this case, for every information processing activity X, there is an *optimistic finish time*, a *most probable finish time* and a *pessimistic finish time*. Furthermore, for every activity there is a responsible *stakeholder*. Finally, for every information processing activity, the *direct preceding information objects* and *direct resulting information objects* are summarized into the input list, but these will initially not change during the experiments.

Also, two intermediate variables can be defined, which are variables that cannot be controlled independently, but are affected by other independent variables. In this case, this is the *throughput time per activity X* and *adaption time per activity X*. These throughput and adaption times are calculated by means of establishing a PERT-Beta distribution based on the optimistic, most probable and pessimistic finish and adaption times.

An example of the input table containing the independent variables can be found in Table 2.



Nr.	Information processing activity	Stakeholder responsible	Preceding information objects #	Resulting information objects direct	Optimistic finish	Most Probable Finish	Pessimistic Finish
1	X1	Stakeholder1	Y#	Y#			
2	X2	Stakeholder2	Y#	Y#			
3	X3	Stakeholder3	Y#	Y#			
4	X4	Stakeholder4	Y#	Y#			

Table 2 Example of input table independent variables

4.3 Model assumptions and constraints

Several assumptions have been made in order to obtain the model as featured in Figure 8. First of all, a normal to premium engineering package is assumed. Based on the desires of the client, a minimum, normal, premium or excellent engineering package can be chosen. If a small engineering package would have been chosen, fewer information objects and processing activities would be present in the concept design and multidisciplinary design stages. For example, no paint plan or wheelhouse plan may have been created. For excellent engineering packages, more elaborate engineering items would have been present in the model.

The second assumption is that subcontractors are expected to comply with functional requirements rather than fixed requirements. This means that subcontractors will provide drawings and schemes themselves rather than simply delivering and installing what the in-house engineers came up with.

The third assumption is that a selective tendering procedure is assumed, where the client already is interested in the shipyard. This has consequences for the first stage, "concept design and contract signing". If for example an open tendering procedure was assumed, less energy was invested in the first stage, meaning that for example no artist impression/3D model would be created.

A fourth assumption is that no employee capacity is taken into account, or in other words, that unlimited employee capacity is assumed. The reason for this is that by not having to take this into account, the model could be further simplified. Also, from practice it is often the case that meeting deadlines is the main priority and additional manpower is hired to comply with a deadline. Whether this assumption can be justified is further investigated in Section 6.1.4.

One constraint of the model is that it is not possible to manually specify release times for information objects. Information objects may only release after a preceding processing activity has finished. Furthermore, the initial information object triggering the rest of the process must become available at t=0. This cannot be released at for example t=15.

Finally, the model is not able to handle loops. Loops occurring during the ship production process will have to be accounted for by means of the input data. An example of this is given by means of Figure 10. By disabling loops in the model, the model can be greatly simplified.

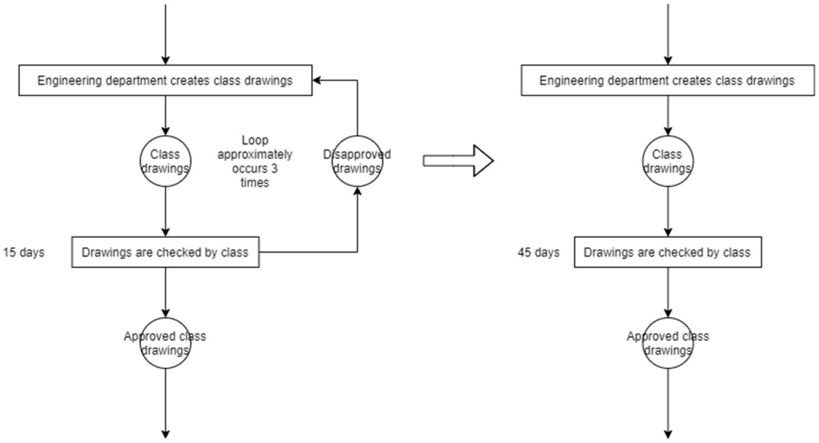


Figure 10 Alternative set-up for loops in the model

4.4 Model modifications

As mentioned previously, the conceptual model should be sufficiently embodying a general ship production, but if modifications in the main structure for whatever reason is required, this is fairly easy. In the input sheet, an additional processing activity or information object can be added. When adding a row, filling in the variables should be done with care. A unique number should be assigned to the new addition and the resulting and preceding information objects or processing activities should be specified. If added correctly, the model will automatically take into account the added processing activities or information objects.

5. Mathematical Model

In this chapter, the mathematical background of the model will be further explained. The full script can be found in Appendix 12.11. In the first section, the model will be broken down according to its functions and the most important functions will be further explained. In Section 5.1, the chosen programming language and its features will be discussed.

5.1 Model breakdown and characteristics

In this section, an elaborate breakdown of the mathematical model will be featured. First of all, the script will be summarized in a flowchart. Subsequently, its main parts will be discussed, which are the Beta-PERT distribution and the Monte-Carlo approach.

5.1.1 Programming flowchart

By summarizing the computer code into a flowchart, the operation of the code can be easily explained to unskilled programmers or persons unfamiliar to the programming language. Furthermore, by breaking the system down, logical errors may be identified and eliminated (Charntaweekhun & Wangsiripitak, 2006). Therefore, the programming flowchart also serves as a verification tool. More about verification is discussed in Chapter 6. The flowchart of the script is established using the symbols as specified by the ISO and can be seen in Figure 11.

When looking at the flowchart in detail, it can be seen that first the input from the excel file is read and subsequently, the visualization graph is formed. Then, the simulations start. As long as the pre-specified number of simulations has not been reached, for every stated information processing activity, the random finish time will be calculated and a process will be defined. Then, all the excel input data (corresponding stakeholder etc.) will be coupled to the process, as well as the calculated finish times. Subsequently, a list is created to check whether activities have already started or been executed. After this, all processes are activated at t=0. Based on a few "if"-statements, questions are asked before an activity may get executed. Has the activity already started or been executed? No? Are all the required information objects for this activity available? Yes? Then the activity may get executed for its pre-defined duration. At t=1, all activities will again be activated and the same questions will be asked[15]. By the time an activity is finished, the resulting information objects will be released and output data will be stored in the checklist. If from this checklist it occurs that all activities are executed, one simulation is finished. One simulation approximately takes 2.5 seconds. More details on the runtime are discussed in Section 5.1.5. The total throughput time and output data will be stored and we return to the question whether the total number of simulations has been reached. If this is the case, the output data of all simulations will be stored in one txt file and the script will stop, otherwise the same loop will be continued.

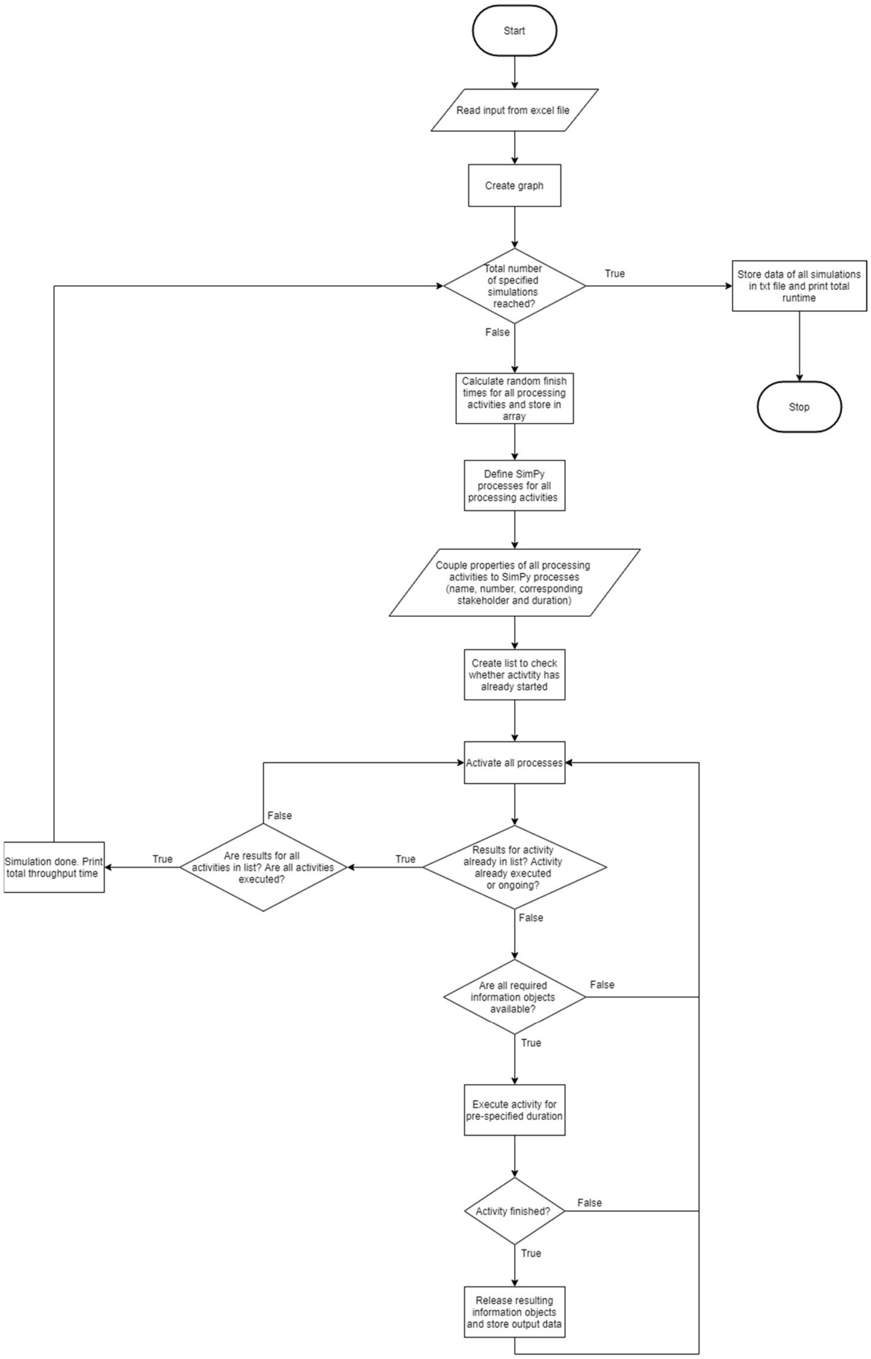


Figure 11 Flowchart of the programmed script

5.1.2 Beta-PERT distribution

One of the main parts of the mathematical model is the calculation of the durations of the information processing activities. This is done according to a Beta-PERT distribution.

There are many different types of probability distributions that are suitable for different applications. For example, a pareto distribution is suitable for empirical phenomena such as population sizes or stock price fluctuations and normal distributions are suitable for describing natural phenomena such as heights of people or their IQ's (Mun, 2008). For the estimation of event durations, two main distributions were deemed suitable, being a beta-PERT distribution or a triangular distribution.

A Beta-PERT distribution is a version of the Beta distribution, but using the same three parameters as the triangular distribution, a minimum (a), mode (b) and maximum (c) value. The main difference between Beta-PERT and triangular distributions is the value for the mean:

$$\mu_{\beta-PERT} = \frac{a + 4b + c}{6}$$

$$\mu_{triangular} = \frac{a + b + c}{3}$$

This shows that the Beta-PERT distributions is 4 times more sensitive to the most likely value than to the maximum and minimum values. Also, the standard deviation of a PERT distribution is less sensitive to its extremes. For duration distributions of project tasks, often a ratio of 2:1 for the (maximum - most likely) to (most likely – minimum) is used as a rule of thumb. When this ratio is used for calculating the standard deviations of a Beta-PERT or a triangular distribution, the standard deviation of the Beta-PERT distribution is about 88 percent lower than the triangular distribution. This implies that using a Beta-PERT distribution results in around 10 percent less uncertainty than using similar input with a triangular distribution (Vose, 2017). Therefore, the use of a Beta-PERT distribution is preferred over a triangular distribution.

The difference between a triangular distribution and a Beta-PERT distribution is visually represented by means of Figure 12.

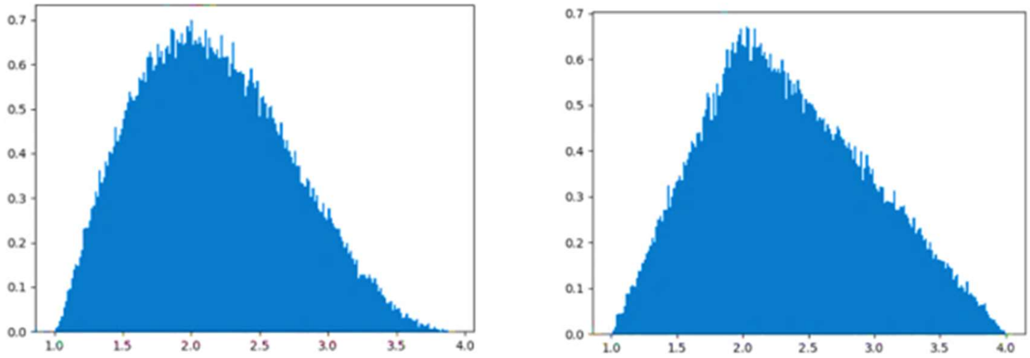


Figure 12 The difference between a Beta-PERT distribution (left) and triangular distribution (right)

The main characteristics of the Beta-PERT distribution are summarized in Table 3.

a	Minimum value, optimistic value	
b	Most likely value, most probable value	
c	Maximum value, pessimistic value	
μ	Mean	$= \frac{a+4b+c}{6}$
α	First parameter Beta distribution	$= \frac{(\mu-a)(2b-a-c)}{(b-\mu)(c-a)}$
β	Second parameter Beta distribution	$= \frac{\alpha(c-\mu)}{(\mu-a)}$
PDF	Probability Density Function	$= \frac{(x-a)^{\alpha-1}(c-x)^{\beta-1}}{B(\alpha,\beta)(c-a)^{\alpha+\beta-1}}$
Var	Variance	$= \frac{(\mu-a)(c-\mu)}{7}$

Table 3 Characteristics of the Beta-PERT distribution

5.1.3 Monte Carlo Simulation

Running the model one single time will give ambiguous results. As an example, try simulating throwing dices. If the dices are thrown only 5 times, the outcome may be 8, 10, 10, 6, 5. Based on the results of this very small sampling experiment, the chance of throwing 10 is 40 percent, whilst the chance of throwing 7 eyes is zero[16]. To get reliable results, the dices should be thrown many times. This is the same for modelling processing activity durations. Simulating a process many times with different starting conditions is called a Monte Carlo Simulation (MCS).

For MCS, the question "how many simulations are sufficient to obtain a reliable result?" should be asked. This is particularly dependent on the costs of running these simulations. The more simulations are executed, the more reliable the results, but the longer the runtime. Therefore, the optimum number of simulations should be investigated. In the following sections, the characteristics of MCS in the form of convergence behaviour and runtimes is further explained.

5.1.4 Convergence behaviour

To investigate how many simulations are required to obtain a stable result, the model is run 2^N times for $N = 1 \dots 10$. After this, the mean value and variance/standard deviation of the total throughput time of the full ship production process are plotted.

The mean is nothing else than the average throughput time of all 2^N simulations. The variance of a dataset is a measurement of the spread between numbers. It measures how far each number is from the mean. A small variance indicates that data points are very close to the mean and to each other. A high variance indicates that data points are widely spread. A variance of zero means that all data is identical. Standard deviation is the square root of the variance and returns an output in the same units as the input data and is therefore more easy to interpret than the variance.

For every number of simulations 2^N, the procedure is re-executed 5 times in order to observe whether the results are stable. The results can be seen in Figure 13.

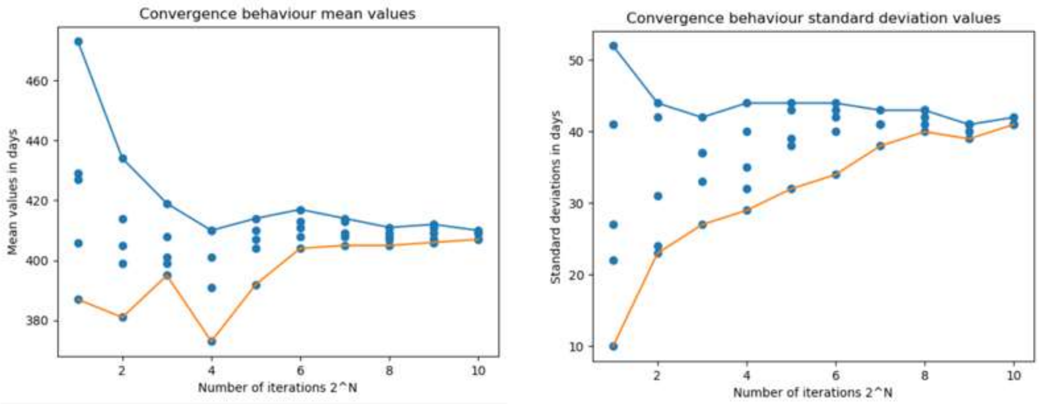


Figure 13 Convergence behaviour mean values

From the figure, it can be seen that for $2^6 = 64$ simulations, the model is starting to become stable. The difference between the highest and lowest mean is here 13 days. The difference between the highest and lowest mean for $2^7 = 128$ iterations is 9 days. For $2^8 = 256$ iterations, also the values for standard deviations are converging. The difference between the highest and lowest mean is here 6 days. The difference between the highest and lowest mean for $2^9 = 512$ runs is also 6 days. As ship production process planning's are often established in weeks, an accuracy of about 1 week is considered sufficiently accurate.

5.1.5 Runtimes

The larger the number of simulations, the longer the runtimes. The simulations are run at 30 percent processor capacity of an Intel Core i7-8565U CPU. Of course, when using full processor capacity, the runtimes may be shortened. As mentioned previously, $2^8 = 256$ iterations were considered sufficiently stable. The corresponding runtime of 256 runs is around 600 seconds or 10 minutes. The runtime for $2^9 = 512$ runs is 1200 seconds or 20 minutes. When looking at Figure 14, the very large increasing runtimes for $N = 9, 10, 11$ and 12 can be observed. When looking at the results of the previous section, it can be concluded that double the runtime is required with $N = 9$ for a similar accuracy with respect to $N = 8$ runs. Therefore, it can be concluded that for reliable results a Monte Carlo Simulation with about 256 runs is suitable for this case.

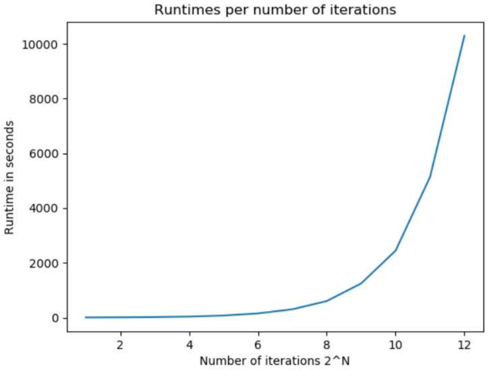


Figure 14 Runtimes per number of iterations

5.1.6 Presentation of results

The results of MCS are often visualized using histograms. For histograms, the so-called number of bins is an important characteristic to manipulate the presentation and interpretation of the data. The number of bins is the number of intervals the data should be divided over. In Figure 15 the effect of the number of bins can be seen. On the left figure, bars of about 25 days width are featured and on the right about 2 days width. As previously mentioned, in ship production processes, a planning is often divided into weeks. Therefore, bars with a spread of 5 working days/1 week are considered sufficiently accurate. This gives the following number of bins:

$$range = 550 - 300 = 250\ days$$

$$width = 5\ days$$

$$bins = \frac{250}{5} = 50$$

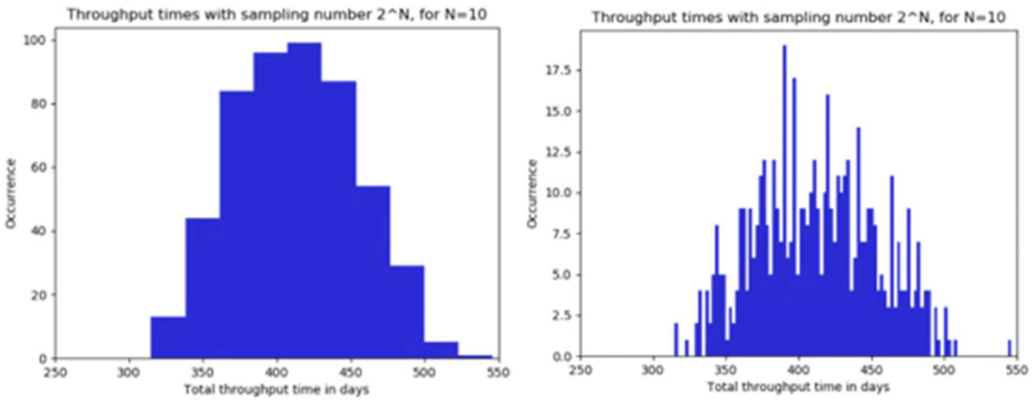


Figure 15 Histogram plot with 10 bins (left) versus 100 bins (right)

In Figure 16, the throughput time for $2^8 = 256$ simulations is plotted. The results of all throughput time histograms are summarized in Appendix 12.13. It can be seen that the histograms are more and more resembling a normal distribution when increasing the sampling number.

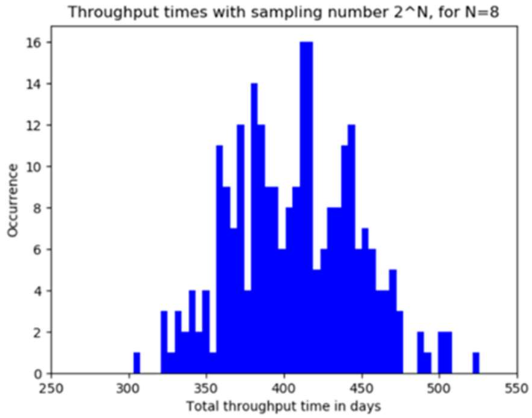


Figure 16 Results of throughput times for 2^10 simulations with 50 bins

5.2 Programming language

For programming of the model, “Python” has been chosen. Python is a general-purpose programming language with an object-oriented approach. This language has been chosen for several reasons. First of all, Python is a free and open-source language and therefore easily accessible for all companies and persons interested in this research. Second, Python is considered easy to understand due to its logical approach and high readability. Third, the Python language offers a specific simulation library, called SimPy, which can successfully be used for creating discrete-event simulations. Finally, there was also already some experience with Python, so using this language would result in a time-saving.

During this project, use has been made of Python version 3.8. In the following subsections, a brief overview of the most used packages in the script is given.

5.2.1 SimPy

SimPy is an essential package for Python which enables simulating Discrete Event Simulations. A DES in SimPy mostly exists of events and processes. Those events and processes may be in 3 states: “might happen”, “is going to happen” or “has happened” (“SimPy Topical Guides,” n.d.). The SimPy library is built upon a special type of Python functions, which are called “generators”. Within SimPy, the most important generator is the “yield” generator. With the yield statements, processes and events can start (for example, a ship entering a harbour), resources can be requested (for example, a ship requesting a bunker ship where only four of are available), resources can be released or other events or processes can be waited on. For this project, the newest SimPy version 3.0.11 was used.

5.1.2 NumPy

NumPy may be considered the fundamental package for scientific computing with Python. The main contribution of NumPy is its ability to support multi-dimensional arrays and matrices and many mathematical functions, for example trigonometric functions and rounding. Furthermore, it offers statistical functions such as finding minima, maxima, means and standard deviations. In this script, NumPy is mostly used for storing data into structured arrays and establishing the random PERT distributions. More about the PERT distribution can be found in Section 5.1.2. For this project, the current newest NumPy version 1.17.4 was used.

5.1.3 GraphViz

The package GraphViz is used to create the visualization of the model. Employing different pre-defined layout engines or algorithms, the best options to position the nodes and edges is found. GraphViz requires the graph to be specified with DOT language, which can be read by various programs. After creating the graph, it is being saved and opened as a .pdf file. For this project, the current newest GraphViz version 0.13.2 is used.

5.1.4 Timeit

The Timeit module is used to keep the execution time of the code in order to define its runtime. By measuring the runtime, it can be stated whether runtimes are too long and it can be predefined how long multiple simulations approximately will take, as is the case for Monte-Carlo Simulations.

More information about the Monte-Carlo simulation technique can be read in Section 5.1.3. Timeit is a part of the standard Python library and does not have to be installed specifically. More information about installing the required packages for running the script can be found at Appendix 12.12.

5.1.5 Pandas

The final package that is used in the script is the Pandas module. Pandas and NumPy are quite comparable in terms of their main function being a data analysis and manipulation tool. Pandas is built on the NumPy package and additionally offers so-called DataFrames functionalities. DataFrames allows storing data in tabular form with rows and columns. For this project, the current newest Pandas version 0.25.3 is used.

Notes:

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[15] The script can be considered not very efficient looping through all activities every timestep, but a total runtime per simulation of 2.5 seconds for about 100 processing activities is considered quite fast

[16] We all know from "Settlers of Catan" that the chance of throwing 7 is not zero.

6 Verification & Validation

When building simulation models, there is a very important step that must not be omitted. This is the process of verification and validation. Verification & validation (V&V) is used to assess the credibility of the model. If decisions are made according to this model, it should be assessed whether the risk of making these decisions weighs up to the uncertainty level of the model (Hu & Paez, 2016). This uncertainty level is examined quantitively throughout this chapter. "*Engineers are not superhuman. They make mistakes in their assumptions, in their calculations, in their conclusions. That they make mistakes is forgivable; that they catch them is imperative."* (Petroski, 1992)

There is a clear difference between validation and verification. For validation, the question "Are we building the right system?" is asked, whilst for verification, we ask ourselves "Are we building the system right?". Validation focuses on the model meeting its practical needs and requirements and obliging to the pre-set goals, which in this report means a reflection on Chapter 4. Verification focuses on the model being error-free and programmed in a right way, which means a reflection on Chapter 5.

Many excellent papers are available, clearly describing verification and validation of simulation models and providing systematic approaches and tools to guide this process. For this project, the papers of Carson (2002) and Sargent (2011) are considered very valuable.

6.1 Validation of the conceptual model

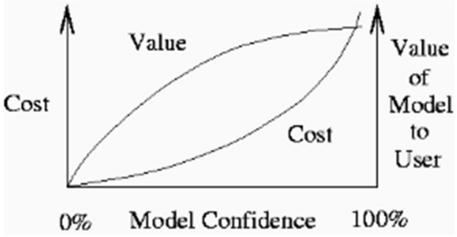

Figure 17 Relation between validation cost, model confidence and user value, obtained from Sargent (2011)

A model can never be validated or verified for the full 100 percent. As previously mentioned, any model is only an approximation of reality (Carson, 2002). It also is often very costly and time-consuming to assure a model is valid over its complete domain. Sargent (2011) offers a visualization of the relation between cost, model confidence and value of the model to the user. This shows that for sufficient value of the model to the user and optimal cost, the model confidence does not need to be as high as possible. Therefore, a selection of validation tests that are deemed most cost-efficient, yet effective to execute will be chosen to validate the model.

6.1.1 Face validity

First of all, face validity is considered an efficient method to ensure the model is valid. Face validity means that experts are asked whether they think the model is reasonable. Throughout the establishment of the model, several iterations were held and improvements were proposed by experts in the company. This means that already some face validity sessions are applied to the model. In the end, a final feedback session had been planned to rate the final model and the feedback had been applied.

Other sources define the concept of face validity slightly different: "*Face validity is the extent to which a test is subjectively viewed as covering the concept it purports to measure. […] In other words, a test can be said to have face validity if it "looks like" it is going to measure what it is supposed to measure".* (Gravetter & Forzano, 2012; Ronald B. Holden, 2010). By not only showing the model but also the experiment plan to the experts in the company, it could be answered whether the model would measure what it should measure. Therefore, both understandings of the concept of face validation are covered.

6.1.2 Operational graphics

The second validation method is called "operational graphics". This means that whilst running the model, data becomes available that enables the user to check the output. In the model, two main examples of operational graphics are implemented. The first is that the data as specified in the input excel is plotted into a graphical plot. By means of this plot, the user may directly check whether he misidentified nodes or edges. Second, the Python script as described in Appendix 12.11 features the possibility of output printing. The printed output may then be checked for its validity.

6.1.3 Extreme condition tests

Executing an extreme condition test means that extraordinary input values are set and the behaviour of the system is further examined. For these extreme condition tests, a so-called "seed" is used. A seed function is used to fixate the random function outputs. The random numbers as generated by the Python script are not "real" random numbers. These are generated using a so-called pseudorandom number generator[17]. By means of an extensive deterministic algorithm, numbers are produced that appear to be random, but in fact are "pseudorandom". By using a seed, the starting conditions of the pseudo-random number generator remains equal and thus every time the same random number is produced. Making use of a seed is very useful for debugging and these extreme condition testing, as changes in output are then guaranteed to be produced by the debugging or extreme condition tests rather than the random number generator.

In total, two extreme condition tests have been imposed on the input values. The first extreme condition that has been tested is the specification of throughput times of zero days, thus specifying at the input sheet an optimistic finish of zero days, a most probable finish of zero days and a pessimistic finish of zero days. This may be specified when certain steps in the process are to be omitted or no time will be spent executing something because it may be automated. When testing this at first, a Zero-Division Error occurred. This is caused by the calculation of the Beta-PERT distribution. From the characteristics in Table 3, it can be seen that for calculating the α and β parameters, division by zero occurs when the a, b and c parameters are zero or when $a = b, b = c$ and/or $a = c$. To account for this, an if-statement has been created before calculating the Beta-PERT distribution.

Also, when $\mu = b$, a zero division error occurs. However, when rewriting the formula for α, this division by zero is eliminated (Taylor, 2015). Therefore, a second if-statement has been added.

Now, when specifying throughput times of zero, the activity will not take any time being executed and the model will work as intended.

The second extreme condition test is setting the input parameters as follows:

$$a < b > c$$

Of course, in reality this combination of Beta-PERT parameters is not possible and it is expected that the model throws an error. Fortunately, this is the case, which means the model is working as expected.

6.1.4 Assumption testing

Another important validation technique is testing whether the assumptions are valid. In Section 4.3, the assumptions of the model were discussed. Some of these assumptions are a matter of course and are difficult or not useful to further assess, but there was one assumption that was considered useful and possible to further investigate. This is the assumption of taking no employee capacity into account. The reason for assuming unlimited employee capacity is that this enables further simplification of the model, and from practice it is often the case that meeting deadlines is the main priority and additional manpower is hired to comply with a deadline. But is this assumption valid?

By specifying how many employees are expected to complete the information processing task for the given duration, the employee occupation can be plotted and the assumption can be checked. In Figure 15 an example of an employee capacity plot is featured. All employee capacity plots can be found in Appendix 12.14. From the plot, it can be seen that especially in the beginning many basic engineers are required and a maximum of 5 engineers are concurrently working at the tasks as specified in the input sheet. From the stakeholder analysis, it became clear that the engineering department at TB shipyards consists of approximately 8 FTE, so the company will be able to handle this peak.

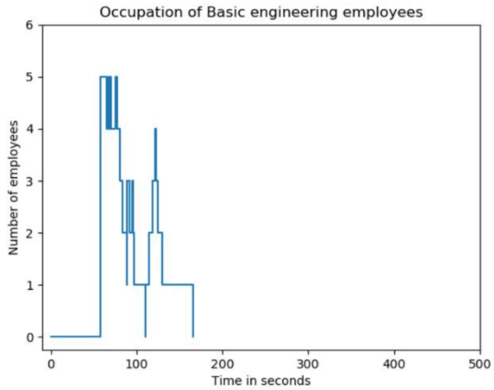

Figure 18 Employee capacity plot for basic engineering

Below, the maximum required employees according to the capacity plots is summarized and compared to the available employees according to the stakeholder analysis. Often, engineers are multi-deployable and are able to execute both concept engineering, basic engineering and detail engineering tasks. The same yields for the procurement/project management department. Therefore, it can be seen that most of the required FTE is available at TB Shipyards. If necessary, salespersons may also be deployed for procurement tasks. This means that the assumption of unlimited manpower does not have a rigorous impact on the validity of the model.

	Max FTE required	FTE available at TB Shipyards
Internal:		
Sales:	2	3
Concept engineering+Basic engineering+Detail engineering	8	8
Project management+Procurement	7	6
Production	9	17[18]
Warehousing/logistics	3	6
Commissioner	2	1

Table 4 Results of unlimited employee capacity analysis

6.1.5 Sensitivity analysis

Finally, a sensitivity analysis may be performed in order to validate the model. However, the first of the experiments is all about modifying input values and analyse the subsequent output. Therefore, the sensitivity of the input parameters will be further discussed in Chapter 7.

6.2 Verification of the mathematical model

Next to validation of the conceptual model, verification of the mathematical model has been performed. To verify the mathematical model, two testing approaches are available, static testing and dynamic testing (Sargent, 2011). For static testing, the computer program is frozen and tests are performed without running the program. For dynamic testing, the program is executed and during running, results are examined.

6.2.1 Static testing

Often used static tests are called "traces". Here, arbitrary branches of the model are selected and followed in order to find errors in the model. For example, before establishing the full model, first the "concept engineering" part was thoroughly implemented in order to find errors. Throughput times were calculated by hand and subsequently compared to the model output. Furthermore, examining properties of the execution program is an example of static testing. This has been done by means of Section 5.2. Additionally, establishment of the flowchart in Section 5.1.1 and examining the convergence behaviour in Section 5.1.4 can be considered verification applications.

6.2.2 Dynamic testing

For dynamic testing, great use has been made of the output printing as also described in Section 6.1.2. Also, internal consistency checks have been performed in order to ensure the model produces equal results under similar conditions. All these small tests are largely executed throughout the establishment of the model and could therefore not be consistently documented.

6.3 Summary

In this chapter, verification and validation of the model had been performed. By doing so, the fifth sub research question can be answered:

"Does the general model coincide with the real-world situation sufficiently?"

By performing several validation tests such as face validity, operational graphics, extreme condition tests and assumption testing, it can be concluded that the conceptual model sufficiently coincides with the real-world situation. Furthermore, by performing static and dynamic testing during establishment of the mathematical model, it can be guaranteed that no major errors are occurring when extracting data from the model.

Notes

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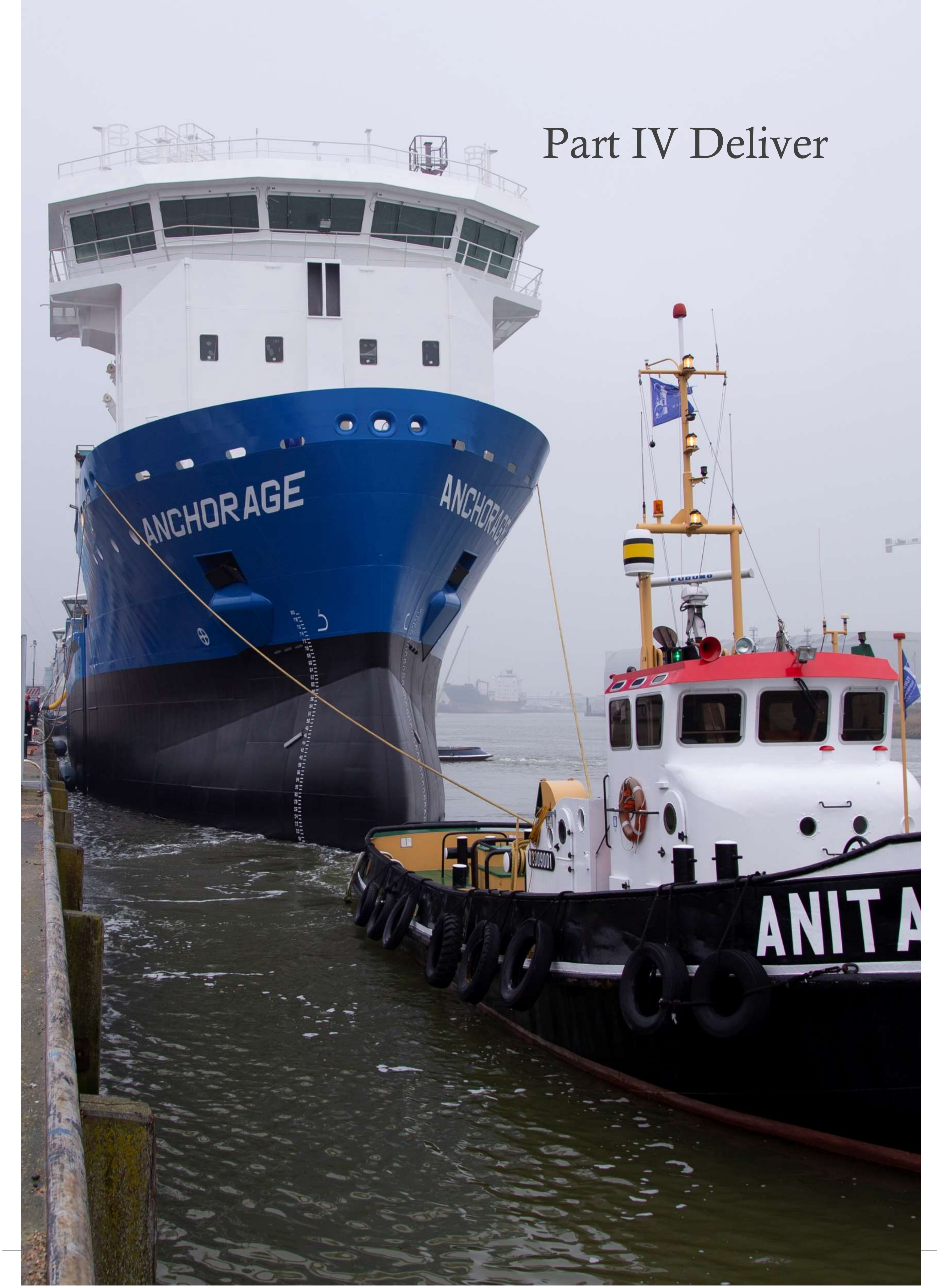
[17] The default random number generator as used by the Python np.random function is a PCG-64 generator, which is a 128-bit implementation of O'Neill's permutation congruential generator (The SciPy community, 2019)

[18] The amount of production employees seems too high, but a part of the employees was transferred to another location to work on another ship.

Part IV Deliver



7 Experimenting

In Chapter 2.4, the experimenting approach had been discussed. In this chapter, the results of these experiments will be discussed. The model as described in Chapter 4 may be applied to several different ship building processes. Its main structure may apply to large complex dredging vessels, container vessels, inland vessels or even superyachts. The input data however is what makes a model case specific. Therefore, the first step of the experimenting phase is determining for which case the experiments will be executed. After this, the results of each of the pre-defined experiments will be discussed. Also, a discussion and roadmap of the experiments is added. Finally, the results of the experiments are summarized.

7.1 Case-study

Before executing the experiments, the sixth sub research question should be answered:

"For which case should the experiment be executed?"

The input- and finish times are making the model case-specific. These finish and throughput times for different activities are varying per company and ship type. Ship types may be further classified according to its size (First Marine International, 2005) and its complexity (Huijgens, 2016). For this case study, TB Shipyards is taken as the case study company and the ship type that is focused on will be a pusher tug, which is a relatively small ship with high complexity level.

TB Shipyards is a Dutch shipyard, owned by Thecla Bodewes. It is specialized in building several types of ships, for example pushers, dredgers, fishing vessels, inland tankers, coasters and passenger ships. Next to building newbuild vessels, also ship repair and -lengthening is performed. The yard has four main locations, being in Harlingen, Kampen, Meppel and Stroobos. The location in Stroobos operates under its original name "Barkmeijer". At the time Barkmeijer was taken over by TB Shipyards due to bankruptcy in 2018, two dredging vessel cascos were still to be finished, from which one has been delivered. The recent sales record of Barkmeijer mainly contained complex dredging vessels. The recent sales record of TB Shipyards mainly contained smaller vessels such as pusher tugs and ferries. TB Shipyards performs some of the engineering in-house and subcontracts some of the engineering to other parties, depending on the project. Accommodation installation, painting, piping, HVAC/Sanitary and electrical installation is always subcontracted to other parties. The full production process and project management is mostly done in-house.

Figure 19 A pusher tug for CFT

At the time of writing, 5 pusher tugs are to be built in both Kampen and Stroobos, whilst the location in Meppel will be focusing on ship repair and maintenance activities and the location in Harlingen will be sold or rented out. The finish of the second dredging vessel casco from the bankruptcy is still to be confirmed. The pusher tugs are approximately 30 metres and can be considered complex due to its high system density, many stakeholders involved in the process and design limitations (Huijgens, 2016). Three of these pusher tugs are to be built for the client “Chemgas” and the other two will be built for “Thyssenkrupp”. The Chemgas pusher tugs are to be built in Stroobos whilst the others will be built in Kampen.

7.2 Initial state case-study

The experiments compare results of the initial state with the results when modifying input values. Therefore, the initial state of the case-study is discussed in this section. The four experiments as described in Section 2.4 feature hypotheses focusing on total throughput times and bottlenecks/stakeholder waiting times. The total throughput time of the case-study, without modification of input values for experiments is around 408 days with a bandwidth or accuracy of approximately 10 days.

A bottleneck is defined as every time one or more input information objects are available, but the processing activity cannot start because it is still waiting on other input objects or other processing activities to finish. A bottleneck has therefore a waiting activity (i.e. “victim”), which is waiting for a specific time in days and experienced by a corresponding stakeholder, and an activity that causes the waiting (i.e. “cause”), with a corresponding stakeholder.

For this case-study, the initial state features the bottlenecks as plotted in Figure 20 and described in Table 5.

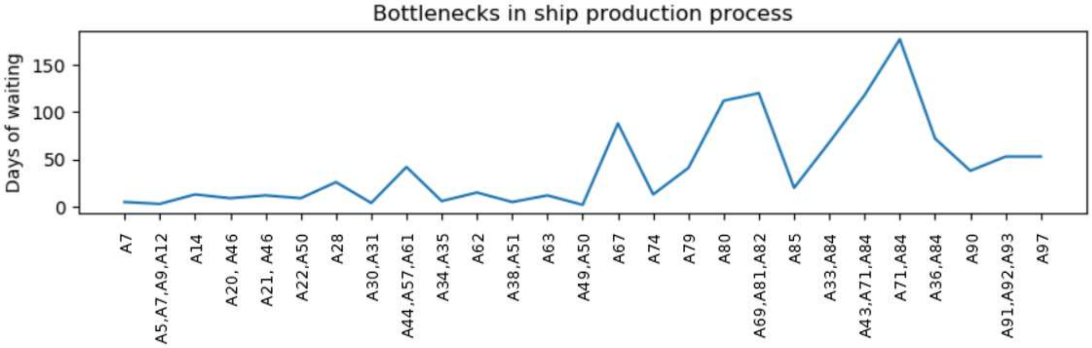


Figure 20 Activities that need to wait during the ship production process

Cause	Name	Mean waiting time in days	Affects	Name
A5	Estimate scope of work & hours for production	3	A14	Summarize and update
A7	Create hull form/lines plan	5	A12	Check stability
A9	Perform additional ship-specific calculations	3	A14	Summarize and update
A12	Check stability	3	A14	Summarize and update
A14	Summarize and update	3	A15	Client shows interest for further engineering & building and provides feedback
A20	Request tenders for piping installation	9	A27	Create system diagrams for main piping
A21	Request tenders for HVAC/Sanitary	12	A28	Create system diagrams for HVAC/Sanitary
A22	Request tenders for electrical installation	9	A29	Create electrical diagrams
A28	Create system diagrams for HVAC/Sanitary	26	A37	Update propulsion configuration
A30	Provide main machinery information	4	A38	Create arrangement/equipment foundation drawings
A31	Provide non-machinery part information	4	A38	Create arrangement/equipment foundation drawings
A33	Check with client and shipyard	68	A89	Provide accommodation installation service
A34	Check diagrams with client and shipyard	6	A41	Approve diagrams
A35	Check diagrams with client and shipyard	6	A41	Approve diagrams
A36	Check diagrams with client and shipyard	72	A93	Provide electrical installation service
A38	Create arrangement/equipment foundation drawings	5	A55	Create initial structural model
A43	Process class remarks diagrams	118	A91	Provide piping installation service
A44	Provide secondary machinery information	42	A39	Create additional outfitting drawings
A46	Create Installation & Systems (I&S) related documents	9	A27	Create system diagrams for main piping
		12	A28	Create system diagrams for HVAC/Sanitary
A49	Create remaining ship specific documents	2	A73	Request tenders for steel delivery
A50	Update and further specify calculations	9	A29	Create electrical diagrams
		2	A73	Request tenders for steel delivery
A51	Update & elaborate construction drawings for class approval	5	A55	Create initial structural model
A57	Process class remarks general outfitting	42	A39	Create additional outfitting drawings
A61	Process class remarks arrangement drawings	42	A39	Create additional outfitting drawings
A62	Create rough routing model	15	A45	Create refined routing
A63	Process class remarks construction plans	12	A65	Update structure part of model
A67	Extract PI from model	88	A74	Cut & deliver steel
A69	Create equipment alignment drawings	120	A83	Install main machinery parts
A71	Create P&O drawings	118	A91	Provide piping installation service
		177	A92	Provide HVAC/Sanitary installation service
A74	Cut & deliver steel	13	A76	Build 2D blocks
A79	Install top plate	41	A80	Pre-outfit section
A80	Pre-outfit section	112	A81	Paint (& insulate) section
A81	Paint (& insulate) section	120	A83	Install main machinery parts
A82	Deliver main machinery parts	120	A83	Install main machinery parts
A84	Weld sections together	68	A89	Provide accommodation installation service
		118	A91	Provide piping installation service
		177	A92	Provide HVAC/Sanitary installation service
		72	A93	Provide electrical installation service
A85	Deliver non machinery parts	20	A86	Install non machinery part & prepare for operation
A90	Deliver secondary machinery parts	38	A95	Position secondary machinery parts
A91	Provide piping installation service	53	A96	Commissioning of systems
A92	Provide HVAC/Sanitary installation service	53	A96	Commissioning of systems
A93	Provide electrical installation service	53	A96	Commissioning of systems
A97	Check if all machinery & equipment is installed & ready for operation	53	A98	Perform sea trials

Table 5 Bottleneck data

7.3 Experiment 1: Bottleneck identification and optimization

The first experiment is to find the bottlenecks and find whether these bottlenecks change or are eliminated when modifying the input values. The corresponding hypothesis is as follows:

H1: For bottleneck X, if the input value of preceding activity Y is set to Z, the total throughput time and stakeholder waiting times will be reduced and bottleneck X may even disappear.

To test the hypothesis as efficient as possible, for every bottleneck the input values of the preceding or causing activities are set to an extreme value: zero. By setting these values to zero we can quickly define which bottlenecks are most affected and subsequently most suitable for improvement.

After running $2^8 = 256$ simulations for each causing activity set to zero, the following conclusions can be drawn of the results.

- If the throughput time of activity "create hull form/lines plan" (A7) is shortened, the mean waiting time of 5 days preceding the activity "check stability" (A12) may be reduced to 0 days.
- If the throughput time of activity "summarize and update concept design" (A14) is shortened, the mean waiting time of 13 days preceding the activity "client shows interest" (A15) may be reduced to 4 days.
- If the throughput time of activity "create system diagram for HVAC/Sanitary" (A28) is shortened, the mean waiting time of 26 days preceding the activity "update propulsion configuration" (A37) may be reduced to 15 days.
- If the throughput time of activity "create rough routing model" (A62) is shortened, the mean waiting time of 15 days preceding the activity "create refined routing" (A45) may be reduced to 0 days.
- If the throughput time of activity "process class remarks construction plans" (A63) is shortened, the mean waiting time of 12 days preceding the activity "update structure part of model" (A65) may be reduced to 6 days.
- If the throughput time of activity "extract PI from model" (A67) is shortened, the mean waiting time of 88 days preceding the activity "cut & deliver steel" (A74) may be reduced to 77 days.
- If the throughput time of activity "weld sections together" (A84) is shortened, the mean waiting times of respectively 68, 118, 177 and 72 days preceding the activities "provide accommodation installation service" (A89), "provide piping installation service" (A91), "provide HVAC/Sanitary installation service" (A92) and "provide electrical installation service" (A93) may be reduced to respectively 49, 99, 136 and 45 days.
- If the throughput time of activity "provide piping installation service" (A91) is shortened, the mean waiting time of 53 days preceding the activity "commissioning of systems" (A96) may be reduced to 37 days.

However, most often, this positive effect of reduced waiting times is not completely translated into the total throughput times. This can be explained as follows; if the bottlenecks that are optimized are not a part of the critical path (i.e. the sequence of activities that are determining the total throughput time), their effect will not be visible in the total throughput time. Please note that this does not mean that there are no benefits of bottleneck optimization at all. Reducing the waiting time of stakeholders may also give benefits in the form of risk minimization, a better division of manpower or other benefits that are not quantitively investigated in this report.

There is one activity preceding bottlenecks “provide accommodation installation service” (A89), “provide piping installation service” (A91), “provide HVAC/Sanitary installation service” (A92) and “provide electrical installation service” (A93), which is the activity “weld sections together” (A84), for which a modification in input value also leads to a significant reduction in the total throughput time. A significant reduction is defined as a reduction of at least 10 days, which is twice the error margin of 5 days as described in Section 5.1.4. The effect of bottleneck cause modification on the total throughput time is visualized in Figure 21. Here, the error margin is depicted as a dashed line.

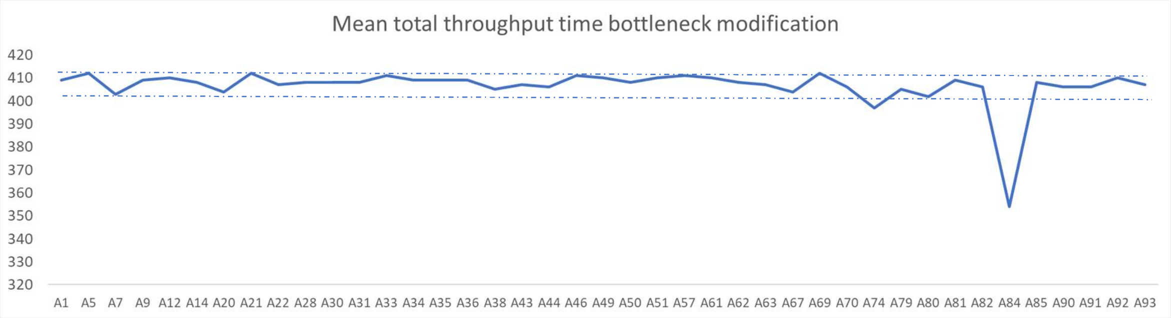


Figure 21 Effect of bottleneck modification on mean total throughput time

For activities “estimate scope of work & hours for production” (A5), “perform additional ship-specific calculations” (A9), “check stability” (A12), “request tenders for piping installation” (A20), “request tenders for HVAC/Sanitary” (A21), “provide main machinery information” (A30), “provide non-machinery part information” (A31), “process class remarks general outfitting” (A57), “process class remarks arrangement drawings” (A61), “check diagrams with client & shipyard piping” (A34), “check diagrams with client & shipyard HVAC/sanitary” (A35), “create arrangement/equipment foundation drawings” (A38), “update and further specify calculations” (A50), “create remaining ship specific documents” (A49), “pre-outfit section” (A80) and “check if all machinery & equipment is installed and ready for operation” (A97) the total throughput time and stakeholder waiting times are not reduced. This can be explained by the fact that most of these bottlenecks have multiple preceding or causing activities, and if only one of these is optimized, the other becomes critical. If subsequently the critical activity does not have a smaller duration than the activity being optimized, no gains will be observed. To be able to optimize these bottlenecks, the input values of multiple preceding activities must be modified. However, this is out of scope for this experiment. An overview of all the results of the experiment can be found in Appendix 12.15.

For TB Shipyards, the results of this experiment has the following consequences:

- Investing in ways to reduce durations of activities “estimate scope of work & hours for production” (A5), “perform additional ship-specific calculations” (A9), “check stability” (A12), “request tenders for piping installation” (A20), “request tenders for HVAC/Sanitary” (A21), “provide main machinery information” (A30), “provide non-machinery part information” (A31), “process class remarks general outfitting” (A57), “process class remarks arrangement drawings” (A61), “check diagrams with client & shipyard piping” (A34), “check diagrams with client & shipyard HVAC/sanitary” (A35), “create arrangement/equipment foundation drawings” (A38), “update and further specify calculations” (A50), “create remaining ship specific documents” (A49), “pre-outfit section” (A80) and “check if all machinery & equipment is installed and ready for operation” (A97) are inefficient as these do not reduce the total throughput time nor the stakeholder waiting times.
- Investing in ways to reduce durations of activities “create hull form/lines plan” (A7), “summarize and update concept design” (A14), “create system diagram for HVAC/Sanitary” (A28), “create rough routing model” (A62), “process class remarks construction plans” (A63), “extract PI from model” (A67), “provide piping installation service” (A91) may reduce the stakeholder waiting times. Reducing the waiting time of stakeholders may give benefits in the form of risk minimization, a better division of manpower, assumption minimization or other benefits that are not quantitively investigated in this report.
- Investing in ways to reduce duration of the activity “weld sections together” (A84) benefits the full process, as it reduces both the total throughput time as the stakeholder waiting times. In order to reduce the duration of this activity, one might think having standardized cascos in stock as is the case with Damen Shipyards, making use of welding robots/gantries to speed up the welding of the casco or (temporarily) make use of night shifts in this part of the process.

7.4 Experiment 2: Pre-mature release

For this experiment, information objects are released pre-maturely. This occurs for example when a tank plan is released when it is done for say 60 percent, so that the HVAC supplier can start creating its system diagrams earlier. It is expected that there are some main activities that will lead to a significant reduction in total throughput time when released pre-maturely. The corresponding hypothesis is as follows:

H2: If information object X is released pre-maturely, a significant reduction in total throughput time and stakeholder waiting times can be obtained.

Information objects are released when the activities are finished. Therefore, for every information processing activity, the information objects are released after 60 percent finished duration. A “significant reduction” in this context means a reduction of at least 2 weeks (10 working days).

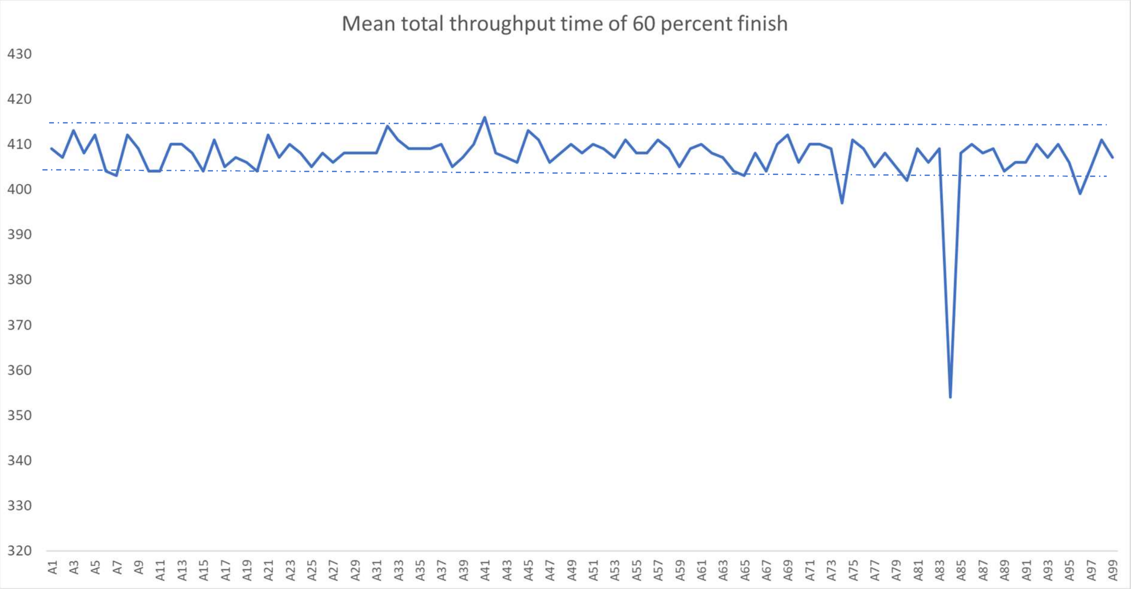


Figure 22 Results of pre-mature release (60 percent) on total throughput time

The reduction in mean total throughput time is plotted in Figure 22. For most of the activities, when these are finished after 60 percent, no significant reductions are obtained. There are two activities that do comply with the hypothesis, which are "cut & deliver steel" (A74) and "weld sections together" (A84).

The effect on the stakeholder waiting times is visualized by plotting the bottlenecks after reduction of each activity. For pre-mature release of some activities, some of the bottleneck plots showed interesting results. From Figure 23, it can be seen that when Activity "request tenders for accommodation installation" (A19) is prematurely released, the bottleneck caused by "install main machinery parts" (A83) and "weld sections together" (A84) significantly increases. This is due to information objects resulting from A19 becoming available earlier, which results in a relatively longer wait before A89 can start. In other words, this is purely due to the definition of a bottleneck. No changes in total throughput time confirm this. This is also observed at Figure 24, where "request tenders for electric installation" (A22) results in an increase for the bottleneck caused by "check diagrams with client and shipyard" (A36) and "weld sections together" (A84). What furthermore can be observed is that the bottleneck graph for Activity A84 (which resulted in a significant decrease in total throughput time) also results in a decrease of waiting time for the latter peaks/bottlenecks.

For TB Shipyards, the result of this experiment means that investing in ways to pre-maturely release cut & deliver steel" (A74) and "weld sections together" (A84) theoretically leads to a reduction in throughput time and stakeholder waiting times. However, these two activities are difficult to pre-maturely release in practice. The experiment for this case-study does not provide recommendations for engineering documents which are practical to pre-release.

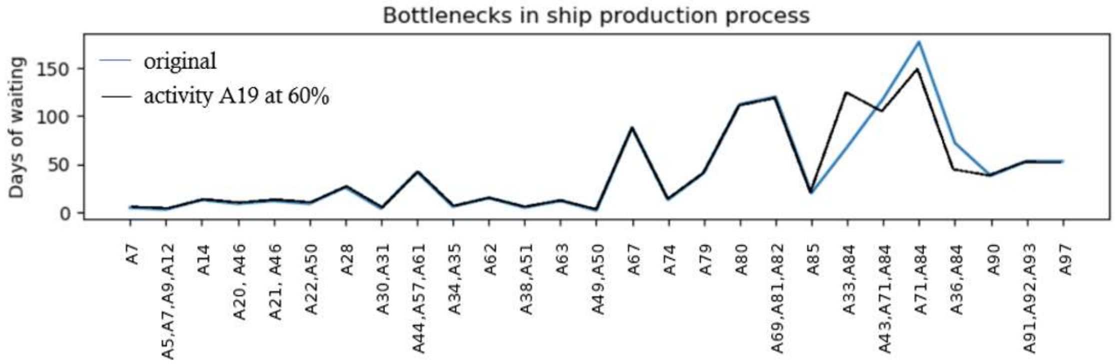


Figure 23 Bottleneck graph for activity A19 at 60%

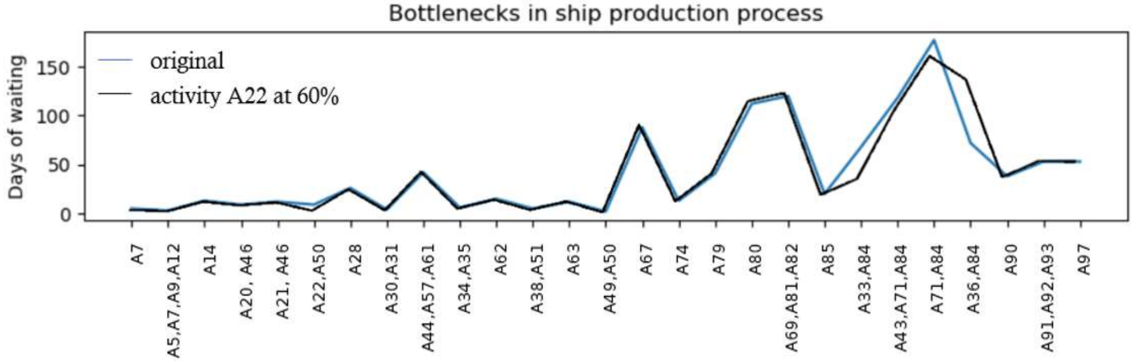


Figure 24 Bottleneck graph for A22 at 60%

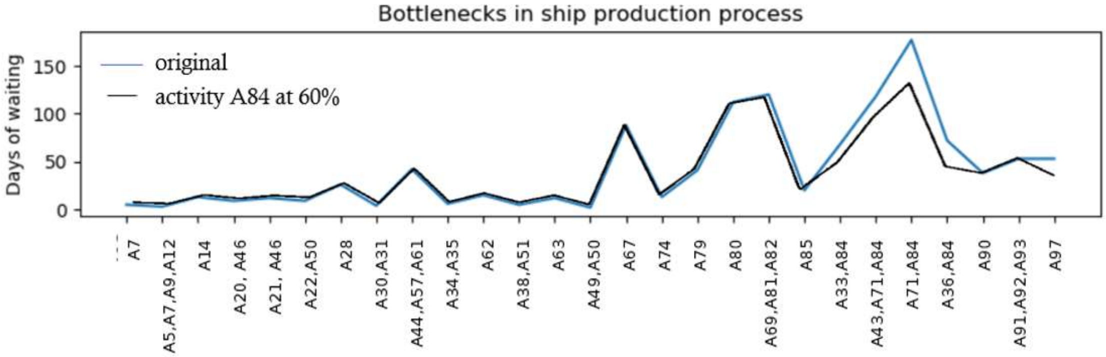


Figure 25 Bottleneck graph for A84 at 60%

7.5 Experiment 3: Eliminate delivery times

Next to the global experiments investigating the model as a whole, 2 additional, more specific experiments are executed. These experiments are based on real-world situations. The first experiment is to see what happens when all main machinery-, secondary machinery- and non-machinery parts are already present, so no delivery times are to be taken into account. This for example happens when all parts are in stock. The corresponding hypothesis is as follows:

H3: If the delivery times of all suppliers in the process (A82, A85, A90) are set to zero, the total throughput time and stakeholder waiting times will be reduced.

After modifying the input sheet and running 256 simulations, no significant reduction in total throughput time could be found, as it stays at a mean of 408 days. When looking at the stakeholder waiting times or the bottleneck plots in Figure 26, it can be seen that the bottlenecks caused by the delivery of the main machinery parts (A82) and secondary machinery parts (A90) significantly decrease. The delivery of non-machinery parts (A85) shows a small decrease. The effects cannot be seen through newly created bottlenecks or disappearance or modification in existing bottlenecks, which confirms that delivery times had no effect on the total throughput time. This means that the delivery times are for this case no part of the critical path and the hypothesis is refuted.

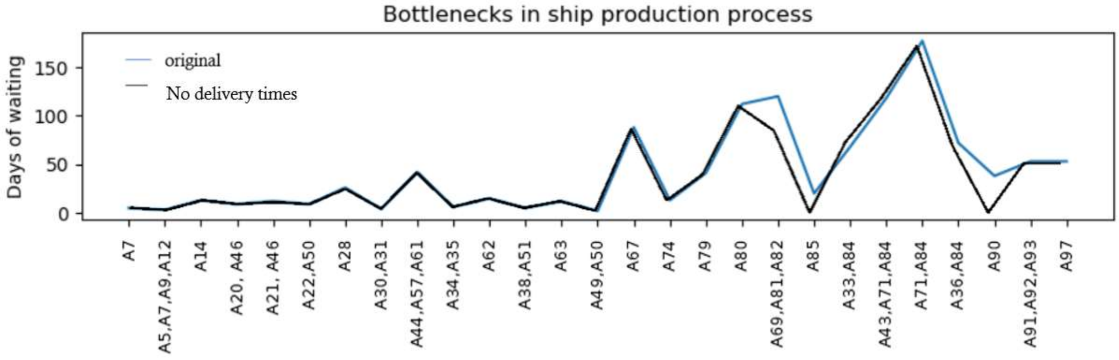


Figure 26 Effect of no delivery times on bottlenecks

For TB Shipyards, this means that all efforts to reduce delivery times are unrewarded in terms of reduction of the total throughput time and that the current “Just In Time (JIT)” delivery strategy does not need to be changed.

7.6 Experiment 4: Delay of construction plan

Another more specific experiment that is executed, is based on the real-world situation that is currently ongoing at TB Shipyards. The basic engineering is subcontracted to another party and the construction plan suffers a great delay. Regardless, TB Shipyards started the production anyway with a chance on reworks, but it is interesting to look what would have happened if the company waited for the plan to finish first to minimize rework chances. Please note that reworks or chances on reworks are not implemented in the model. The corresponding hypothesis is as follows:

H4: If the throughput time of the specification of the primary construction (A48) is increased, the total throughput time and stakeholder waiting times will increase.

Originally, specifying the primary construction was assumed to take 10 days minimally, most probably 15 days and in the worst case scenario 20 days. First, all three values (optimum, most probable and pessimistic) are set to 130 days or 6.5 months to fix the value in order to examine the pure effect. After this, the mean total throughput time increases from 408 days to 461 days. A delay of 115 days on the construction plan leads to a total delay on the full project of 53 days. Please note that the quantitative results of these kind of experiments are never a hundred percent certain. The numbers are purely for enhancing insight of the consequences.

From the bottleneck plots, it can be seen that the already existing peaks significantly increase and additionally the peaks for A62 "create rough routing model", A38 "create arrangement equipment drawings", A51 "update & elaborate construction drawings for approval" and A63 "process class remarks construction plan" increase.

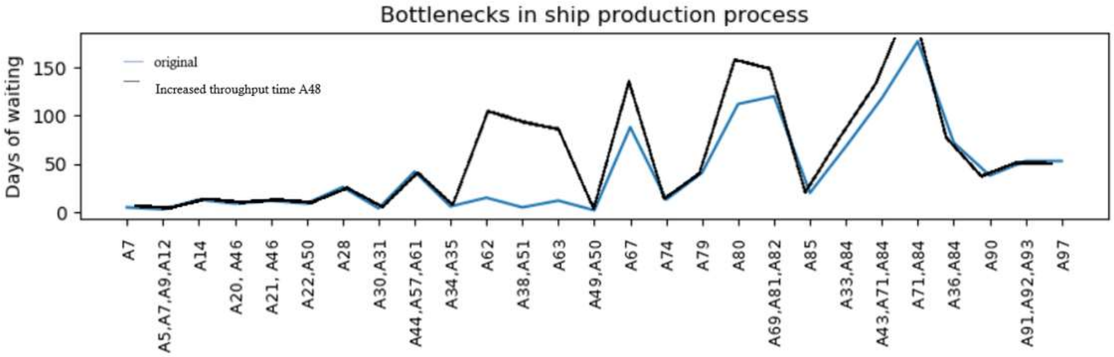


Figure 27 Effect of increase throughput time construction plan

As a consequence of this situation, for future projects, the pessimistic input value of activity A48 "specify primary construction" could be increased to 130 days. The optimistic and most probable value still remain. If this is the case, the mean total throughput time changes from 408 days to 426 days. This shows how important the input values are and to enhance the accuracy of the model, the accuracy of the input should be further enhanced.

For TB Shipyards, this means that it should be prevented that the specification of primary construction is delayed. This could be achieved by specifying this in the contract terms when the basic engineering is subcontracted or by closely tracking progress of this activity when it is performed in-house.

7.7 Discussion of the experiments

After having performed the experiments and analysed the results, it is time to reflect on the experiments and answer the final sub research question:

"Are the results of the case study reliable? Does the case-specific model coincide with the real world sufficiently?"

First of all, the results of the case study are relatable when looking at the process and the conceptual model. For example, it is reasonable that the sooner the ship is welded together (Activity A84), the sooner the subcontractors can finish (or sometimes even start) their outfitting activities and the sooner the ship will be ready. Furthermore, a throughput time of approximately 410 days or 1.5 year from contract to delivery also is considered valid for the small ship high complexity scenario.

However, it was expected that the experiments would give more results in terms of decreasing throughput time. If more attention had been spent on defining the critical path(s) beforehand, the low number of results may have been foreseen and experiments could be defined differently. On the practical side of the case-study, not much time was available to improve the Python scripts to enable easy experimenting. Therefore, experimenting is now quite time-consuming and error-sensitive.

Furthermore, to fully verify and validate the case-study, additional case-studies should be executed, featuring different input values in order to compare output and results. Also, the input sheet should be continuously updated with data of ongoing projects to increase its accuracy.

Finally, the model and its experiments now fully focuses on information timing. From Section 2.2, it became clear that there are multiple aspects of information flow improvement, such as information deficiency, information instability, information discrepancy, information mutation or wrong information. To enlarge the application area of the model, further research could focus on this as well.

7.8 Roadmap for further implementation model

To support TB Shipyards with the further implementation of the model and enhance its usability, a roadmap has been created based on the points as mentioned in Section 7.7. The roadmap is not only applicable for TB Shipyards, but also for other companies interested to exploit the potential of the model. This roadmap may be “looped” for every new ship production project. The four main steps for implementation are:

1. Use model for predictions
2. Increase reliability of the model
3. Experiment with the model
4. Expand the model.

At the beginning of each ship production project, the model can be used to form predictions. Before doing so, it should be checked if the input sheet is representative for the project. For example, there might be different input sheets for relatively small and complex ships (like the pusher tugs) and different input sheets for large and simple ships (dry bulk carrier). The model will then show what the approximate throughput time of the project will be, but also when activities are expected to start and finish and which bottlenecks will occur. This can be used to enhance the project planning or perform risk analyses. Also, experiments may be executed at the beginning of the projects to further gain insight in the planning or risk analyses. The experiments should be carefully defined and saved as these experiments might be relevant for later projects as well.

During the project, data should be collected on the actual start, finish and duration of activities and the input sheet of the project should be updated. The input sheet will become more and more reliable for the specific ship production case and this will benefit further projects. During the project, also additional experiments can be executed in order to gain more insights.

At the end of each project, a reflection on the model and its results should be performed in order to further increase reliability of the model. Furthermore, if required, the model may be further expanded by adding other aspects of information flow improvement such as information deficiency, information instability, information discrepancy, information mutation or wrong information.

The roadmap is featured in Figure 28.

	Ship production Project 1			Ship production Project 2			
Use model for predictions	Use model to predict throughput time and bottlenecks, check if input sheet is representative for this project			Use model to predict throughput time and bottlenecks, check if input sheet is representative for this project			etc.
Increase reliability of model	Collect data during project, update input data and use for following similar projects		Reflect on input and results at the end of the project	Collect data during project, update input data and use for following similar projects		Reflect on input and results at the end of the project	etc.
Experimenting with the model	Gain insights at start of project by means of experiments	Gain insights during project by means of executing experiments		Gain insights at start of project by means of experiments	Gain insights during project by means of executing experiments		etc.
Expanding the model	Add other aspects of information flow improvement			Add other aspects of information flow improvement			etc.

Figure 28 Roadmap for further implementation of the model

7.9 Summary

In this chapter, results were obtained by executing two large experiments applied to the full model and two smaller experiments focusing on specific activities. The first hypothesis

"H1: For bottleneck X, if the input value of preceding activity Y is set to Z, the total throughput time and stakeholder waiting times will be reduced and bottleneck X may even disappear."

Was partly true for bottlenecks caused by A7, A14, A28, A62, A63, A67 and A91 reducing the stakeholder waiting times but not the total throughput time, and fully true for bottlenecks caused by activity A84 which also led to a smaller mean total throughput time. The hypothesis is refuted for activities A5, A9, A12, A20, A21, A30, A31, A57, A61, A34, A35, A38, A50, A49, A80 and A97 showing very little to no effect on total throughput time and stakeholder waiting times.

For TB Shipyards, this means that investing ways to reduce the durations of activities A5, A9, A12, A20, A21, A30, A31, A57, A61, A34, A35, A38, A50, A49, A80 and A97 are inefficient as these do not reduce the total throughput time nor the stakeholder waiting times. Investing in ways to reduce durations of activity A7, A14, A28, A62, A63, A67 and A91 may reduce the stakeholder waiting times, which gives benefits in the form of risk minimization, a better division of manpower, assumption minimization or other benefits that are not quantitively investigated in this report. Investing in ways to reduce duration of the activity "weld sections together" (A84) benefits the full process, as it reduces both the total throughput time as the stakeholder waiting times. For this, one might think having standardized cascos in stock as is the case with Damen Shipyards, making use of welding robots/gantries to speed up the welding of the casco or (temporarily) make use of night shifts in this part of the process.

The second hypothesis,

"H2: If information object X is released pre-maturely, a significant reduction in total throughput time and stakeholder waiting times can be obtained."

could only be accepted for activity A84 and A74. For activities A19 and A22 also changes in bottlenecks/stakeholder waiting times could be observed, but these could not be considered "significant reductions". Theoretically, it is possible, but in practice it is difficult to pre-release activity A84 and A74. The experiment for this case-study unfortunately did not provide recommendations for engineering documents which are more practical to pre-release.

The third hypothesis,

"H3: If the delivery times of all suppliers in the process (A82, A85, A90) are set to zero, the total throughput time and stakeholder waiting times will be reduced."

was completely refuted. Reducing the delivery times to zero did show now effect on the total throughput time and no additional effects in the bottleneck plots. Therefore, TB Shipyards should keep to its current Just In Time delivery strategy.

For the final experiment, the fourth hypothesis was as follows:

“H4: If the throughput time of the specification of the primary construction (A48) is increased, the total throughput time and stakeholder waiting times will increase.”

This hypothesis was confirmed by the experiment, as a delay of the construction plan lead to an increase in mean total throughput time for the simulations and an increase in stakeholder waiting times for the activities A62 “create rough routing model”, A38 “create arrangement equipment drawings”, A51 “update & elaborate construction drawings for approval” and A63 “process class remarks construction plan”. For TB Shipyards, this means that it should be prevented that the specification of primary construction is delayed. This could be achieved by specifying this in the contract terms when the basic engineering is subcontracted or by closely tracking progress of this activity when it is performed in-house.

From the discussion on the experiments, it becomes clear that additional case-studies should be added to the model and more project data should be used to further enhance the reliability of the input. Furthermore, more time should be invested in defining, executing and interpreting experiments and other aspects of information flow improvement (information deficiency, information instability, information discrepancy, information mutation or wrong information) should be treated. By means of a road map, the further implementation strategy of the model is discussed.

8 Conclusion

The objective of the research was to identify and improve the professional communication exchange of shipyards and the companies it exchanges information with. In order to do so, the following main research question was asked: “Which measures are effective for improving information handling in a general ship production process for TB Shipyards?”

From literature, it became clear that to find improvement measures for information handling, a model should be established. First of all, it was asked how the information flow for a general ship production process could be modelled. After having defined a theoretical framework, it became clear that simulation models and more specifically System Dynamics-, Agent Based- and Discrete Event Simulation models are suitable for modelling information flow. To make a choice between these, it was asked what the focus of the model was going to be and how that would influence the formation of the model. By means of a survey under TB employees, it was concluded that the model should focus on information timing and based on this, a Discrete Event Simulation model supported by Petri Net theory was chosen. The third sub research question focused on which potential improvement measures were interesting to test and how these would transform into specific experiments. As a result, four experiments were defined, focusing on bottleneck identification and optimization, pre-mature release and shortening and delaying specific activities in the process.

To create the model, it was important to define which stakeholders were of importance in the information flow. This sub research question was answered by means of a stakeholder analysis. The most relevant internal stakeholders in the process were considered the engineering-, sales-, project management-, production- and warehousing/logistics and procurement department. The most important external stakeholders were considered the client, classification society, suppliers and subcontractors. Next, by means of the Stage Gate approach and Petri Nets, a conceptual model was defined and subsequently the underlying mathematical part of the model was created with as main parts the Beta-PERT distribution and Monte Carlo technique. After the creation of the model, the fifth research question could be answered whether the general model coincided with the real-world situation sufficiently. By means of verification and validation tests, it could be concluded that the model was approved.

When the model was finished and approved, the experiments could be executed. Here, it was important to answer for which case the experiments should be executed. It was chosen to define input values for a relatively small but complex ship, a pusher tug.

After this, the four experiments were performed and the effective measures for improving the information handling for TB Shipyards could be defined. It became clear that to improve the total throughput time of information in a ship production project, TB Shipyards should focus on ways to reduce duration of the activity “weld sections together”, for example by stocking standardized cascos, making use of welding robots or night shifts and that TB Shipyards should make sure that the specification of the primary construction in the basic engineering phase does not suffer from any delays. For example by specifying this in the contract terms when the basic engineering is subcontracted or by closely tracking progress of this activity when it is performed in-house.

9 Discussion

In this chapter, the results of the research are further interpreted and discussed.

When focusing on the establishment of the model, well-founded arguments were given for using a Discrete Event Simulation model enhanced with Petri Net theory based on an extensive theoretical framework, but there might be other valid arguments for using other models or techniques.

Furthermore, in Chapter 4 the model was established with the help of the Stage Gate approach, resulting a model which can be applied at different ship production companies, as its main structure is of a general and descriptive nature. However, there is a chance that others would produce a different model as the shipbuilding process offers room for different interpretations and definitions.

The answer to the main question is for a specific case study and focusing on information timing, or more specifically, total throughput time. It should be made clear that for a different case study, different results are obtained. Therefore, as discussed in Section 7.7, more case studies should be performed and more input data should be obtained to enhance the reliability of the model and the results. Also, other aspects of information improvement such as information deficiency, information instability, information discrepancy, information mutation or wrong information as specified from the survey in Section 2.2 should be focused on.

With respect to the experiments, it was expected that the experiments would give more results in terms of decreasing throughput time. If more attention had been spent on defining the critical path(s) beforehand, the low number of results may have been foreseen and experiments could be defined differently.

On the practical side of the case-study, not much time was available to improve the Python scripts to enable easy experimenting. Therefore, experimenting is now quite time-consuming and error-sensitive. This could be improved in the future.

If the objectives as specified in Section 1.4 are consulted, it can be stated that the conceptual model, mathematical model and case study comply with the main objective, being "to identify and improve the professional communication exchange of shipyards and the companies it exchanges information with". Additionally, the scientific goals were reached, being the provision of a clear basis on information flow, fill the knowledge gap and elaborate and complement on existing literature. The practical goals are also reached, which were supporting TB Shipyards and others in their way to improve information exchange, provide an overview of the communication barriers and stimulate a culture of measurement. The societal goals, minimization of defects due to communication errors, enhance success rate of information improvement measures and reduce work stress of employees will be reached whenever the results of the research will be further put in practice.

In summary, the conceptual model, mathematical model and case study can be considered a decent attempt to identify the information flow for a ship production process and a starting point for experiments in order to improve the information flow.

10 Recommendations

When focusing on the practical recommendations for TB Shipyards, it can be said that for a relatively small and complex ship, the total throughput time of the project might be reduced by shortening the duration of the activity “weld sections together”. For this, one might think having standardized cascos in stock as is the case with Damen Shipyards, making use of welding robots/gantries to speed up the welding of the casco or (temporarily) make use of night shifts in this part of the process. Furthermore, it should be made sure that no delays in the specification of the primary construction occur. This could be achieved by specifying this in the contract terms when the basic engineering is subcontracted or by closely tracking progress of this activity when it is performed in-house.

If TB Shipyards plans to further exploit the model for other cases, it is recommended to adopt the roadmap as discussed in Section 7.8. The roadmap is subdivided in activities “using the model for predictions”, “increase reliability of the model”, “experiment with the model” and “expand the model”. These activities may be repeated for every new ship production project, ultimately enhancing the accuracy of the model.

With respect to scientific recommendations, this research is recommended to use to further investigate potential communication digitalization or -automation possibilities. Also, the other aspects of information improvement (information deficiency, information instability, information discrepancy, information mutation or wrong information) may be further researched.

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12 Appendices

12.1 Literature study approach

The literature study can be subdivided keeping two main purposes in mind:

6. As a part of the problem analysis in Chapter 2, where it produces an overview of the available literature in order to define the knowledge gap and the relevance and objectives of the research;
7. As part of the theoretical framework in Chapter 3 where it guides to design a solution to the problem.

For the first purpose, a systematic approach has been adopted. The approach to finding scientific literature is as follows:

1. Search into the on and offline repository of the TU Delft, google, google scholar and online (educational) books for relevant sources.
2. For every found source, read the abstract and scan through the section titles, figures and introduction and conclusion to determine whether the source is relevant. If the source is considered relevant, it is saved to read later or the book is reserved at the TU Delft library.
3. Collect & read relevant sources and find additional relevant sources by means of the "snowball" technique. The snowball technique means that the reference list of a relevant source is used to identify additional relevant sources (Wohlin, 2014).

From a practical perspective (suggested by TB Shipyards), it became clear there was an interest in improving the professional communication exchange, both internally as externally. From a scientific perspective (suggested by the university), it became clear that it might be interesting to make use of modeling or simulating techniques. Therefore, the searching tags are largely based on these suggested directions. First, some general sources were found using the searching tags "communication" or "information flow". These sources provided a general view of the many aspects of communication. Second, the searching tags "communication/information flow" were combined with "simulation" or "modelling" in order to investigate whether simulation is a common approach to analyse information flow. When many papers confirmed this possibility, specific searching tags were used which were a combination of the words "simulation" or "modelling", "information flow" or "communication" and "ship building" or "ship production" to find out whether this has also been done for a ship production process. Hardly any relevant sources were found, so additionally the combination "simulation/modelling" and "shipbuilding/ship (production)" was used to find out whether simulation techniques were used to solve ship production-related problems which were not specifically focused on information flow. Finally, the combination "information flow/communication" and "shipbuilding/ship production" was used to find out whether studies were available, which were not specifically making use of simulation or modelling techniques. The results of this literature study and the corresponding knowledge gap are further explained in Section 2.3. Furthermore, the literature study has been taken one step further by going out in the field in order to find societal and practical views on the subject, making an appointment with one of the experts in the field, Jenny Coenen in order to gather more understanding of her research and advice concerning the subject. Also, by appearing at events and talking about the research with others from the industry and the company, some additional useful sources have been found. For example, documents concerning the MEI-project provided by Conoship in 1999, which stands for Management of Engineerings Information. The goal of this project was to create a tool to support project engineers in managing the information flow. The tool has never been created, but it emphasizes the always present desire to better control information flow. Additionally, from the company, a University of Applied Sciences thesis has been found on improving communication insights for Barkmeijer Shipyards from the year 2000.

For the second purpose, to create the theoretical framework in Chapter 3, a targeted literature review approach has been adopted. This type of literature review is less systematic and used to produce an informative rather than all-encompassing overview of the literature on the topic. Furthermore, a targeted literature review is largely based on a selection of high-quality articles (Huelin, Iheanacho, Payne, & Sandman, 2015). Here, the review paper of Durugbo (2013), quoting many other experts in the field, was of great importance. Of course, before adopting statements from this paper, they have been thoroughly criticized with the help of other papers.

12.2 Examples of Diagrammatic modelling techniques

In order to illustrate the available tools and indicate differences and similarities between them, a very basic example case is introduced which is the same for each example:

Example case:

An in-house detail engineer of a shipyard produces a drawing of a platform, which is to be manufactured by a worker and to be fitted on top of a dredging vessel in order to be able to manually close valves.

In this example case, the drawing of the platform can be considered a physical information object.

Please note that diagrammatic approaches could be explained by means of other examples.

12.2.1 Pictorial representation: rich picture technique

For pictorial representations, the rich picture technique can be used. The technique is studied by many scientists and many different definitions and interpretations of the technique exist (Bronte-Stewart, 1999), but explaining the technique can best be done by showing an example. In Figure 29, an example of a rich picture of the example case is featured. The rules for drawing a rich picture are minimal and by proposing this loose and undefined way of diagramming, keeping a holistic view is encouraged (Harry, 1994). The rich picture may be used as a way of communicating or improving ones understanding of a situation without having to read extensive narratives (Stowell & West, 1995). Furthermore, the popularity of rich pictures indicate that there is a desire to be able to include softer aspects (attitudes, tensions, organisational culture, politics etc.) in analysing situations (Bronte-Stewart, 1999).

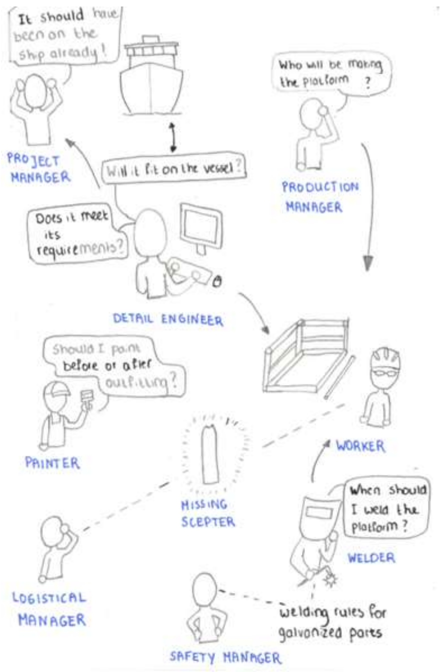


Figure 29 Example of a rich picture of the example case

12.2.2 Graph representations: structured analysis and network analysis

For **graph representations**, one sub technique that can be used is called “structured analysis”. By means of a collection of well-defined tools, which are often describing a system in a hierarchical, functional or procedural way, interacting units are analysed. The main goal of the structured analysis tools is to provide feasible solutions to problems (Durugbo et al., 2013).

One example of a structured analysis tool is the Petri Net. Petri Nets are invented by Carl Adam Petri in 1939 in order to describe chemical processes (Olimpo, 2011). A Petri Net consists of circles, which indicate “places” and segments, which indicate “transitions”. There can be no link between nodes of the same type. Furthermore, places may contain so-called “tokens”. The tokens can “fire” transitions and are determining the dynamic aspect of the model. Petri Nets do not specify temporal sequences, but only relations of logical precedence (Olimpo, 2011). In Figure 30, a possibility to model the example case with Petri Net theory is viewed. There are over 8000 publications on Petri Nets and variations of them (He & Murata, 2005), so there are multiple ways of using Petri Nets for modelling a situation, but in almost all cases, the graphical theory is substantiated with a clear underpinning mathematical definition (Olimpo, 2011).

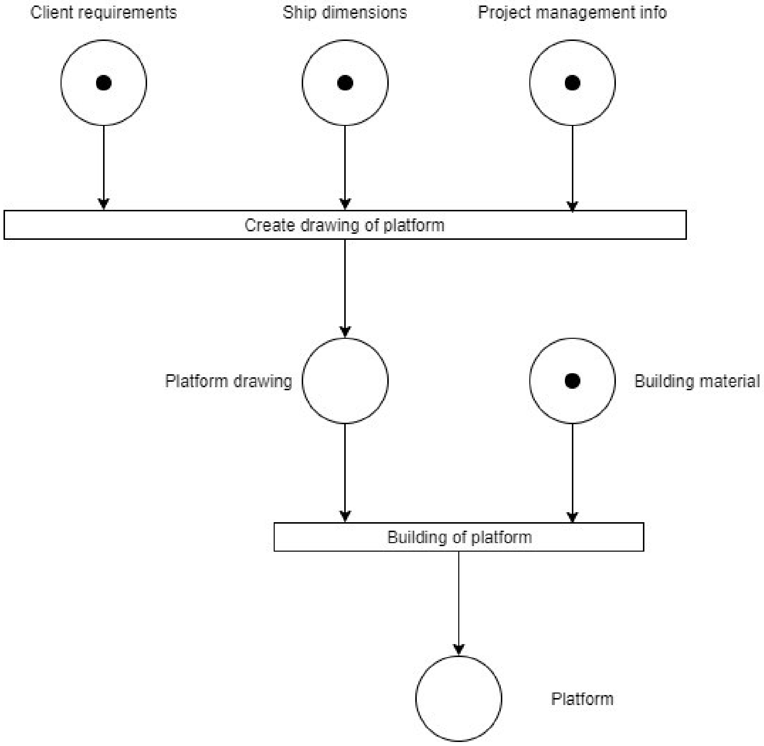


Figure 30 Possibility to model example case with Petri Net theory

Another example of a structured analysis tool is the Entity-Relationship Diagram (ERD). ERD’s consist of “entities”, which are important business objects with properties, and “relationships”, which represent an association between entities (I.-Y. Song, Evans, & Park, 1995). There are many different types of notations, but in general, the main idea is the same. As is the case for all structured analysis tools, ERD also contains an underlying mathematical definition. An example of an ERD for our example case can be found in Figure 31.

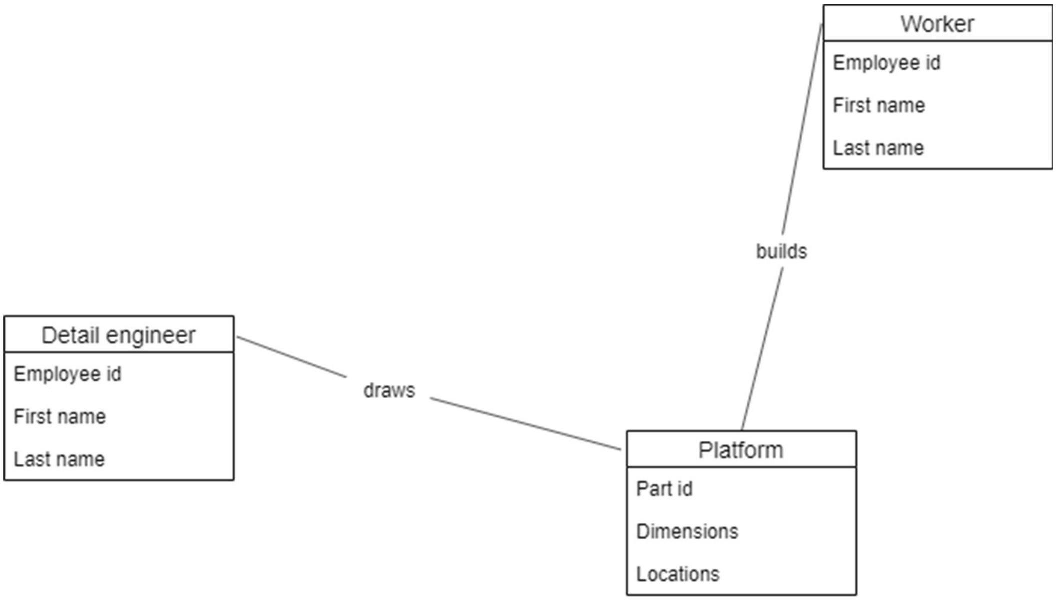


Figure 31 Example of an Entity Relationship Diagram

A final example of a structured analysis tool is a swimming lane diagram, also known as the Rummler-Brache diagram. In swimming lane diagrams, every lane is the responsibility of a stakeholder. The steps in a process are subdivided into the lanes and lines between the steps indicate communication between different stakeholders. An example of a swimming lane diagram is featured in Figure 32.

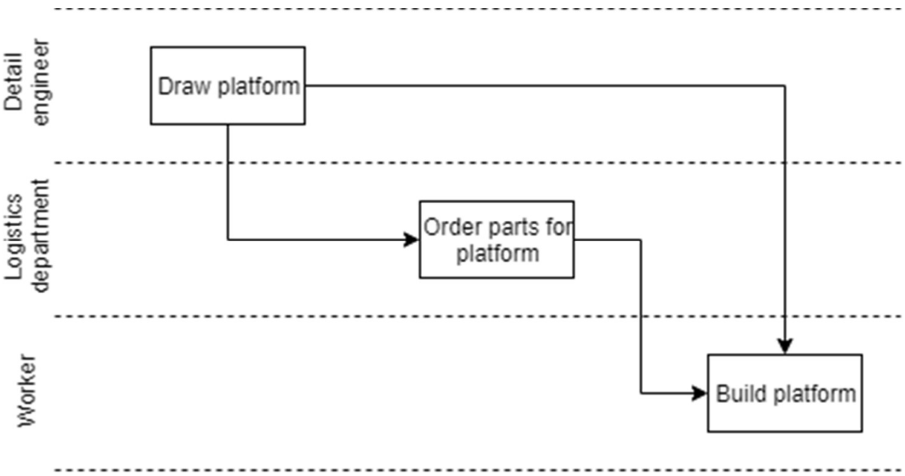


Figure 32 Example of swimming lane diagram

Next to "structured analysis" as a sub technique for graph representations, there is also "network analysis". Network analysis focuses on relationships between people in order to distinguish communication patterns (Zwijze-Koning & De Jong, 2005). The technique is quite simple as it consists of nodes and lines only. Nodes are often representing people and lines are symbolizing the links between them (Borgatti, Mehra, Brass, & Labianca, 2009). Additionally extra frameworks can be added to indicate different departments. An example of a network analysis diagram is featured in Figure 33.

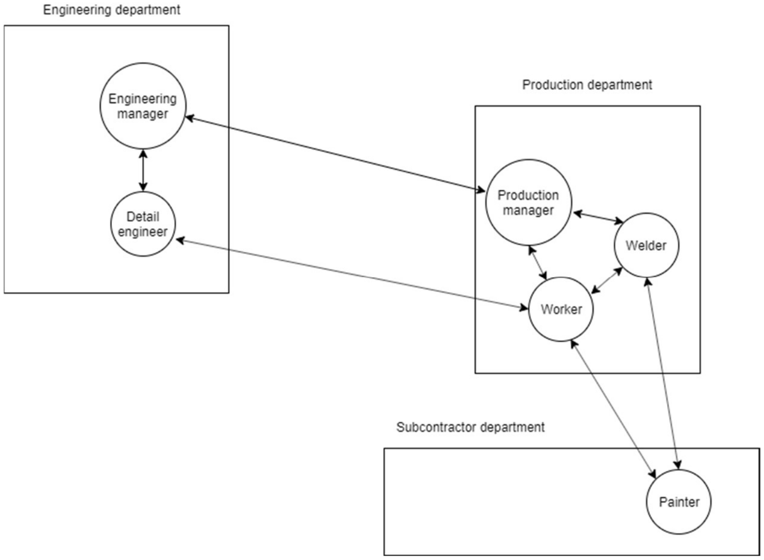
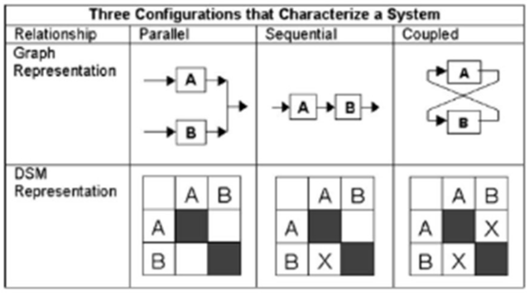


Figure 33 Case example visualized as simple network analysis diagram

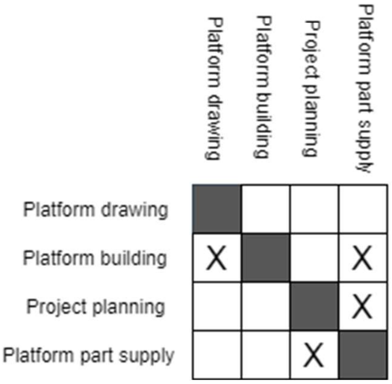
12.2.3 Matrix representations: Design Structure Matrix

The final category that is a part of the diagrammatic modelling approach is **matrix representations**. Matrix representations are convenient in a case where complex processes result in messy graphs. One example of a matrix representation technique is the Design Structure Matrix (DSM). The DSM is able to visualize dependency, independency, interdependency and conditionality of information flow (Durugbo et al., 2013). Different elements are set against both axes of a 2 dimensional matrix and when the elements are sequential or coupled, boxes are ticked (Pektaş & Pultar, 2006). An example of a DSM for the example case can be found in Figure 22.



Three Configurations that Characterize a System

Relationship	Parallel	Sequential	Coupled
Graph Representation	A B	A B	A B
DSM Representation	A B A ■ B ■	A B A ■ B X ■	A B A ■ X B X ■



	Platform drawing	Platform building	Project planning	Platform part supply
Platform drawing	■			
Platform building	X	■		X
Project planning			■	X
Platform part supply			X	■

Figure 34 Design Structure Matrix for the example case

12.3 Survey model focus

English version

1. **Which causes of communication errors have a negative influence on the ship production process according to you? Select a maximum of 4 answers.**
    - ☐ **Information damaging:** by using different software or communication channels, information gets lost or damaged.
    - ☐ **Information mutation:** because of misinterpretations or different viewpoints, information changes.
    - ☐ **Information mutation:** because of misinterpretations or different viewpoints, information changes.
    - ☐ **Information mutation:** because of misinterpretations or different viewpoints, information changes.
    - ☐ **Information discrepancy:** what a receiver needs and what a sender thinks a receiver needs does not coincide.
    - ☐ **Information timing:** when one has to wait too long for the necessary information.
    - ☐ **Information instability:** when information changes too often during a project.
    - ☐ **Information inaccuracy:** because of working with information that is often based on rough estimations
    - ☐ **Untargeted information:** when it is unclear who the information is intended for.
    - ☐ **Wrong information**: when information is simply incorrect or conflicting
    - ☐ **No confirmation:** because there is no confirmation whether information is received or understood
    - ☐ **Use of jargon:** incomprehension caused by use of too many specific technical terms
    - ☐ **Culture difference:** because different departments and companies speak "different languages"
    - ☐ **Language barriers:** because people literally speak different languages
    - ☐ **Otherwise** …

2. **If possible, rate your answers of the previous question from most relevant (1) to least relevant (4)**

    1. ……………………………………………………..

    2. ……………………………………………………..

    3. ……………………………………………………..

    4. ……………………………………………………..

3. **How would you describe your function within the ship production process?**
    e.g. engineer, project manager, subcontractor, production worker, supplier, client etc.
    …………………………………………………………………………………………
    …………………………………….

Dutch version

1. **Welke oorzaken van communicatieproblemen hebben volgens u het meest een negatieve invloed op een scheepsproductieproces? Selecteer maximaal 4 antwoorden.**
   - ☐ **Informatie beschadiging:** door bijvoorbeeld het gebruik van verschillende software of communicatiekanalen raakt informatie verloren of beschadigd.
   - ☐ **Informatie mutatie:** door bijvoorbeeld misinterpretaties of verschillende standpunten verandert bepaalde informatie.
   - ☐ **Informatie overvloed:** doordat teveel informatie wordt gegeven, gaat de essentie verloren.
   - ☐ **Informatie tekort:** doordat er te weinig informatie wordt gegeven worden er aannames gedaan en ontstaan er communicatieproblemen
   - ☐ **Informatie discrepantie:** doordat er geen overeenkomst is tussen wat de ontvanger nodig heeft en wat de verzender denkt dat de ontvanger nodig heeft
   - ☐ **Informatie timing:** doordat men te lang moet wachten op de benodigde informatie
   - ☐ **Informatie instabiliteit:** doordat informatie te vaak verandert gedurende het project
   - ☐ **Informatie onnauwkeurigheid:** doordat er met informatie gewerkt wordt die vaak gebaseerd is op schattingen
   - ☐ **Informatie ongerichtheid:** doordat het onduidelijk is voor wie bepaalde informatie bestemd is.
   - ☐ **Niet kloppende informatie:** doordat informatie simpelweg niet juist is of tegenstrijdig
   - ☐ **Geen bevestiging:** doordat er geen bevestiging is of informatie is ontvangen of begrepen
   - ☐ **Jargongebruik:** onbegrip veroorzaakt door gebruik van teveel vakjargon
   - ☐ **Cultuurverschil:** doordat verschillende afdelingen en bedrijven “andere talen spreken”
   - ☐ **Taalbarrières:** doordat mensen letterlijk andere talen spreken
   - ☐ **Anders,** namelijk …

2. **Indien mogelijk, rangschik uw antwoorden van de vorige vraag van meest relevant (1) tot minst relevant (4)**

   1. ……………………………………………………

   2. ……………………………………………………

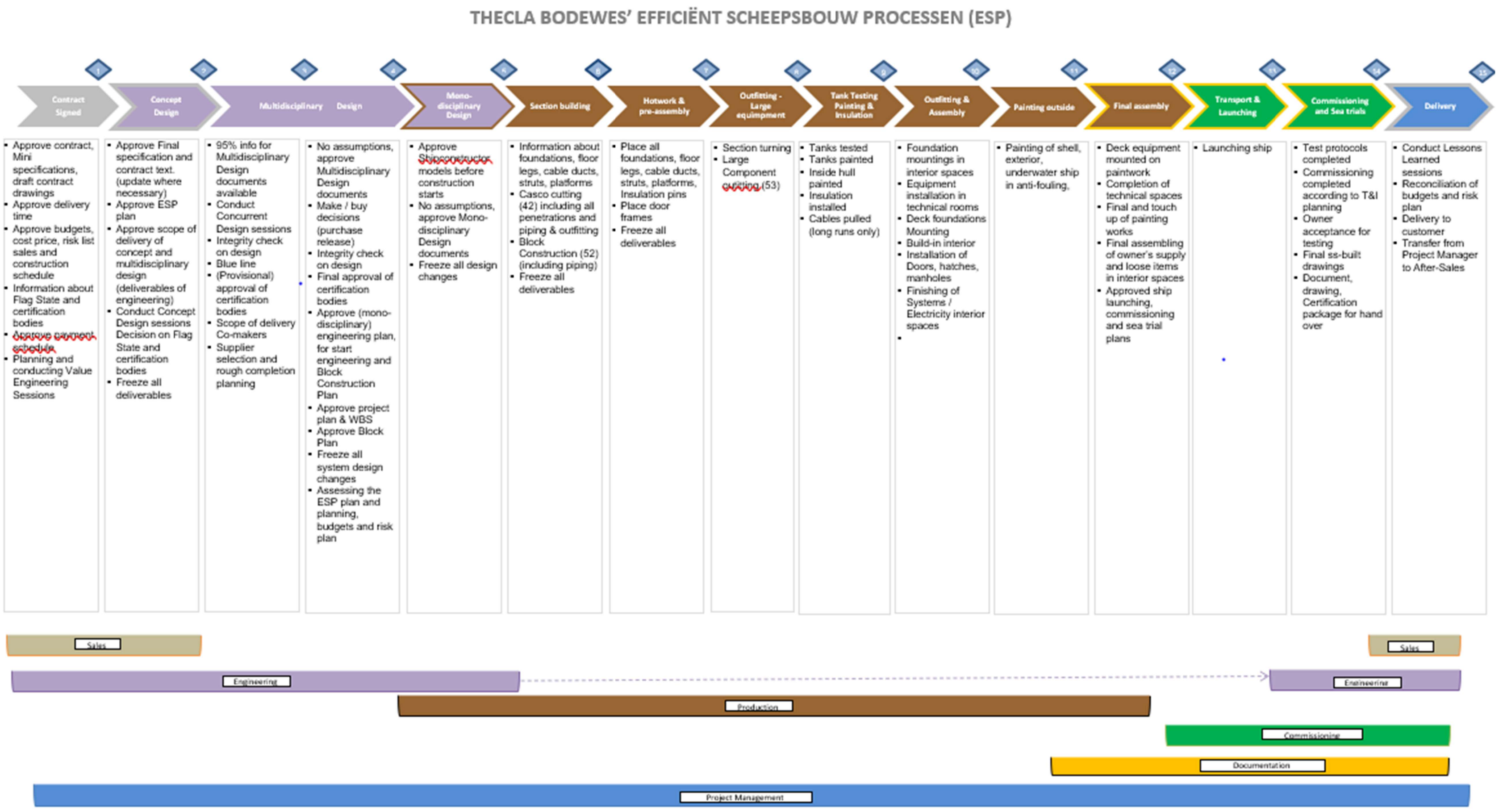
   3. ……………………………………………………

   4. ……………………………………………………

3. **Hoe zou u uw functie binnen het scheepsbouwproces omschrijven?**
   (bijvoorbeeld engineer, project manager, onderaannemer, productiemedewerker, lasser, etc.)

   ………………………………………………………………………………………

12.4 Stagegate chart TB Shipyards

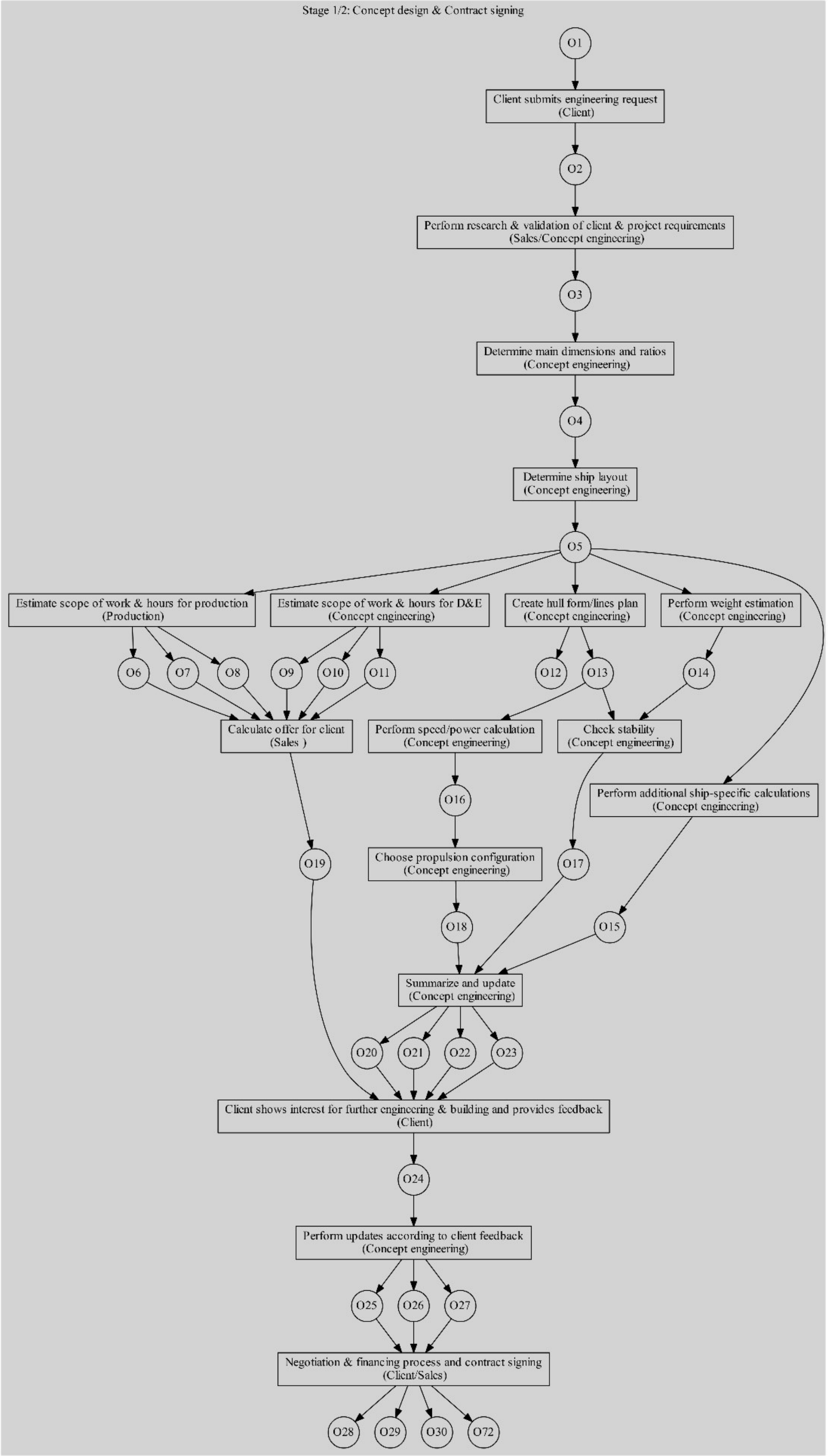


THECLA BODEWES' EFFICIËNT SCHEEPSBOUW PROCESSEN (ESP)

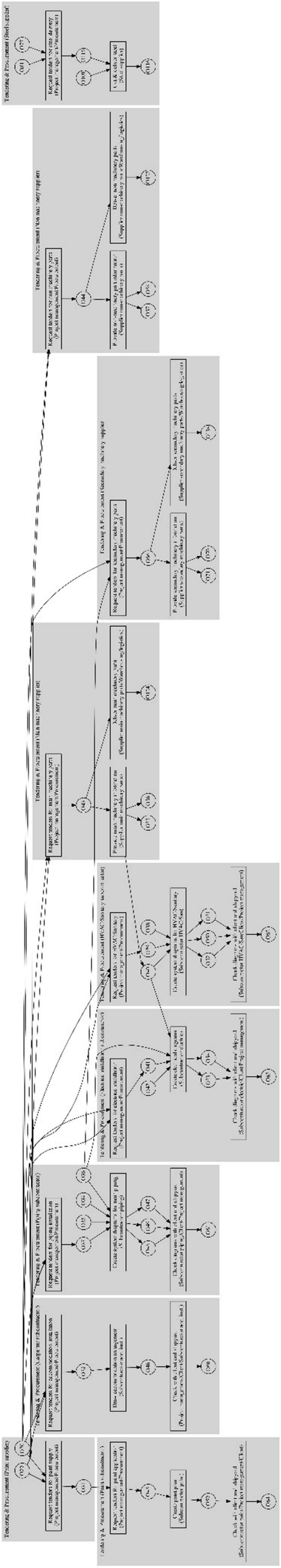
Contract Signed	• Approve contract, Mini specifications, draft contract drawings • Approve delivery time • Approve budgets, cost price, risk list sales and construction schedule • Information about Flag State and certification bodies • Approve payment schedule • Planning and conducting Value Engineering Sessions
Concept Design	• Approve Final specification and contract text. (update where necessary) • Approve ESP plan • Approve scope of delivery of concept and multidisciplinary design (deliverables of engineering) • Conduct Concept Design sessions Decision on Flag State and certification bodies • Freeze all deliverables
Multidisciplinary Design	• 95% info for Multidisciplinary Design documents available • Conduct Concurrent Design sessions • Integrity check on design • Blue line • (Provisional) approval of certification bodies • Scope of delivery Co-makers • Supplier selection and rough completion planning
	• No assumptions, approve Multidisciplinary Design documents • Make / buy decisions (purchase release) • Integrity check on design • Final approval of certification bodies • Approve (mono-disciplinary) engineering plan, for start engineering and Block Construction Plan • Approve project plan & WBS • Approve Block Plan • Freeze all system design changes • Assessing the ESP plan and planning, budgets and risk plan
Mono-disciplinary Design	• Approve Shipconstructor models before construction starts • No assumptions, approve Mono-disciplinary Design documents • Freeze all design changes
Section building	• Information about foundations, floor legs, cable ducts, struts, platforms • Casco cutting (42) including all penetrations and piping & outfitting • Block Construction (52) (including piping) • Freeze all deliverables
Hotwork & pre-assembly	• Place all foundations, floor legs, cable ducts, struts, platforms, Insulation pins • Place door frames • Freeze all deliverables
Outfitting - Large equimpment	• Section turning • Large Component outfitting (53)
Tank Testing Painting & Insulation	• Tanks tested • Tanks painted • Inside hull painted • Insulation installed • Cables pulled (long runs only)
Outfitting & Assembly	• Foundation mountings in interior spaces • Equipment installation in technical rooms • Deck foundations Mounting • Build-in interior • Installation of Doors, hatches, manholes • Finishing of Systems / Electricity interior spaces •
Painting outside	• Painting of shell, exterior, underwater ship in anti-fouling,
Final assembly	• Deck equipment mounted on paintwork • Completion of technical spaces • Final and touch up of painting works • Final assembling of owner's supply and loose items in interior spaces • Approved ship launching, commissioning and sea trial plans
Transport & Launching	• Launching ship
Commissioning and Sea trials	• Test protocols completed • Commissioning completed according to T&I planning • Owner acceptance for testing • Final ss-built drawings • Document, drawing, Certification package for hand over
Delivery	• Conduct Lessons Learned sessions • Reconciliation of budgets and risk plan • Delivery to customer • Transfer from Project Manager to After-Sales

Stage Gates provide approval deadlines for when a list of deliverables set by the Project Team, Buyer and Steering Group must be completed as a whole and approved before any further works can continue. The aim is to ensure works happen systematically and as efficiently as possible. Each Project has its Stage deliverables defined by the project team. However, please take into account that projects at TBS are of varied types, durations and complexity, so some Stages may need to be combined, started in parallel, omitted or added. Any decisions deviating from the ESP will be outlined in the Project Plan, and will be approved by the Steering Group and Buyer.

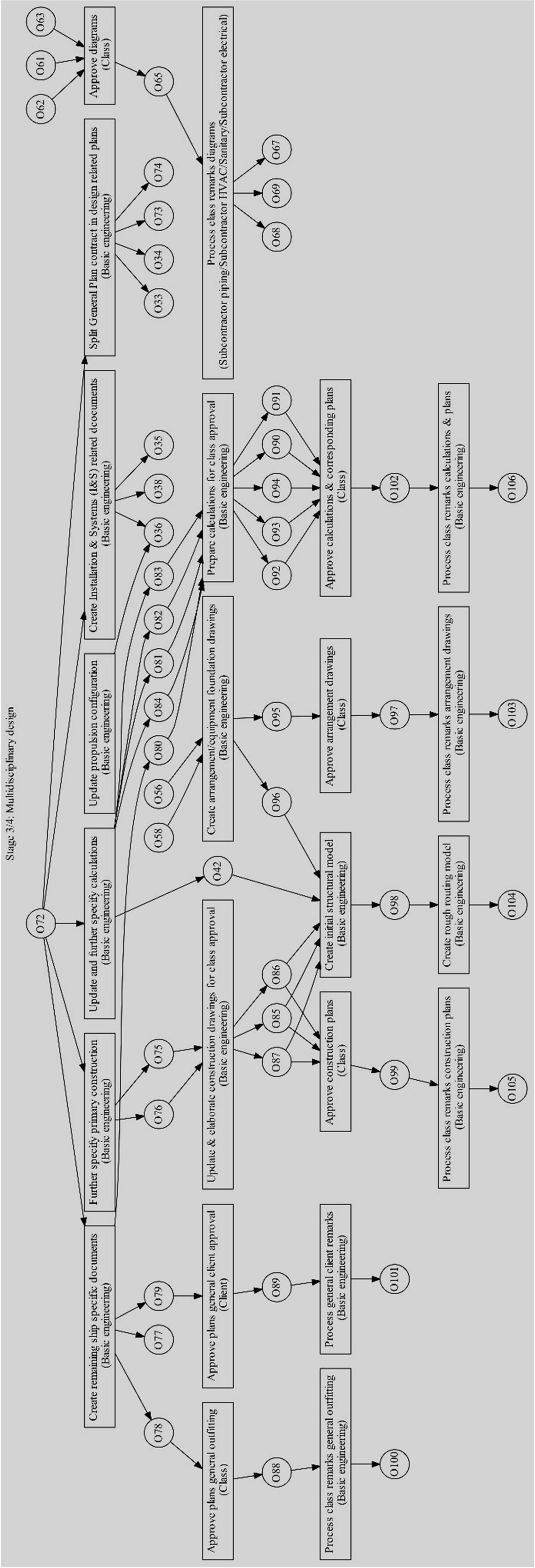
12.5 Conceptual Model – Stage 1/2 Concept Engineering & Contract signing



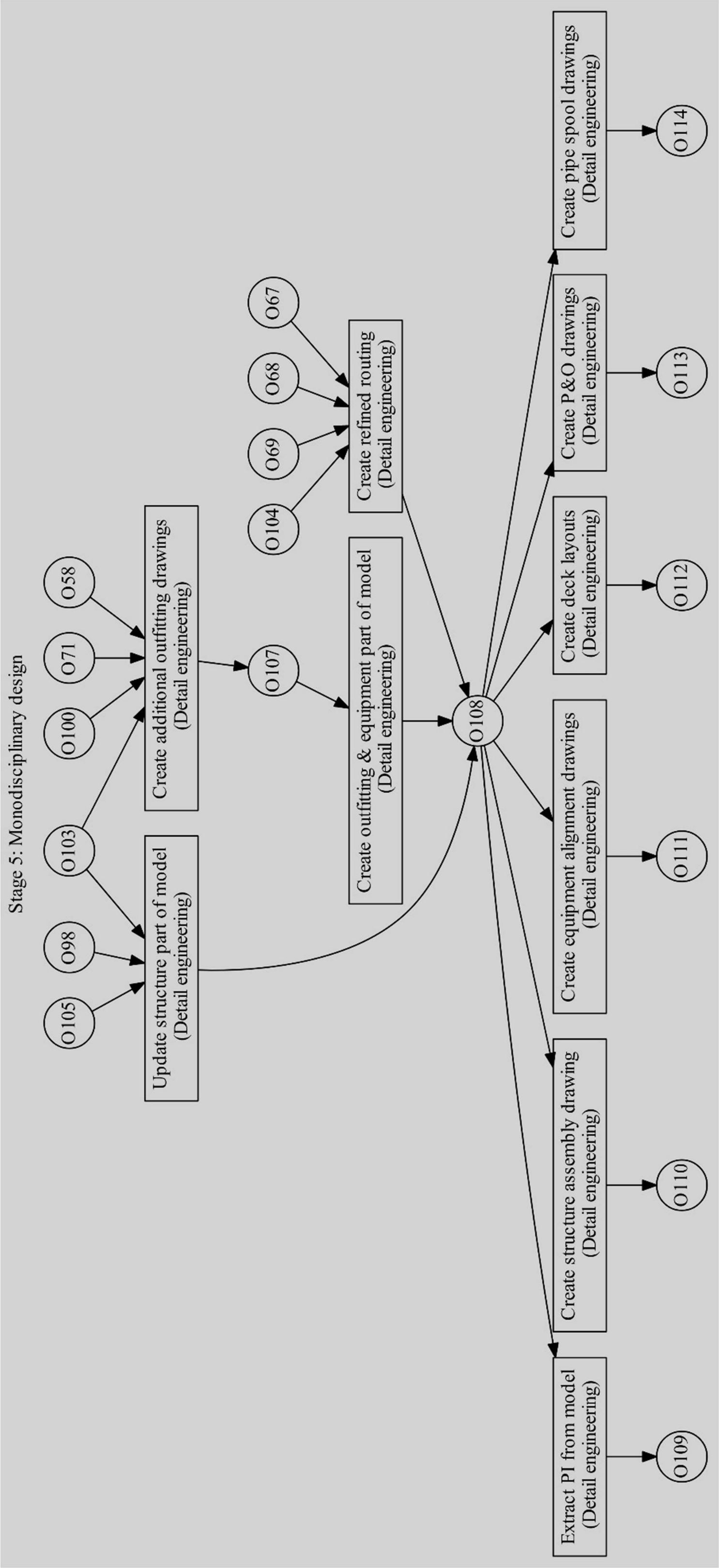
12.6 Conceptual Model – Tendering & Procurement



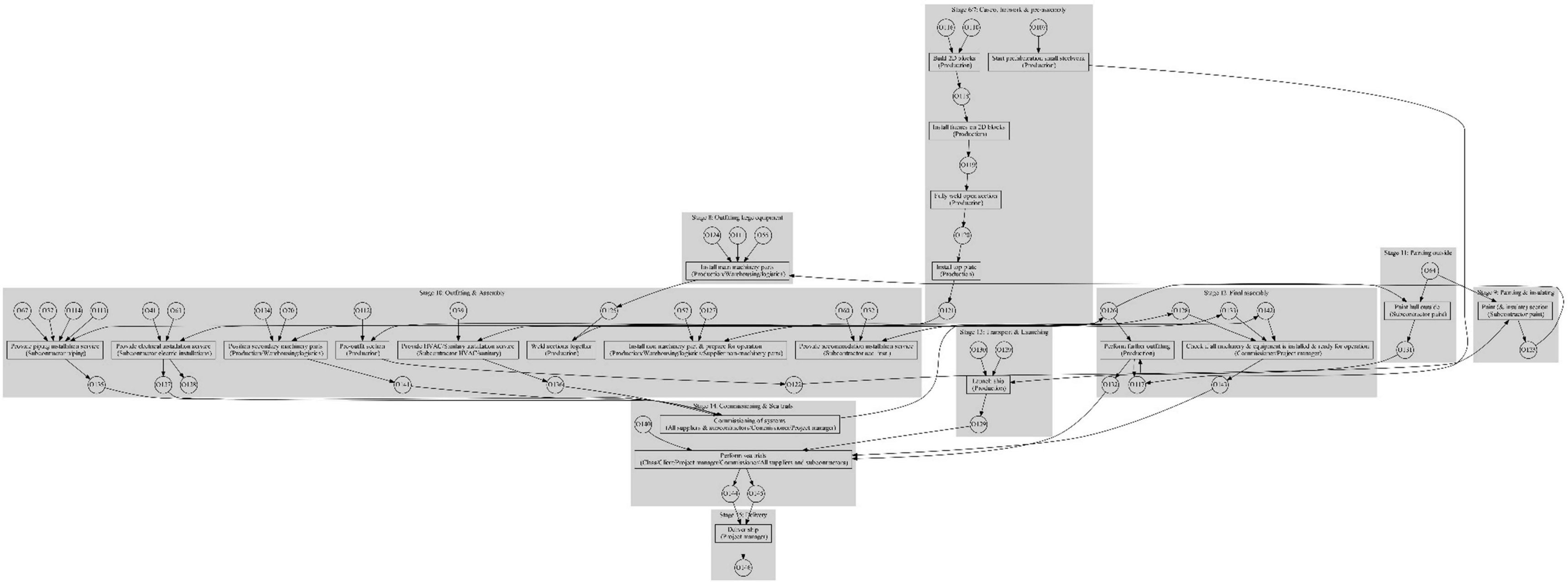
12.7 Conceptual Model – Stage 3/4 Multidisciplinary engineering



12.8 Conceptual Model – Stage 5 Monodisciplinary engineering



12.9 Conceptual Model – Stage 6-15 Production to delivery



Appendices

12.10 List of involved stakeholders project case

Internal stakeholders:

- Management
- Sales
- Engineering
- Project management
- Production
- Warehousing/Logistics/Procurement
- (QHSE)

External stakeholders:

- Client
    - Chemgas
- Class
    - Bureau Veritas
- Engineering/Design
    - Ankerbeer
- Suppliers
    - Nader te bepalen (Liquids)
    - Centraalstaal (steel)
    - Bijma (aluminum floors ER)
    - Blokland (cathodic protection & boxcoolers)
    - Beerens & Winel (doors & aluminum details)
    - TB Shipyards (hatches)
    - Schutte (manholes)
    - Rafa (windows)
    - DMT (winches)
    - Van Wijk (mooring equipment & car crane) (?)
    - Datema (safety equipment)
    - Tukker (workboat)
    - Minimax (firefighting)
    - D&A (diesel electric)
    - Alphatron (navigation & communication)
    - PON (main engines)
    - Van Stigt (gearbox)
    - Scheepsschroeven Kampen (propeller)
    - DMC (propeller nozzle)
    - JCB (generator sets)
    - Discom (exhaust gas silencers)
    - DMC (rudder, steering gear)
    - De Waal (propeller shaft installation
    - Veth (bow thruster)
    - Kampers (liftable wheelhouse)
    - Fendercare (Fendering)

- Subcontractors
    - Belkoned (Sea trials)
    - Intersona (Noise)
    - Kuurman (paint)
    - Admiraal (carpenty and insulation)
    - Breman (HVAC, ventilation & sanitary system)
    - Werkina (electrical equipment) (?)
    - HR Piping (piping)

12.11 Script Simulation

```
#SIMULATION OF THROUGHPUT TIME AND BOTTLENECKS SHIP PRODUCTION PROCESS
#AUTHOR: ESTHER DOUMA
#VERSIONDATE: June 9th 2020
#--------------------------------------------#

#IMPORT REQUIRED PACKAGES
import pandas as pd
import numpy as np
import simpy
from graphviz import Digraph
import timeit

#--------------------------------------------#
#CALCULATE RUNTIME, SET STARTING TIME
start = timeit.default_timer()

#IMPORT DATA FROM EXCEL
from openpyxl import load_workbook
wb = load_workbook("Template_Data_CE.xlsx")

#For Sheet 1: Information Objects
ws1 = wb[wb.sheetnames[0]]
columnA1 = ws1['A']
columnB1 = ws1['B']
columnC1 = ws1['C']
columnD1 = ws1['D']
columnE1 = ws1['E']
columnF1 = ws1['F']
columnG1 = ws1['G']


#For Sheet 2: Processing Activities
ws2 = wb[wb.sheetnames[1]]
columnA2 = ws2['A']
columnB2 = ws2['B']
columnC2 = ws2['C']
columnD2 = ws2['D']
columnE2 = ws2['E']
columnF2 = ws2['F']
columnG2 = ws2['G']
columnH2 = ws2['H']
columnI2 = ws2['I']
columnM2 = ws2['M']
columnN2 = ws2['N']

#Transform data into lists
informationobject_nr = [columnA1[x].value for x in range(len(columnA1))]
informationobject_name = [columnB1[x].value for x in range(len(columnB1))]
informationobject_drawing_nr = [columnC1[x].value for x in range(len(columnC1))]
informationobject_preceding_activities = [columnD1[x].value for x in range(len(columnD1))]
informationobject_resulting_activities = [columnE1[x].value for x in range(len(columnE1))]
informationobject_int_or_ext = [columnF1[x].value for x in range(len(columnF1))]
informationobject_time_present =  [columnG1[x].value for x in range(len(columnG1))]


processingact_nr = [columnA2[x].value for x in range(len(columnA2))]
processingact_name = [columnB2[x].value for x in range(len(columnB2))]
processingact_stakeholder = [columnC2[x].value for x in range(len(columnC2))]
processingact_preceding_informationobjects= [columnD2[x].value for x in range(len(columnD2))]
processingact_resulting_informationobjects = [columnE2[x].value for x in range(len(columnE2))]
processingact_stagegate = [columnF2[x].value for x in range(len(columnF2))]
```

```
processingact_optfinish = [columnG2[x].value for x in range(len(columnG2))]
processingact_probfinish = [columnH2[x].value for x in range(len(columnH2))]
processingact_pessfinish = [columnI2[x].value for x in range(len(columnI2))]

processingact_time_starting = [columnM2[x].value for x in range(len(columnM2))]
processingact_time_ending = [columnN2[x].value for x in range(len(columnN2))]

#--------------------------------------------#
#PLOT DATA
#Remove title row in excel
informationobject_nr.pop(0)
informationobject_name.pop(0)
informationobject_drawing_nr.pop(0)
informationobject_preceding_activities.pop(0)
informationobject_resulting_activities.pop(0)

processingact_nr.pop(0)
processingact_name.pop(0)
processingact_stakeholder.pop(0)
processingact_preceding_informationobjects.pop(0)
processingact_resulting_informationobjects.pop(0)
processingact_stagegate.pop(0)

#Define sources and destinations for creating the network graph
source = []
destination = []

#Put data into source and destination lists, be capable of handling "None" or multiple destinations
#From information objects to activities
for i in range(len(informationobject_nr)):
    if informationobject_resulting_activities[i] != "None" and not "," in informationobject_resulting_activities[i]:
        source.append(informationobject_nr[i])
        destination.append(informationobject_resulting_activities[i])
    if "," in informationobject_resulting_activities[i]:
        multiple = informationobject_resulting_activities[i].split(",")
        for j in multiple:
            source.append(informationobject_nr[i])
            destination.append(j)

#From activities to information objects
for k in range(len(processingact_resulting_informationobjects)):
    if processingact_resulting_informationobjects[k] != "None" and not "," in processingact_resulting_informationobjects[k]:
        source.append(processingact_nr[k])
        destination.append(processingact_resulting_informationobjects[k])
    if "," in processingact_resulting_informationobjects[k]:
        multiple = processingact_resulting_informationobjects[k].split(",")
        for l in multiple:
            source.append(processingact_nr[k])
            destination.append(l)

#Put sources and destinations into dataframe
df = pd.DataFrame({ 'from':source, 'to':destination})

#Create plot by means of Graphviz
e = Digraph('Plot', filename='graphviz_plot.gv', engine='dot')

#Create combined lists for input graph
processingactlist = np.column_stack([processingact_nr, processingact_name, processingact_stakeholder])
informationobjectlist = np.column_stack([informationobject_nr, informationobject_name])

e.attr('node', shape='box')
for number,name,stakeholder in processingactlist:
    e.node(number, label=name+ "\\n ("+stakeholder+")")

```

```
e.attr('node', shape='circle')
for number,name in informationobjectlist:
    e.node(number, label=number, **{'fixedsize':'true'})

df = pd.DataFrame({ 'from':source, 'to':destination})

for index, row in df.iterrows():
    e.edge(row['from'], row['to'], **{'arrowsize':'0.5'})

#Show figure, please make sure the figure has not already been opened in pdf or a permission denied error occurs.
e.view()




#-------------------------------------------#
#MODEL BOTTLENECKS

#Set seed
##seed = np.random.seed(10)

#Remove title row in excel
processingact_optfinish.pop(0)
processingact_probfinish.pop(0)
processingact_pessfinish.pop(0)
processingact_time_starting.pop(0)
processingact_time_ending.pop(0)
informationobject_time_present.pop(0)


#Set number of simulations
throughput_allsimulations = []
bottleneck_result=[]
num_simulations = 1
for number in range(num_simulations):

    #Calculate finish times by means of a Beta-PERT distribution
    "Please note that the excel should contain real integers (so not 1/8) and that most probable-mu is not zero"
    processingact_finish = []
    for i in range(len(processingact_nr)):
        optimal = processingact_optfinish[i]
        most_probable = processingact_probfinish[i]
        pessimistic = processingact_pessfinish[i]
        if most_probable == optimal == pessimistic:
            processingact_finish.append(int(most_probable))
        else:
            mu = (optimal+4*most_probable+pessimistic)/6
            if most_probable-mu == 0:
                alpha = 1+4*((most_probable-optimal)/(pessimistic-optimal))
            else:
                alpha = ((mu-optimal)*(2*most_probable-optimal-pessimistic))/((most_probable-mu)*(pessimistic-optimal))
            beta = (alpha*(pessimistic-mu))/(mu-optimal)
            processingact_finish.append(int(np.random.beta(alpha,beta)*(pessimistic-optimal)+optimal))

    #Check results
    resultscheck = np.column_stack([processingact_nr, processingact_name, processingact_finish])

    #Simulation functions
    import random
    import simpy

    ##duration = None
    alreadystarted = []
```

```python
    available_informationobjects = []
    times = []
    bottleneck_start = []
    bottleneck_cause = []
    bottleneck_victim = []
    bottleneck_stakeholder_victim = []
    bottleneck_stakeholder_cause = []
    finishtimes = []
    lookuplist_preceding = np.column_stack([informationobject_nr,informationobject_preceding_activities])
    lookuplist_stakeholder = np.column_stack([processingact_nr,processingact_stakeholder])

    def create_environment(env):
        #Define all activities as processes
        for i in range(len(processingact_nr)):
            nr = processingact_nr[i]
            name = processingact_name[i]
            stakeholder = processingact_stakeholder[i]

        #Specify duration according to Beta-PERT data
            duration = processingact_finish[i]
            c = execute_activity(env, nr, duration, name, stakeholder)
            env.process(c)

        #Kick-off all processes
        yield env.timeout(0)


    def execute_activity(env,nr,duration,name,stakeholder):
        if any(nr in sublist for sublist in alreadystarted):
            pass
    ##        print("Activity "+nr+" has already been executed or is ongoing")
        else:

            #Check if required information object is available
            requiredlist = np.column_stack([processingact_nr,processingact_preceding_informationobjects])
            presentlist = np.column_stack([informationobject_nr,informationobject_time_present])
            required = []
            multiple_required = []
            multiple_presentlist = []

            #For multiple required objects
            for x,y in requiredlist:
                if nr == x:
                    required.append(y)

                    #For multiple required objects
                    if "," in y:
                        multiple_required = y.split(",")
                        for p in multiple_required:
                            for l,m in presentlist:
                                if p == l:
                                    multiple_presentlist.append(m)

            #For multiple required objects
            if multiple_required:

                if all (g in available_informationobjects for g in multiple_required) or all (h is not None for h in multiple_presentlist):
    ##                print("Activity %s started at %d" % (nr,env.now))

                    #Document that the activity has started so it will not start again
                    alreadystarted.append([nr,env.now])

                    #Execute activity
                    yield env.timeout(duration)
    ##                print('Activity '+nr+" finished at "+str(env.now))
```

```
                    finishtimes.append([nr,env.now])

                    #Release information objects
                    resultinglist = np.column_stack([processingact_nr,processingact_resulting_informationobjects])
                    for a,b in resultinglist:
                        if nr == a:
                            resulting = b

                            #For multiple resulting information objects, split by comma
                            if "," in resulting:
                                multiple_resulting = [x for x in resulting.split(",")]
                                for c in multiple_resulting:
                                    #Create list for results
                                    available_informationobjects.append(c)
                                    times.append(env.now)
    ##                                print('Information Object '+c+' becomes available at '+str(env.now))

                            #For single resulting information objects
                            else:
                                available_informationobjects.append(resulting)
                                times.append(env.now)
    ##                            print('Information Object '+resulting+' becomes available at '+str(env.now))

                            #Start simulation again with newly obtained information objects
                            yield env.process(create_environment(env))

                #Register bottleneck actvities
                elif any (g in available_informationobjects for g in multiple_required):
    ##                print("Activity "+ nr+"is waiting for all information objects to appear")
                    for i in multiple_required:
                        if i not in available_informationobjects:
                            #Get precedent activity
                            for x,y in lookuplist_preceding:
                                if i == x:
                                    #make sure bottleneck cause is only registered once:
                                    if y not in bottleneck_cause:
                                        bottleneck_start.append(env.now)
                                        bottleneck_cause.append(y)
                                        bottleneck_victim.append(nr)
                                        bottleneck_stakeholder_victim.append(stakeholder)
                                        if y == "None":
                                            bottleneck_stakeholder_cause.append("No stakeholder")
                                        elif "," in y:
                                            bottleneck_stakeholder_cause.append("Multiple stakeholders")
                                        else:
                                            for k,l in lookuplist_stakeholder:
                                                if k == y:
                                                    bottleneck_stakeholder_cause.append(l)


            #For single required objects
            else:
                for i,j in presentlist:
                    for y in required:
                        if y == i:
                            if i in available_informationobjects or j is not None:
    ##                            print("Activity %s started at %d" % (nr,env.now))

                                #Document that the activity has started so it will not start again
                                alreadystarted.append([nr,env.now])

                                #Execute activity
                                yield env.timeout(duration)
    ##                            print('Activity '+name+" finished at "+str(env.now))
```

```
                                finishtimes.append([nr,env.now])


                                #Release information objects
                                resultinglist = np.column_stack([processingact_nr,processingact_resulting_informationobjects])
                                for a,b in resultinglist:
                                    if nr == a:
                                        resulting = b

                                        #For multiple resulting information objects, split by comma
                                        if "," in resulting:
                                            multiple_resulting = [x for x in resulting.split(",")]
                                            for c in multiple_resulting:
                                                #Create list for results
                                                available_informationobjects.append(c)
                                                times.append(env.now)
    ##                                            print('Information Object '+c+' becomes available at '+str(env.now))

                                        #For single resulting information objects
                                        else:
                                            available_informationobjects.append(resulting)
                                            times.append(env.now)
    ##                                        print('Information Object '+resulting+' becomes available at '+str(env.now))

                                        #Start simulation again with newly obtained information objects
                                        yield env.process(create_environment(env))


    #SET UP AND START SIMULATION
    print('Start Simulation '+ str(number))
    ##random.seed(seed)
    env = simpy.Environment()

    # Start processes and run
    env.process(create_environment(env))
    env.run()

    #PRINT OUTPUT DATA
    print("")
    total_throughput = env.now
    print('The total throughput time is '+str(total_throughput)+ ' days.')
    print("")

    # Bottleneck & stakeholder waiting times
    bottleneck = np.column_stack([bottleneck_cause,bottleneck_victim,bottleneck_start, bottleneck_stakeholder_victim, bottleneck_stakeholder_cause])
    for u,v,w,z,a in bottleneck:
        for x,y in finishtimes:
            if u==x:
    ##            print("Activity "+ v+" had to wait "+str(int(y)-int(w))+" days for Activity "+u+" to finish")
                bottleneck_result.append([v,str(int(y)-int(w)),u,z,a])

    #Store output data of all simulations and save into txt file
    throughput_allsimulations.append(["Simulation "+str(number), total_throughput, bottleneck_result])


# Print runtime of script
stop = timeit.default_timer()
print("Runtime of script is", stop-start)

# Save all output data into one txt file

```

```
txtfile = open("results_experiment1_3.txt","w")
for row in throughput_allsimulations:
    for elements in row:
        txtfile.write("%s\n" %str(elements))
txtfile.close()

txtfile = open("results_experiment1_3.txt","w")
for row in bottleneck_result:
    for elements in row:
        txtfile.write("%s\n" %str(elements))
txtfile.close()
```

12.12 Notes for successful script execution

Step 1: Download Python. A free and save download of Python may be found here: https://www.python.org/downloads/

Step 2: Install the required packages. This can be done via the Python package installer (pip) which is automatically installed when downloaded Python 3.8 via de last step. Open windows command prompt (as administrator) and type pip install [package]. For this script, install the following packages:

```
pip install pandas

pip install numpy

pip install simpy

pip install graphviz

pip install timeit
```

Step 3: After having installed the packages, the script should work. Open the script by clicking on the python file with the left-mouse and choose "Edit with IDLE" (if the option shows, choose IDLE 3.8). The IDLE window allows to read and modify the script.

Step 4: Check if the input excel file is in the same folder as the Python script and that the name of the file equals the name in the script at line 21.

Step 5: Check whether the number of simulations as specified in line 161 of the code equals the amount of simulations that you want to run. From this report, 256 simulations are expected to give reliable results.

Step 6: Check if the output txt file names are as desired. If the script is run multiple times, please make sure to change the names or the results will be overwritten.

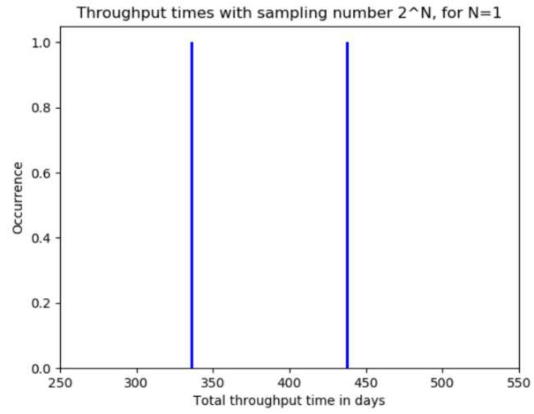
Step 7: Start the script by saving it first (CTRL+S) and press F5.

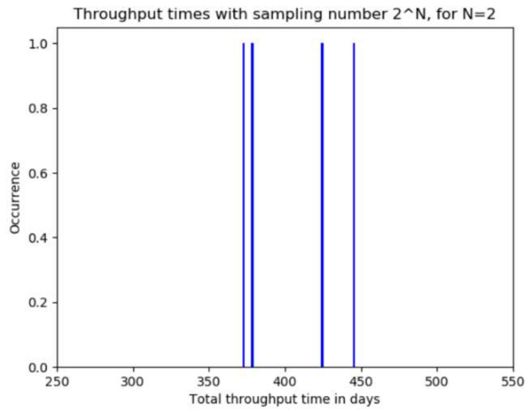
Step 8: Wait for the script to finish and analyse the results with another Python script or excel.

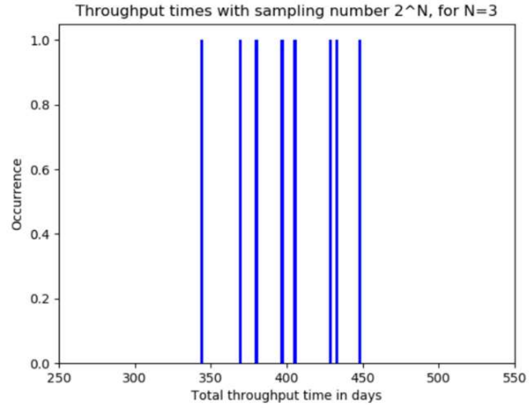
Common occurring errors:

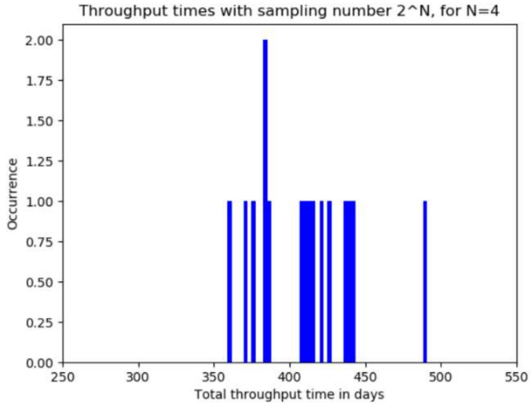
- Err no 13: Permission denied error: Occurs when the excel input file or pdf graph file is opened and the script is not allowed to overwrite it.
- TypeError (can only concatenate str (not "int") to str: Occurs when in the excel input file the finishing times are not correctly filled in. Make sure that the finishing times are real numbers (5) or floats (5.0) and no strings ("none") or blanks or sums in excel (=1*5).
- TypeError (argument of type 'NoneType' is not iterable): Occurs when in the excel input file additional text is written below the data

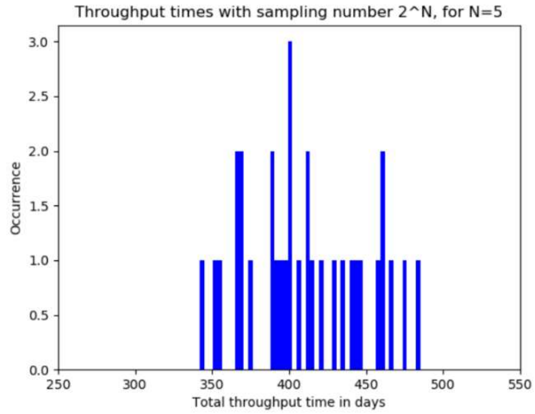
12.13 Results Monte Carlo Sampling optimization

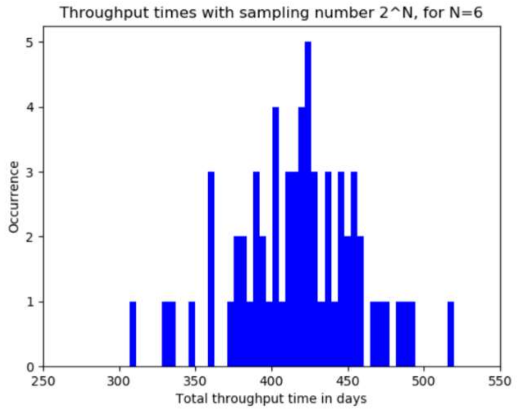


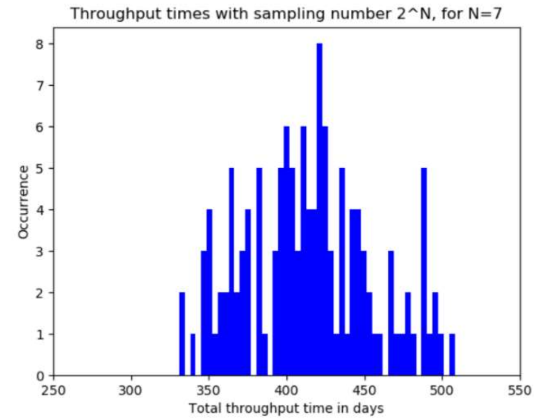


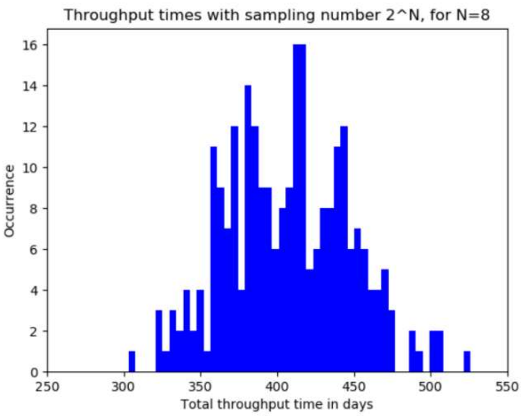


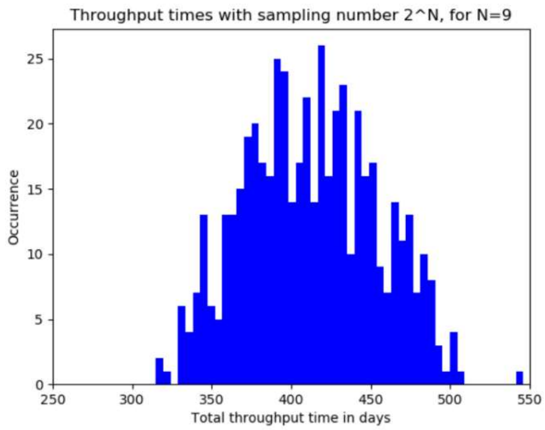


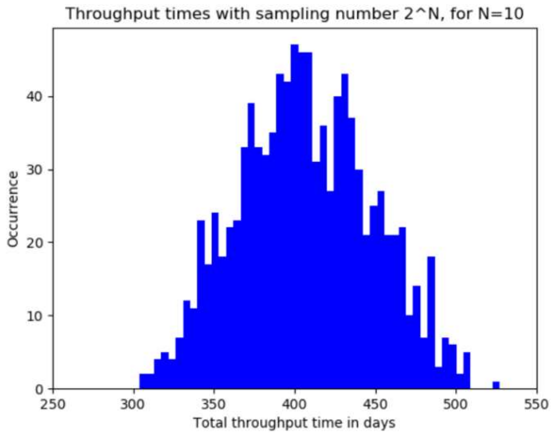


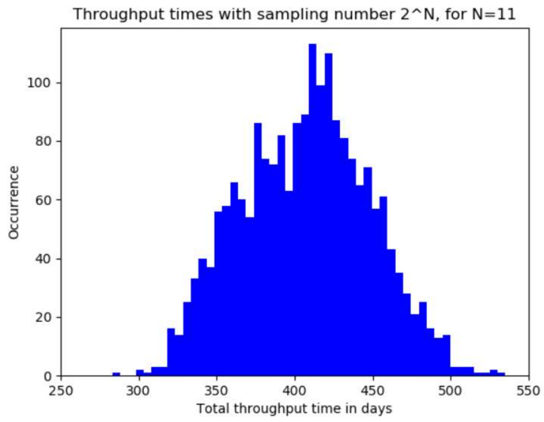


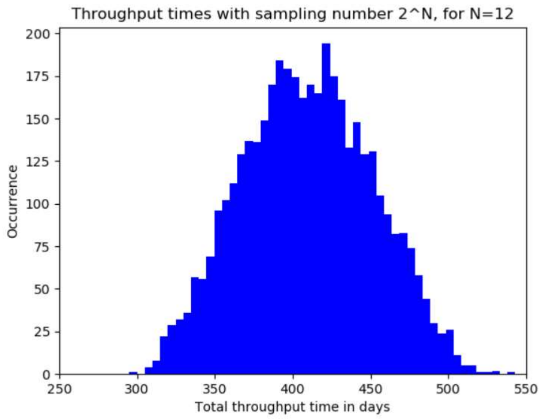

Throughput times with sampling number 2^N, for N=7


Throughput times with sampling number 2^N, for N=8

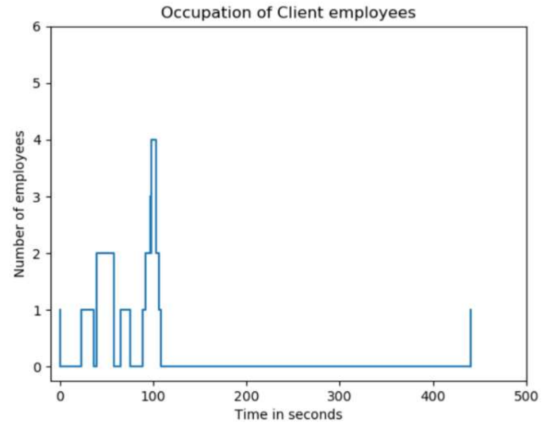

Throughput times with sampling number 2^N, for N=9

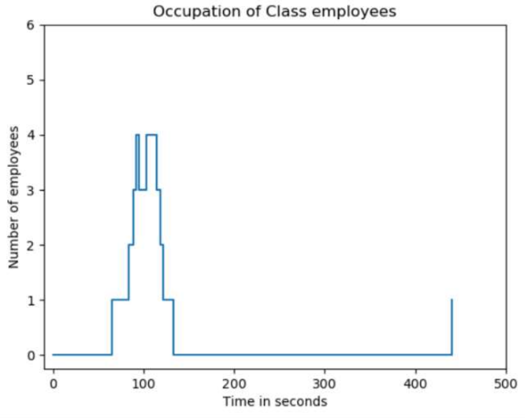

Throughput times with sampling number 2^N, for N=10

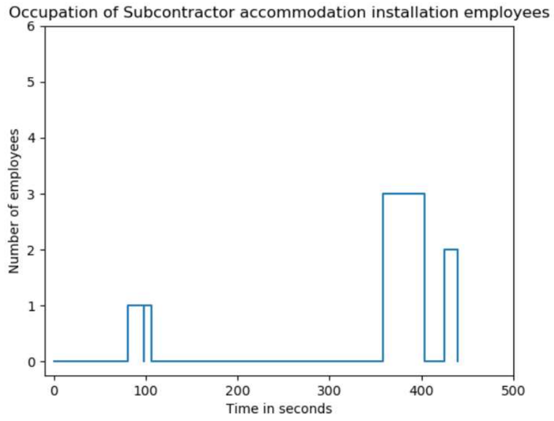

Throughput times with sampling number 2^N, for N=11

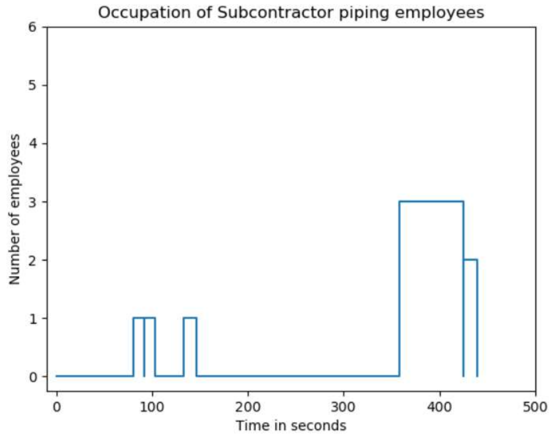

Throughput times with sampling number 2^N, for N=12

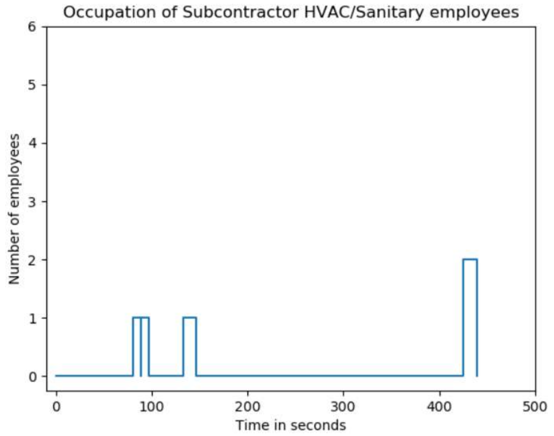
12.14 Results stakeholder assumption test

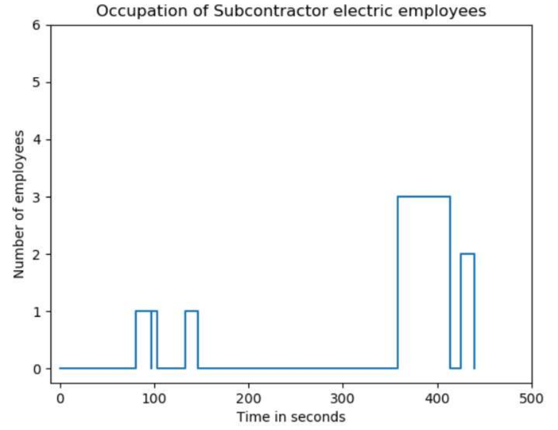


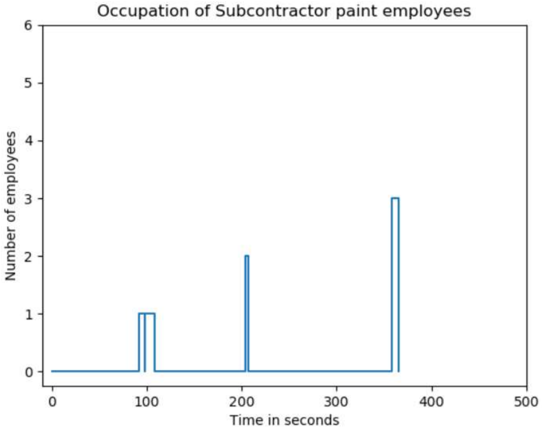


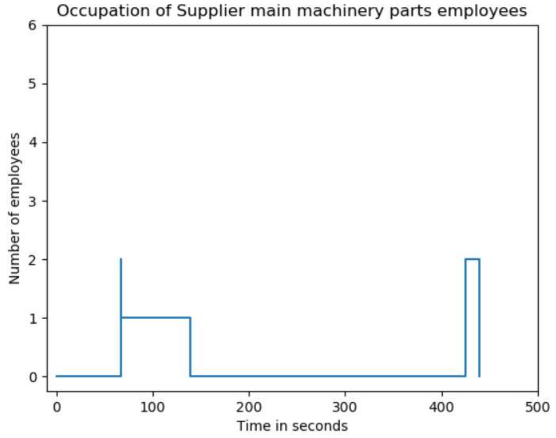


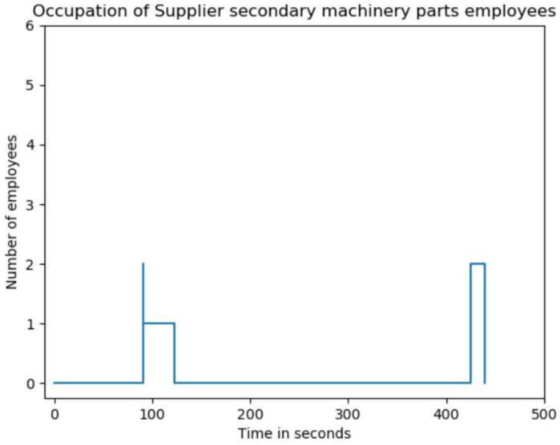


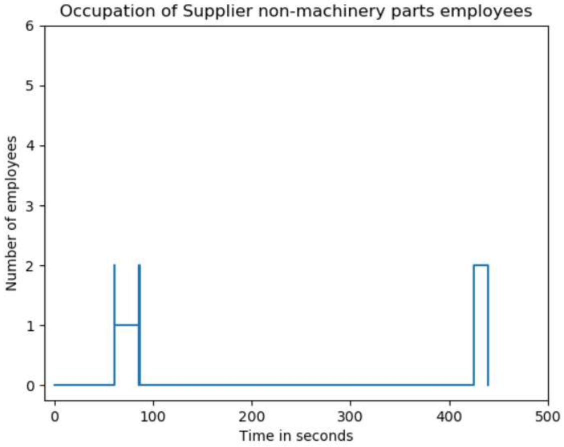


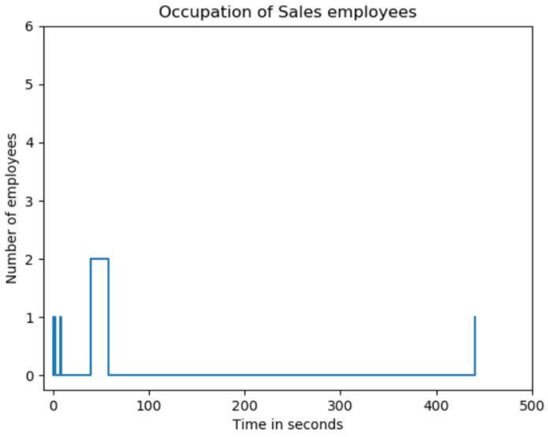

Occupation of Subcontractor electric employees
Number of employees
Time in seconds
0
1
2
3
4
5
6
0
100
200
300
400
500

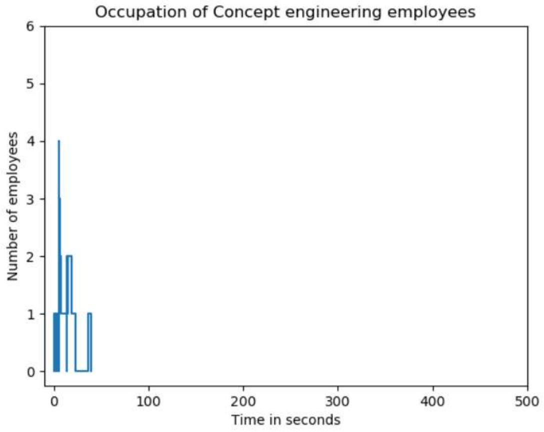

Occupation of Subcontractor paint employees
Number of employees
Time in seconds
0
1
2
3
4
5
6
0
100
200
300
400
500

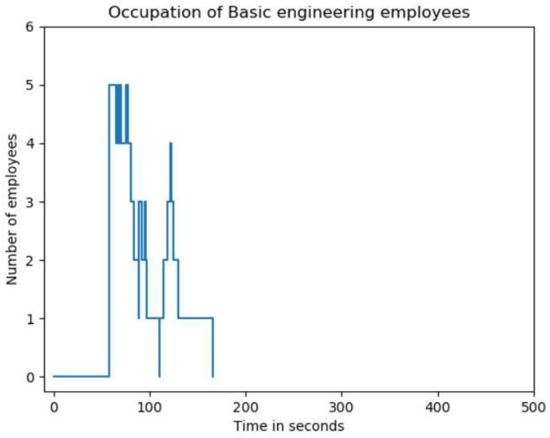

Occupation of Supplier main machinery parts employees
Number of employees
Time in seconds
0
1
2
3
4
5
6
0
100
200
300
400
500


Occupation of Supplier secondary machinery parts employees
Number of employees
Time in seconds
0
1
2
3
4
5
6
0
100
200
300
400
500

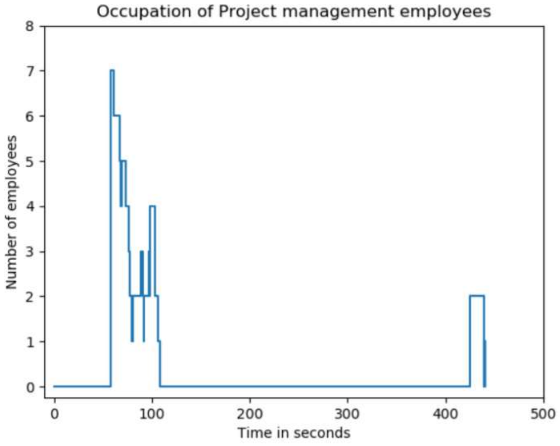

Occupation of Supplier non-machinery parts employees
Number of employees
Time in seconds
0
1
2
3
4
5
6
0
100
200
300
400
500

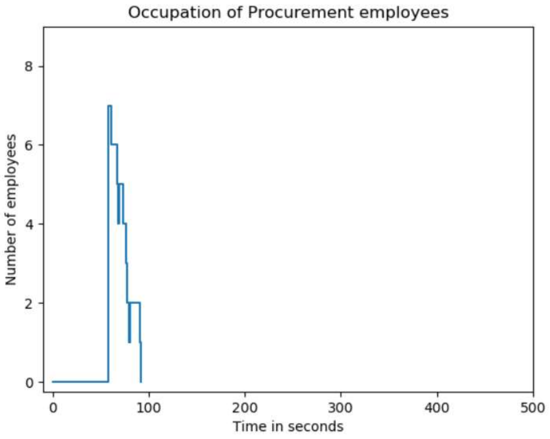

Occupation of Sales employees

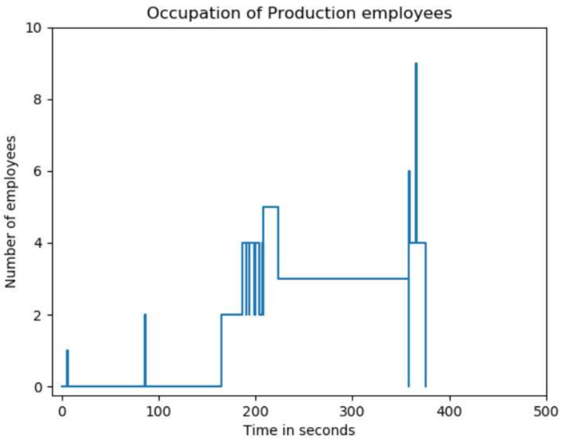

Occupation of Concept engineering employees

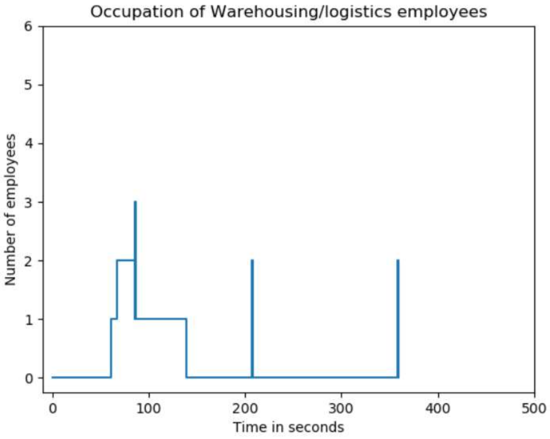

Occupation of Basic engineering employees

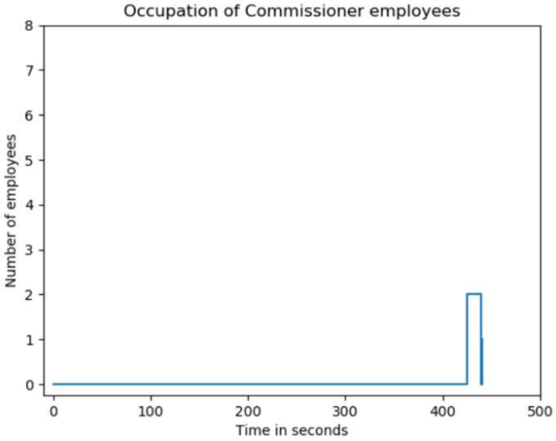

Occupation of Detail engineering employees


Occupation of Project management employees


Occupation of Procurement employees


Occupation of Production employees
Number of employees
Time in seconds
0
2
4
6
8
10
0
100
200
300
400
500


Occupation of Warehousing/logistics employees
Number of employees
Time in seconds
0
1
2
3
4
5
6
0
100
200
300
400
500


Occupation of Commissioner employees
Number of employees
Time in seconds
0
1
2
3
4
5
6
7
8
0
100
200
300
400
500

12.15 Summary results experiment 1

Nr.	Name	Stakeholder	Waiting time in days	A5=0	A7=0	A9 = 0	A12 = 0	A14=0	A20=0	A21 = 0	A22=0	A28=0	A30=0	A31=0	A33=0	A34=0	A35=0	A36=0	A38=0	A43=0	A44=0	A46=0	A49=0	A50=0
A12	Check stability	Concept engineering	5	0	0	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
A14	Summarize and update	Concept engineering	3	5	5	5	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
A15	Client shows interest for further engineering & building and provides feedback	Client	13	14	14	13	12	4	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
A27	Create system diagrams for main piping	Subcontractor piping	9	9	9	9	9	9	17	8	9	9	10	10	10	10	9	10	9	10	9	16	9	9
A28	Create system diagrams for HVAC/Sanitary	Subcontractor HVAC/San	12	12	12	12	12	12	11	16	12	12	13	12	13	13	13	12	13	13	13	15	12	12
A29	Create electrical diagrams	Subcontractor electric	9	10	10	10	10	10	10	10	9	10	10	10	10	10	10	10	10	10	10	15	10	15
A37	Update propulsion configuration	Basic engineering	26	26	26	26	26	26	27	25	27	15	26	26	26	26	26	27	26	27	27	22	26	26
A38	Create arrangement/equipment foundation drawings	Basic engineering	4	5	5	5	5	5	4	0.4	0.8	5	4	5	4	4	4	5	4	4	4	0	5	1
A39	Create additional outfitting drawings	Detail engineering	42	43	43	42	43	43	42	43	43	42	42	42	42	42	42	43	34	43	42	35	40	42
A41	Approve diagrams	Class	6	6	6	6	6	6	7	6	6	11	6	6	6	8	8	9	6	6	6	10	6	6
A45	Create refined routing	Detail engineering	15	15	15	15	15	14	15	15	15	15	15	15	15	15	16	16	11	28	14	17	16	14
A55	Create initial structural model	Basic engineering	5	6	6	5	5	5	5	5	6	5	5	6	5	5	5	5	21	5	5	5	5	5
A65	Update structure part of model	Detail engineering	12	13	13	13	13	13	13	13	12	13	13	13	14	13	13	13	15	13	14	13	14	13
A73	Request tenders for steel delivery	Project management/Procurement	2	3	3	3	3	3	3	3	1.4	3	3	3	3	3	3	3	3	3	3	1	10	7
A74	Cut & deliver steel	Steel supplier	88	90	90	89	89	89	89	89	90	89	89	89	89	89	90	90	85	89	88	89	90	91
A76	Build 2D blocks	Production	13	14	14	13	13	13	13	14	14	13	13	13	13	13	13	14	14	13	13	13	14	14
A80	Pre-outfit section	Production	41	41	41	41	41	41	41	41	41	41	41	41	41	41	41	42	41	41	41	41	41	42
A81	Paint (& insulate) section	Subcontractor paint	112	114	114	113	113	113	112	114	113	113	112	113	112	113	113	114	108	113	113	113	113	113
A83	Install main machinery parts	Production/Warehousing/logistics	120	122	122	120	120	122	121	121	122	120	121	121	120	120	122	121	118	121	120	120	121	119
A86	Install non machinery part & prepare for operation	Production/Warehousing/logistics/Supplier non-machinery parts	20	20	20	20	20	21	21	21	21	20	20	21	20	20	20	20	20	21	20	21	20	21
A89	Provide accommodation installation service	Subcontractor acc. inst.	68	76	76	75	68	80	19	19	19	72	75	76	67	75	77	72	72	73	72	31	79	72
A91	Provide piping installation service	Subcontractor piping	118	118	118	122	118	117	176	73	94	120	115	115	115	119	119	118	119	110	124	96	114	122
A92	Provide HVAC/Sanitary installation service	Subcontractor HVAC/sanitary	177	177	177	182	181	178	0	219	131	179	180	183	179	178	174	174	181	178	175	138	168	184
A93	Provide electrical installation service	Subcontractor electric installations	72	79	79	63	81	67	24	24	166	72	73	71	79	71	79	73	71	79	73	29	82	67
A95	Position secondary machinery parts	Production/Warehousing/logistics	38	37	37	38	38	38	39	38	38	38	38	37	39	38	37	38	38	38	38	149	38	39
A96	Commissioning of systems	All suppliers & subcontractors/Commissioner/Project manager	53	53	53	53	53	53	53	53	53	53	53	53	53	53	53	53	53	53	53	53	53	53
A98	Perform sea trials	Class/Client/Project manager/Commissioner/All suppliers and subcontractors	53	53	53	52	52	52	52	53	53	53	52	52	53	52	52	53	53	51	52	53	52	52
A88																						
			🟩	reduction																		
			🟨	no increase or reduction																		
			🟥	increase																		

Nr.	Name	Stakeholder	Waiting time in days	A51=0	A57=0	A61=0	A62=0	A63=0	A67=0	A69=0	A71=0	A74=0	A79=0	A80=0	A81=0	A82=0	A84=0	A85=0	A90=0	A91=0	A92=0	A93=0	A97=0
A12	Check stability	Concept engineering	5	5	5	5	6	5	5	5	6	5	5	5	5	5	5	5	5	5	6	5	5
A14	Summarize and update	Concept engineering	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
A15	Client shows interest for further engineering & building and provides feedback	Client	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
A27	Create system diagrams for main piping	Subcontractor piping	9	9	9	9	9	9	9	10	10	9	9	9	9	9	10	9	9	10	9	9	9
A28	Create system diagrams for HVAC/Sanitary	Subcontractor HVAC/San	12	12	13	13	12	13	12	13	13	12	12	13	13	13	13	12	12	13	12	13	13
A29	Create electrical diagrams	Subcontractor electric	9	10	9	10	10	10	10	9	10	10	10	10	10	10	11	10	10	10	10	10	10
A37	Update propulsion configuration	Basic engineering	26	26	26	26	26	27	26	26	26	26	26	26	27	26	26	26	27	27	26	26	26
A38	Create arrangement/equipment foundation drawings	Basic engineering	4	5	5	4	4	4	4	5	4	5	5	4	5	4	5	5	4	4	5	4	5
A39	Create additional outfitting drawings	Detail engineering	42	42	🟨 42	🟨 40	42	42	42	43	42	43	42	42	42	42	42	42	42	42	43	42	42
A41	Approve diagrams	Class	6	6	6	5	6	6	6	6	6	6	6	5	6	6	6	6	6	6	6	6	6
A45	Create refined routing	Detail engineering	15	15	15	16	🟩 0	15	15	15	15	14	15	15	14	14	15	15	15	15	16	15	16
A55	Create initial structural model	Basic engineering	5	🟥 19	6	6	5	5	5	5	5	5	5	5	5	5	5	5	5	5	6	5	6
A65	Update structure part of model	Detail engineering	12	5	13	13	13	🟩 6	13	13	13	13	14	14	13	13	13	13	13	14	12	13	13
A73	Request tenders for steel delivery	Project management/Procurement	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
A74	Cut & deliver steel	Steel supplier	88	88	90	85	89	87	🟩 77	89	89	89	89	89	88	88	90	89	89	89	90	89	88
A76	Build 2D blocks	Production	13	14	14	13	13	14	3	13	13	🟨 12	14	14	13	14	14	14	14	14	14	14	13
A80	Pre-outfit section	Production	41	42	41	41	41	41	30	41	41	28	🟨 40	41	41	41	42	41	42	41	41	41	40
A81	Paint (& insulate) section	Subcontractor paint	112	111	114	108	113	111	101	112	112	99	111	🟨 108	112	113	114	113	112	112	113	113	111
A83	Install main machinery parts	Production/Warehousing/logistics	120	120	121	119	120	120	117	🟨 112	121	116	121	120	🟨 119	🟩 86	120	120	122	121	121	121	121
A86	Install non machinery part & prepare for operation	Production/Warehousing/logistics/Supplier non-machinery parts	20	20	20	21	21	20	21	21	20	20	21	21	20	21	20	🟩 0	21	21	20	20	20
A89	Provide accommodation installation service	Subcontractor acc. inst.	68	66	69	72	70	74	67	74	78	72	72	84	73	60	🟩 49	71	78	73	75	80	74
A91	Provide piping installation service	Subcontractor piping	118	120	117	112	117	121	119	116	🟩 100	116	120	114	118	119	🟩 99	119	120	117	119	119	122
A92	Provide HVAC/Sanitary installation service	Subcontractor HVAC/sanitary	177	177	176	178	181	179	180	174	🟩 147	173	175	177	178	180	🟩 136	180	177	174	180	173	183
A93	Provide electrical installation service	Subcontractor electric installations	72	76	85	73	66	66	71	78	72	69	71	68	77	74	🟩 45	71	69	76	69	68	69
A95	Position secondary machinery parts	Production/Warehousing/logistics	38	39	38	38	37	38	38	37	37	38	39	38	38	37	37	39	🟩 0	37	37	38	36
A96	Commissioning of systems	All suppliers & subcontractors/Commissioner/Project manager	53	53	53	53	53	53	53	53	53	53	53	53	53	53	54	53	53	🟩 37	🟩 37	🟩 37	53
A98	Perform sea trials	Class/Client/Project manager/Commissioner/All suppliers and subcontractors	53	52	52	53	52	53	53	52	52	52	53	52	51	53	35	53	53	51	50	50	🟨 51
A88															20					1	
			🟩	reduction																	
			🟨	no increase or reduction																	
			🟥	increase																	