How mature are your lead time estimations?

The proposal of a planning and estimation maturity framework for the maritime industry.

by

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to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Wednesday December 4, 2019 at 10:00 pm.

Student number:	4106121	
Report number:	SDPO.19.029.M.	
Project duration:	Feb 4, 2019 – December 4, 2019	
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Abstract

During the start of a project, organisations make an estimation on the expected amount of work and the corresponding project duration, also known as the lead time. An organisation strives to make this lead time estimation with the lowest amount of uncertainty. Falsely estimating the lead time can result in project delay and cost overruns. Therefore, it is important to make these estimations with a low uncertainty, but how can an organisation make these lead time estimations? That is the main research question of this thesis. *How to estimate ship production lead times with the lowest possible level of uncertainty.*

To answer this question, a maturity framework is proposed which gives organisations a way of establishing which lead time and man-hour estimations methods to use that fit their maturity. The frameworks are called the *estimation pyramid* and the *planning pyramid*. Both pyramids contain different maturity levels that correspond to the maturity of an organisation. For example, if the organisation is well established and has a lot of historical data, more estimation and planning methods are possible, in contrast to an organisation with little to no historical data. Performing a maturity level higher than the maturity of the organisation could lead to estimations with a higher uncertainty due to lacking data. Table 1 presents the maturity levels of the two frameworks. The two frameworks are used together in this thesis, which means that the *estimation pyramid* will provide man-hour estimations from which the lead time is determined. The validity of the proposed frameworks is tested using Royal van Lent shipyards (RvLs) as case study. The maturity of RvLs is assessed to be level two for the *estimation pyramid* and a combination of level one, two and three for the *planning pyramid*. To test the assumption that a maturity level higher than the maturity of the organisation could lead to result with a high uncertainty, the preceding maturity level is included in the analysis. Levels 1, 2, and 3 are examined for both frameworks. The lead time of two reference vessels are estimated. These estimations are compared to the actual man hours and base-line lead times for those vessels.

Table 1: Maturity levels estimation and planning pyramid.

level	*Estimation pyramid*	Method	*Planning pyramid*	Method
1	CGT	CGT	Analogical	Expert
2	Analogical	Expert	Resource inclusion	Lead time
3	Data driven	Parametric	Network phase	Critical path
4	Rapid engineering	Automated design	Data driven	Pert/Monte Carlo
5			Risk	Event chain
6			Optimisation	Smart routing

The results of the *estimation pyramid*, *planning pyramid* and their alignment will be discussed separately. The case study of *estimation pyramid* showed that level 1 *CGT* resulted overall in the highest uncertainty. Level 3 *data driven* does not perform better than level 2 *analogy* which is in line with the hypothesis that if an organisation's data are not sufficient, the same or inferior results can be expected.

The *planning pyramid* showed that the higher maturity levels resulted in a more realistic planning. To translate man-hours to lead time it was found that one craftsman per 8$m^2$2 of vessel floor space is a good starting point. The analysis also showed that the lead time does not need to increase with increased vessel size because more personnel can work simultaneously, assuming there are no other bottlenecks.

The analysis on the combination of the frameworks gave the following observations. CGT man-hour estimations can be seen as the method which gave the highest uncertainty. However, level 2 *analogical* did not perform better than level 3 *data drive*, this was because the estimated parameters differed. The man-hours estimation of *analogical* where better but due to the miss alignment. The lead time results are worse than level 3. With the above presented analysis the answer to the research question is:

Estimating lead times with the lowest possible level of uncertainty is achieved by selecting the correct estimation method corresponding to the maturity of the organisation, and by aligning the *estimation pyramid* and *planning pyramid* based on maturity and estimation parameters.

Preface

Before you lies the thesis *"How mature are your lead time estimations?"* where I investigated different planning and man-hour estimation methods and their relations to the capabilities of an organisation. This thesis is written to obtain the degree Master of Science at the Delft University of Technology. This research was performed at Royal van Lent Shipyards, a world renown Dutch super yacht manufactured. This research was performed under the supervision of Dr. Ir. Jeroen Pruyn of the TU Delft and Nick Mallee at Royal van Lent Shipyards.

This thesis started out as an investigation what effect a super yachts of 140+ meters would be on your production times and how this would affect the critical path. Royal van Lent shipyard had just finished their new dry dock that can accommodate super yachts up to 160 meters. During my research into estimation methods it became apparent that their is actually not a guideline for the maritime industry how to make such estimations. Estimations can be done in a lot of different ways, but what is the best method for an organisation? Is the experts opinion just fine or do you need a computer simulation. During that stage I changed the scope of this thesis to the proposal of a planning and man-hour estimation maturity model for the maritime industry. Because this would be the first time such a model was implemented at RvLs, the investigation into larger yachts was left out of this thesis. First, the model needed to be tested on an inbound estimation on the validity. With this maturity framework I think it could give maritime organisation a guidance how to improve their lead time estimations. So next time someone wants to know how to make the best lead time estimation, they can lookup this thesis and see what methods are the best for his or her organisation.

During my research I gained a lot of insight into estimation and planning methods. What I found interesting was that when you look at these methods first glance you think it is straight forward. But in reality it is not as easy as it seems, an a simple "How long thus that take" can result in long discussion about the wide range of possibilities.

I would like thank J.Pruyn for his support and insights which improved this thesis every time. From RvLs it would like to thank Nick Mallee as my supervisor, he really helped me in understanding the company and their practises. Besides Nick I would like to thank all the other RvLs employees for letting me see all the aspects and Joey Koeckhoven for showing me a day the live of a craftsman.

Lastly, I would like to thank my girlfriend, family and friends for their support feedback and advised during these months.

Hopefully you will gain some insights from this thesis and the next time you need to make an estimation or a planning you will think back at this thesis and think how certainty methods can be used to make it even better.

I hope you enjoy your reading.

T.J.P Bregt
Delft, September 2019

Definitions

This page gives a overview of specific definitions and abbreviations used in this thesis.

Definitions

Maturity The quality and professionality of the people, processes, technology and data available at the organisation.

Framework Structure or system to realise a specific goal, a framework might contain multiple models to reach that goal.

Lead time The time between initiation and completion of a task,

Man-hour Time indication of the amount of work for one person in one hour.

Super structure Mostly the top half, on top of the hull, of a super yacht.often constructed from aluminium in the case of super yachts.

Vessel component Part or combinations of part of a super yacht, e.g. casco or all the electrical systems. In this thesis the hours to build this component or components is used.

Outbound An outbound estimation is an estimation with specification not within the data set,e.g an extrapolation.

Inbound An inbound estimation is an estimation with specification within the data set, e.g an interpolations.

Uncertainty Uncertainty is defined as an error range of the estimation. However, in this thesis the term *uncertainty* is also used to indicate the found error during the case study. This is done to keep the terminology consistent because in reality a fixed error for an estimation is not expected but a possible range.

Abbreviations

RvLs Royal van Lent shipyards

CGT Compensated gross tonnage

CER Cost estimation relationships

LOA Length overall

TLT Total lead time

LT Lead time

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1 Introduction

On Thursday the 16th of May, Máxima Zorreguieta officially opened the new yard of Royal van Lent shipyards (RvLs)[1]. This new shipyard in Amsterdam has a dry dock 160 meters long, capable of housing two 80 meter super yachts or one of 160 meters. This addition can double the number of ships RvLs produces simultaneously. The duration a vessel occupies a dock space is determined by its lead time, which is defined as *"the time between the initiation and completion of a production process"*[2]. This dock space is a valuable asset of RvLs, if a customers wants to buy a new vessel, but it RvLs is not certain the dock space will be available in order to deliver the vessel on time, the customer might go to the competition. Therefore knowing the exact lead time of the production of a vessel could mean that RvLs could schedule vessels quicker after another and therefore optimise its dock availability. But how can an organisation, like RvLs, estimate these lead time with a low uncertainty? And is this uncertainty dependent on the maturity of the organisation?

This chapter presents the introduction to the research study. It will first provide an inside into the problem statement and the purpose why this research was performed. It will give the reader a first glimpse into lead times estimations. This will result in the research objective and scope of this thesis.

1.1. Problem statement

This section will explore the problem statement in more detail. First, this section presents why correct lead times can aid in optimising the dock space and why having a good lead time estimation can aid the organisation in general. Secondly, it will investigate how the estimate good lead times. Finally, the concept of organisational maturity will be introduced and how this could aid creating lead times with an uncertainty as low as possible.

1.1.1. Why correct lead times are crucial

RvLs wants to optimise the occupation of its docks. For this optimisation it first needs to be able to estimate lead times with a low uncertainty. This section first presents why a correct lead time is needed for optimisation. Secondly, it presents why correct lead time estimations are essential for generally managing the organisation.

The lead time of a vessel dictates when the subsequent vessel can start the production. If the vessel is delayed, the subsequent vessel cannot enter the dock and is consequently also delayed. To mitigate this risk, additional lead time is added to the total lead time as buffer. RvLs also owns a dock which can accommodate the production of two ships simultaneously, while having only a single exit. For production in this dock it is imperative that the vessel closest to the exit is finished first. Failure to do so will result in the launch having to be delayed due to the exit being physically blocked by the other later vessel.

These dock slots are reserved years before the actual ships are build. Incorrectly estimating the lead time at the start of a project can thus have big consequences years later. Therefore, if lead times can be estimated with a high certainty, the dock occupation can be better estimated and optimised. Effectively this allows

[1] Royal van Lent's (RvLs) roots date back to 1849. It originally started as a small family run business that made barges for potato's (RvLs, HRM). This changed to making custom yachts and in 1949 in Café De Roode Leeuw Feadship was born. Feadship stands for, ***F****irst* ***E****xport* ***A****ssociation of* ***D****utch* ***ship****builders.* This was a mix of five different shipyards in the Netherlands that united to have a stronger brand in America.

the finish date of a vessel and the start date of production of the next vessel to be placed closer to each other, decreasing contingency time reserved for possible construction delays. Also, if there is an empty slot between two vessels this time can be perfectly filled with a yacht re-fit, but only if RvLs is certain it will not influence the starting time of the vessel after it.

Another aspect of why having lead times with a high certainty is that the affect of new building strategies can be better analysed. The affects of production outsourcing, skid/modular building, building strategies, etc. can be better evaluated if the organisation can accurately determine the lead time. For example, if there is an uncertainty of ±20% in the lead time estimation a possible improvement could not be noticed in the lead time calculation. Another factor is that accurately knowing what influences the lead time could give insight in what production steps have the biggest impact on this lead time. This could aid in making strategic decisions what productions processes need to be improved to have the biggest impact. These are two optimisation examples that need an accurate lead time estimation as input. Not only RvLs but other organisations could benefit from accurately knowing the lead time as well, because one should always strive to further improve their production to stay ahead of the competition.

Having a low uncertainty estimation does not only give access to optimisation possibilities, but is also crucial for generally managing the organisations itself. A company such as RvLs possesses multiple dry docks spaces, four in total. This means vessels are being produced simultaneously, each potentially in a different phase, one vessel. One vessel could be in the outfitting phase when another vessel is almost completed and receives its interior. Different phases require different craftsmen and different resources, these resources need to be evenly distributed over the year, e.g the carpentry craftsmen need an even work load over the year, having them without work costs a lot of money. RvLs always strives to balance these resources evenly over the year, as it does not want to send its craftsmen home.

Another factor is that if a vessel is delayed more resources (craftsmen) are needed to meet the original deadline. This could result in another vessel being delayed because it does not receive the required resources. One can imagine that this second vessel also has the also is in the risk of being delayed because it does not receive the resources needed and the circle continues. RvLs can hire external personnel to balance these dips and peaks but these fluctuations ideally need to be known before hand. Knowing the lead time of a vessel with a low uncertainty, RvLs is capable of better estimating the resources needed over the year.

Making lead times with a low uncertainty is thus essential in order to plan the dock occupation and the resources needed to build the vessels. Furthermore, it gives the opportunity to optimise the dock occupation and asses the effect of new building strategies. But how to make lead time estimations with a low uncertainty? The next section will explore the possibilities.

1.1.2. How to get good lead time estimations?

Knowing the lead time of a vessel with a low uncertainty can thus act as the foundation for dock improvements. Furthermore it is also valuable for managing the organisation in general. But how can an organisation make lead time estimations with a low uncertainty? The first step is determining how to calculate the lead time. In essence, the lead time, in hours, can be calculated by dividing the total number of hours by the number of craftsmen as shown in equation 1.1.

$$Leadtime_{hours} = \frac{\sum Man_{hours}}{\sum craftsmen} \tag{1.1}$$

If a production process needs 100 hours of work and there are 10 craftsmen available, the time between the start and finish of the production is 10 hours. Thus a lead time of 10 hours is obtained.

One might expect that obtaining the lead time is not as straight forward as using equation 1.1. In real life there are more aspects. The first aspect is the amount of craftsmen to perform the tasks, in the example it was a fixed number, but in real life RvLs can hire external personnel. However, tasks(production processes) can not be divided infinitely to accommodate infinite workers, this would result in a ship being produced in an instance. Thus the first bottleneck is the number of workers that can perform this task. The organisation needs to judge how many workers can perform a task simultaneously to meet a wanted deadline. But the lead time is not only dependent on the number of workers, some processes cannot be accelerated, such as painting which needs a predefined drying time between layers. Another aspect that can influence the lead time of a task are physical constrains, a corridor might restrict the number of workers or goods entering the vessel thus influencing the lead time.

The second aspect of the estimation is the dependencies of tasks. The placement of the ship's interior cannot start before the casco is ready. This creates estimation dependencies resulting in higher uncertainty. Because the tasks are linked, delay in one task could delay total production, also known as the critical path[19]. If there is a 10% chance of a task delaying, the chance for the whole process delaying increases with the number of tasks(i) linked together, $0,9^i$. Different methods are available to estimate the effects of these planning uncertainties. Methods like PERT and event chain can aid in creating better lead time estimations[42][50], but is an organisation capable of performing such methods?

Looking back at equation 1.1, one aspect has not been discussed, $\sum Man_{hours}$, or the number of man-hours needed to produce a vessel. But how to estimate these man-hours? The next section will explore the difficulties concerning estimating man-hours for a vessel.

1.1.3. Difficulties concerning estimating man-hours

RvLs makes bespoke super yachts, thus every vessel is different. This means that original production hours cannot be directly used in the estimation of the new man-hours of a vessel. Other shipping companies could face the same problems when making a new vessel. How many man-hours are needed to produce a new vessel? These uncertainties in the man-hour estimation could ultimately lead to uncertainties in the lead-time estimation, as explained in section 1.1.2.

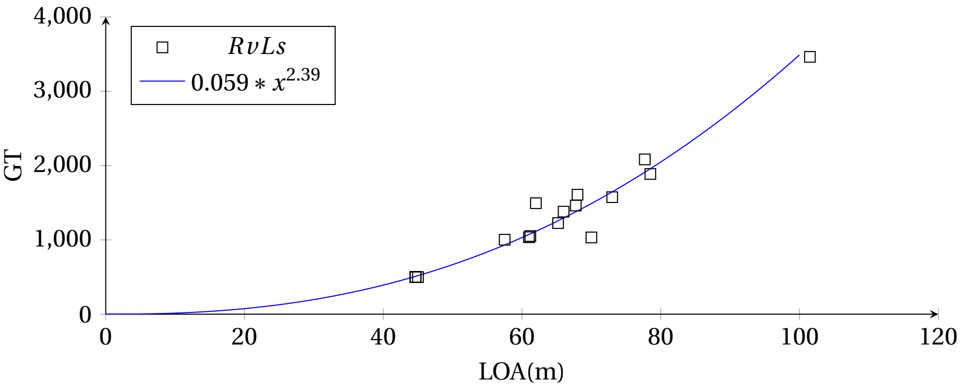


Figure 1.1: Increase of gross tonnage (GT) for a higher Length overall (LOA).

But how to make a man-hour estimation for a vessel? Figure 1.1[124] shows that vessel parameters are not linear linked to each other. This difference is also expected in the production process of a vessel, e.g. the amount of hours needed to install the interior floor of the yacht may be correlated with the volume of the vessel. But painting the outside of the vessel could be correlated with the the surface area of the hull. The effect is that flooring and painting have different scaling factors. Another example is the engine room; does the engine room lead time differs between vessel sizes? If the mounting procedure for a $2000kW$ engine is the same as for a $3000kW$ engine the installation time needed is the same regardless of the vessel size.

Production times can also be subjective to discrete differences. With increasing size, the ceiling height might increase to such extend that the small ladder used in previous vessels is no longer adequate and scaffolding is required. This could cause a sudden jump in man-hours needed for the ceiling installation. Such a discrete factor could also be present for the engine installation. If the yards crane is not sufficient to hoist the new engine, an external crane is needed adding additional time. All these effects could influence the man-hour estimation, even for vessel sizes that have been build before. A client might ask for a more powerful engine, so what effect does this have on the lead time? A company could estimate these effects based on knowledge of an expert, or build a parametric model based on previous data. But which method should the company chose in order to ensure the lowest uncertainty? Estimating man-hours with a low uncertainty is thus needed in order to determine the lead times with a low uncertainty. The next section will discuss if an organisation can make these estimation with a low uncertainty.

1.1.4. Can the organisation make correct estimations?

Determining the lead time with a low uncertainty could be done several ways. Different methods such as critical path, Program Evaluation and Review Technique (PERT) or the experience of an expert can be used to analyse the actual lead time of a project. Another factor is that this lead time is also influenced by the man-hour estimations.

Maturity of an organisation means the level of professionality and knowledge a company has. E.g. an organisation that has limited experience and production data could have more trouble making estimation with a low uncertainty, than for an organisation which has a lot of data and experience.

To reduce estimation uncertainties, an organisation can use different methods and techniques. The first possible method is to hire an expert, he or she may have experience at another organisation and can implement that knowledge in a different organisation. If the organisation already has an expert hiring more experts might not decrease the uncertainty of estimations. The organisation could then make a parametric model to predict the man-hours and planning for a ship. But creating such a model without proper data could result in disappointing results, or as Rhamnd[101] stated *"No mathematical model can be made without shipyard expertise data and it can be concluded that the expertise data is still valuable in this shipbuilding industry."* But the expert can also make mistakes, D.Kahneman and A. Tversky[123] described that people have the tendency to under-predict duration of tasks, also known as the planning fallacy. This effect was also found by Flyvbjerg[49], and this effect is also called Hofstadter's law *"It always takes longer than you expect, even when you take into account Hofstadter's Law."*[109]. However, overestimating can also result in undesirable effects, as described by Parkinson's law[14], which states that a project will fill the time available, even if it could be done in less time. Using the PERT method could help reduce these uncertainties[39] and misjudgements but this could also give undesirable results if no expertise data is available, as Rhmand stated.

Implementing the wrong methods to reduce the uncertainty could result in even worse results due to limited knowledge or input needed for this new method. Building a parametric model with only two data points could give unreliable results. The company is not ready to implement the method yet if it wants to benefit from the additional insight the method creates.

But when is an organisation ready to implement new methods for estimating man-hours and the creation of a planning? To the author's knowledge, no estimation and planning maturity model was found for the maritime sector, the writers of the paper *Capability Maturity Model Integrated for Ship Design and Construction* [31] also stated that there are few to no maturity models for the maritime sector. This thesis proposes a framework with which companies can asses their maturity level and see what method corresponds to their maturity level. This will ensure that organisations use the estimation methods which result in the lowest lead time uncertainty for their maturity.

There will always be uncertainty when making man-hour and planning estimations for a new project. But one must always strive to reduce this uncertainty, the overall goal of this thesis is proposing a framework with which organisations can evaluate which methods ensure that they make the best estimation for their capabilities. And provide them with the opportunity to evaluate what steps need to be taken to reduce the uncertainty even further, enabling better estimation in the future.

1.2. Research objective and scope

Up to date, no framework exists which allows companies to judge which methods to use for their maturity level, for both estimation and planning methodologies. In this section the objective of this research paper will be captured with the main research question and corresponding sub-questions.

> **Research question**
> *How to estimate ship production lead times with the lowest possible level of uncertainty.*

To answer this research question a framework will be created that will help answering the main research question.

> **Research question**
> *Develop a maturity framework to asses man-hour estimation methods based upon the maturity of the organisation.*

> **Research question**
> *Develop a maturity framework to asses ship production lead time estimation methods based upon the maturity of the organisation.*

In order to achieve the above mentioned research questions a number of sub goals are defined. The sub goals also correspond to the chapters in this thesis.

1. *Identify current maturity frameworks from literature.*
   In order to develop a maturity framework for the maritime industry, first the current maturity frameworks need to be identified.

2. *Identify (man-hour)estimation methods from literature.*
   Insight must be gathered into different estimation methods, the findings of this literature study will be used in the creation of the estimation maturity model.

3. *Identify planning methods from literature.*
   Insight must be gathered into different planning methods, the findings from this literature study will be used in the creation of the planning maturity model.

4. *Map the current production and planning method of Royal van Lent shipyards.*
   Royal van Lent shipyards will be used as a case study for the maturity framework. Therefore the current practices of RvLs need to be understood.

5. *Validate maturity framework using Royal van Lent shipyard data.*
   The, to be, proposed maturity frameworks will be assessed using RvLs as the case study organisation. The validity of the framework will be tested using actual company data.

Sub goals 1, 2 and 3 correspond to the sections presented in the literature study of Chapter 2. Sub goal 4 will be answered in chapter 4. The final sub goal, corresponds to chapter 5 where the the case study will be performed. The conclusion will give answer to the above presented research questions.

1.2.1. Thesis scope

In this section, the scope of the thesis is discussed. As discussed, this thesis contains three main parts. The creation of the estimation and planning maturity framework and the case study on the application of the frameworks. For the creation of the theoretical framework a scope is created to limit the boundaries.

The first boundary of the framework is that not all methods will be tested or verified in this thesis, the framework will be a reference for a company. The company shall verify and validate the methods used themselves.

The created theoretical framework will not contain all estimation and planning methodologies available. It will suggest the method relevant to the maturity level, which will give a low uncertainty. The framework will not be a database for all the relevant estimation and planning methodologies.

The case study will be performed estimating the lead time for an inbound estimation. Thus, this thesis will not investigate the effect on lead time of larger ships that have never been build before. In chapter 7, a recommendation will be given how to apply this thesis for the lead time estimations of vessels sizes that have never been build before.

This thesis will not evaluate the production lead times of multiple vessels being build simultaneously. It will asses the lead time for a single vessel, it is assumed it will not be hindered by the production of other vessels.

For the case study only the lead time for one vessel will be evaluated, the dock optimisation is beyond the scope of this thesis. This thesis will act as the foundation to make these optimisations possible as presented in the problem statement, section 1.1. This optimisation will be suggested as a further study using the observations made in this thesis, this will be discussed in chapter 7.3.

1.3. Thesis outline

This thesis has the following structure. Firstly, chapter 2 presents the literature review. This review is divided into three parts, first literature on maturity frameworks are discussed, secondly estimation methods are discussed that could be used. Finally, literature is presented concerning methods that could aid in reducing the level of uncertainty for the estimation of a planning.

After the literature study the estimation and planning maturity model will be presented. This will be done in chapter 3. Chapter 4 gives the reader insight into the current processes of RvLs before the start of the case study.

To asses the effectiveness of the maturity framework a case study is performed using RvLs as example, in chapter 5. This case study will first asses the maturity level of RvLs from which the methods corresponding to that maturity will be performed. This chapter will asses what the effect is of different maturity levels on the estimation and planning uncertainties are.

Lastly, this thesis will finish with the conclusion, discussion and recommendations for further research in chapter 6 and chapter 7, respectively.

2 Literature

There is not a single solution to calculate the lead time of a vessel with the lowest amount of certainty. Organisations differ from another or become more mature over time, this means that new methods for estimating the lead time could become available. The same holds for man-hour estimations, one organisation could rely just on the expert opinion but another organisation can make statistical judgements. However, their is no clear way to asses this choice which method(s) are most suited for an organisation. There is not a framework where they can asses if they are using the correct methods for their organisation, or a road-map to investigate which maturity steps they need to make in order to improve their estimations. In order to create this framework the current methods on, maturity frameworks, lead time calculations and man-hour estimations, first need to be established and understood. This literature review will investigate what literature is available on these research topics. First, the layout of the literature study will first be discussed to aid the readability. Secondly, the literature assessment criteria will be presented and lastly the literature itself will be discussed.

2.1. Literature layout

Figure 2.1 shows the structure of the literature study. The literature study contains three parts, estimation, maturity and planning literature. Firstly, the literature study will start with the exploration into maturity frameworks.

The second part of the literature study concerns estimation methodologies. Firstly general estimation techniques will be discussed followed by a well known cost estimation relationship(CER) framework by NASA. In this framework three elements are identified, analogy, parametric and engineering. Estimation techniques found in literature can be categorised under these three elements. To give the reader a reference frame where he or she can place the information.

The third and last part of the literature study is the investigation into planning methodologies. First the fundamentals of a planning will be discussed, project breakdown and project network. Literature found, regarding network, can be divided in two ways, uncertainty and network analysis. Literature regarding uncertainty, are risks or probability methodologies. The network analysis are techniques such as critical path.

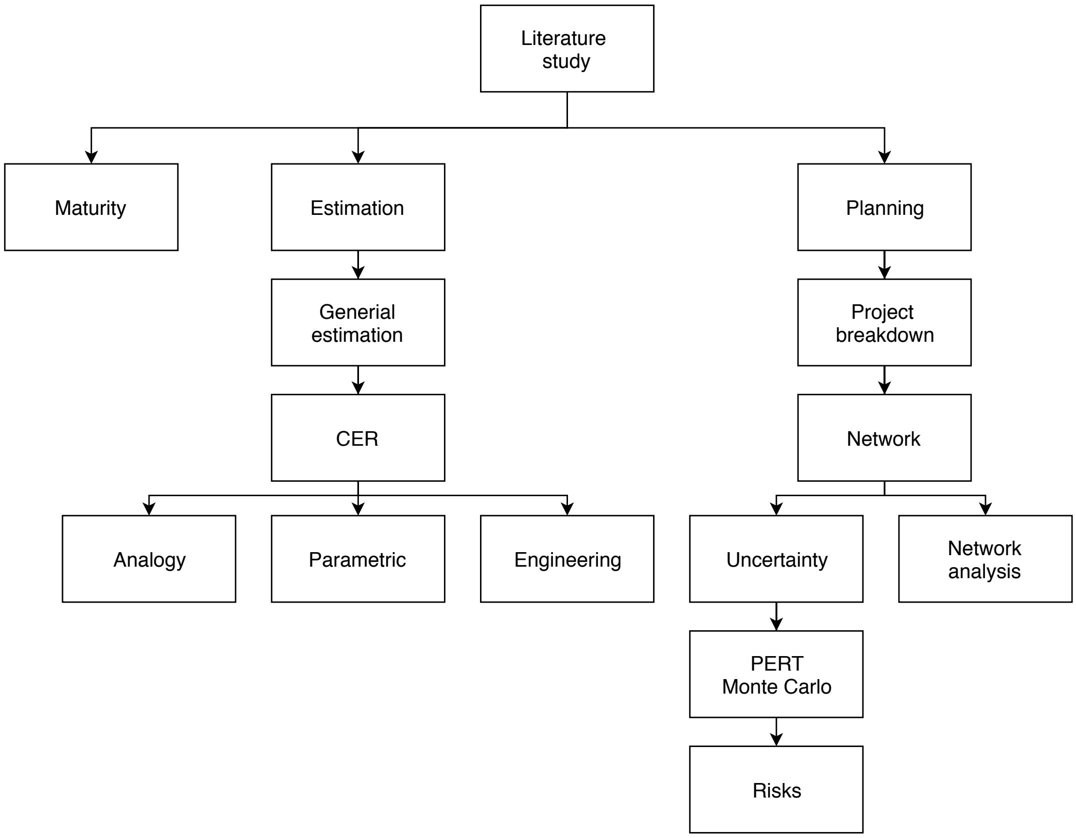


Figure 2.1: Diagram showing the structure of the literature study.

2.1.1. Selection criteria

In order to evaluate the applicability of the literature, three assessment criteria are created where literature will be assessed upon. These criteria will give clearly why certain literature will be used or not. Another benefit is that criteria also creates the ability to have discussion why certain choices where made. The three trade off criteria are presented in the list below. At the end of each section the literature found will be assessed using these three criteria.

- Generic
  The first criteria is concerned with how generic the literature is. This means that the methods found should be applicable to the entire maritime industry, thus not only for super yachts or dredgers.
- Applicable
  Applicability means the usability of the method or theory. It could be possible that a method sound good in theory but is unpractical in a real life situation.
- Scientific
  The last criteria is scientific, this criteria will ensure that the literature found will have a scientific foundation and is commonly accepted by the community. This is assessed using the number of citations, the number of citations are checked on Scopus[5].

2.2. Review of maturity frameworks from literature

Maturity models found in literature can be classified in two categories. Models concerning processes and model which focus on specific methods[32], also called capability models and progression models respectively[1]. The process models concern the level in which processes within an organisation are handled. Are their project guidelines for instance. Models concerning methods state which methods can be used in what maturity level of an organisation. For instance, what lean methodologies to use for different organisational maturity. For both methods the use in the maritime industry will be investigated. First the process maturity models are discussed.

2.2.1. Process maturity framework

The most well known process maturity model is the Capability Maturity Model Integration(CMMI) [36]. In this model two different process levels are defined, maturity and capability. Maturity means if a organisation has their process in a well documented way and know what they are doing. Capability means if the organisation satisfies the specified product quality or process performance. The maturity model consists of 5 levels and the capability model of 4. Table 2.1 show the different levels and a little explanation.

Table 2.1: Table with strengths and weaknesses of the three estimation methods(NASA).

Model levels	explanation
Maturity	
Level 1: Initial	In this level the processes are unpredictably and poorly controlled, tasks are taken care off when they arise, they are ad hoc.
Level 2: Managed	Process are known for the project and the problems are solved less ad hoc. The processes are managed per project, there is not a standard method within the organisation.
Level 3: Defined	In this level all the methods and processes are defined across the organisation. All the projects use the same methods.
Level 4: Quantitatively	The processes are performed using the methods described by the organisation, the same as in level 3. The difference is that the decisions and the performance of the projects are backed by data.
Level 5: Optimising	The last step is the optimising phase, at this level the organisation is continuously check if the current processes can be improved. These improvements can be based on data from level 4.
Capability levels	
Level 0: Incomplete	The work is done without meeting all the specific goals are not satisfied for the process. Or no goals exist for this level.
Level 1: Performed	The work is accomplished and the processes areas are satisfied.
Level 2: Managed	The work is performed according to the policy of the organisation. Skilled people are on the project and the work performance stays that the same level during times of stress.
Level 3: Defined	The last level the process are defined and undergo tailoring to make them even better for the organisation.

This is one example of a maturity model, but different maturity models can be found in literature. With different levels or tailored to different industries, such as IT. Models exist[68] like, Organizational Project Management Maturity Model(OPM3) [96], People Capability Maturity Model(P-CMM), Capability Maturity Model Integration(CMMI), Testing Maturity Model(TMM), Portfolio, Programme, & Project Management Maturity Model(P3M3), Level of Information System Interoperability(LISI), Organizational Interopera-bility

[1] The mixture of the two is called, hybrid models.

Model(OIM), enterprise information management maturity(EIMM), Business Process Maturity Model(BPMM), Federal Aviation Administration Integrated Capability Maturity Model(FAAiCMM), Kerzner's Project Management Maturity Model(KPMMM), Ibbs and Kwak Maturity Model.

Kerzner's Project Management Maturity Model[65] also states that there are five levels of maturity, common language, common processes, singular methodology, benchmarking and continues improvement, This has resemblance to the CMMI. OPM3 has the the same levels but includes the domains, project, program and portfolio, creating a matrix maturity model[96]. A comparison study between SPICE, LISI, OIM, LCIM and EIMM performed by W.Guédria[55] stated that SPICE could be considered the generic maturity model where other models are based around, like the well know CMMI model. Thus for the creation of a new maturity model the SPICE is a good starting point, SPICE is also an official ISO and IEC standard *ISO/IEC 15504*[107]. T.F Souza and C.F. Gomes[53] assessed different maturity models on their frequency of use, and came to to conclusion that CMMI is the most common maturity model, *"As a result, a large concentration of studies on the CMMI model could be observed, given that the focus of this model lies on technology and related areas."*. The paper also state that OPM3 was to be the best for construction organisations. T.F Souza and C.F. Gomes asses the usage on the number of citations per model but came to the conclusion that the use of maturity models are still limited. This was also concluded by a paper by F.Backlund [22], he stated that in construction organisation maturity models are still limited. This finding is also backed by L. Carmen, in the paper *The Maturity of Usability Maturity Models*[74]. It was stated that maturity models lack specific guidance which is a reason why there use is limited, *" In our study, we have found that five out of the 11 retrieved models (45%) do not offer specific guidance for identifying the usability of maturity levels in an organisation."*.

Maturity models specifically for lead time estimations cannot be found by the author of this thesis, one planning maturity model by "liberty advisory group"[4] which advised to start with making planning definitions and finally making decisions based on a planning. Man-hour estimation maturity models where also not found, for software there are cost estimation maturity models. One maturity model was found based on CMMI, *The Estimation Maturity Framework* by an organisation Galorath Inc[59]. The paper *Impact of CMMI Based Software Process Maturity on COCOMO II's Effort Estimation*[136] combined CMMI and the Constructive cost model(COCOMO) model for software cost estimation, they came to the following conclusion, *"The study shows that our proposed model (with the new PMAT rating values) yields better estimates comparing with the Generic COCOMO II modelpsilas estimates"*, L.Buglione[27] also presented a hybrid cost estimation model using CMMI. However, both models are not used directly to estimate man-hours. The author of this thesis did not find maturity models specifically lead time or man-hour estimations.

The use of process maturity models in the maritime sector are limited. The paper *Capability Maturity Model Integrated for Ship Design and Construction*[31] is one of two papers found specially for the maritime sector, the paper enforced this observation that no models are present to their knowledge. The paper used CMMI as foundation for their model. They used the same 5 levels but added assessment criteria where these CMMI levels need to be assessed upon, they are contract design, design and engineering, planning and coordination, production and assembly, procurement and lastly logistics. The second process maturity model found is is the *An Innovation and Engineering Maturity Model for Marine Industry Networks* by K. Jansson[62]. In this paper a maturity model is made with 6 dimensions, Innovation dimension, Internationalisation dimension, Collaboration dimension, Project Management dimension, Technology dimension, and Knowledge management. These levels are then further explored in four area's, customers, staff & personnel, experience, and organisation nationality. All these dimensions are then explored to get insight into the marine innovation in maritime networks.

2.2.2. Method maturity framework

More specific maturity models are also presented, which focus less on processes and more on methodologies. Models such as an industry 4.0 maturity model [112] which focuses on adaptability capabilities of the organisation. Another method based maturity model is the model by A.Kosieradzka [72] which presents a maturity model of production management. The methodology in her maturity model is not a sequence of different methods but places all the different methods on the same level and then uses the same five levels from table2.1 to asses how the different production methods are being used, like 5S, lean, six sigma, etc. It therefore states that there is not maturity different between the methods. Another production maturity model is the supply chain management maturity model of M. Lahti and A.H.M. Shamsuzzoha [75] they defined four levels of maturity, called stages. The stages are, functional focus, internal integration, external integration and cross-enterprise collaboration. These steps focus less on methodologies involved but in the communication lines between the stakeholders within the supply chain. One method maturity framework which is related to planning is a the Continuous Delivery 3.0 Maturity Model(CD3M)[130], this is a software delivery maturity model focused on delivering software, and cannot be used directly for the maritime market because it advises specific software test like A/B tests. For the construction industry such a models where not found.

Maturity method models specifically developed for the maritime sector are not found.

2.2.3. Conclusion maturity models

In the previous section various maturity models where discussed. Ranging from process maturity models, such as the CMMI, to method based approaches such as the maturity model presented by A.Kosieradzka. During the maturity model exploration it became apparent that there are limited maturity models specifically for the maritime industry. Also, method maturity frameworks are limited concerning planning and estimation. Not all methods described above will be discussed, only the type of maturity model, process or method. They are assessed on the criteria described in section 2.1.1.

Table 2.2: Table with summation and assessment of the different obtained maturity models.

Method	Generic	Applicable	Scientific
Process maturity models	the maturity of the process maturity models, like CMMI, can be used in all industries, and are thus generic within the	Process maturity focused and less on methodologies, therefore it is less applicable for the estimation and planning methodology.	A paper assessing CMMI has been cited 160 times(scopus). Therefore it can be said that process maturity models are not a novel idea.
Method maturity models	The production methodologies used in this model can be used over different industries. Therefore it is a generic maturity model and thus would comply to this criteria.	The model is not directly applicable for the maritime industry. But the method of stating specific methods in the maturity model could be applicable for the creating of the maritime maturity model.	The industry 4.0 maturity model alone was cited 117 times. Making these types of maturity models not a novel idea.
Maritime maturity models	Both models for the maritime industry are generic and thus could be used.	One model is a translated CMMI and the other for concerns innovation. Therefore, both models are not directly applicable for an estimation and planning maturity model.	The two maritime models found where only cited 8 times combined. So less then the other two, this follows in line with the statement that maritime maturity models are common practice.

To conclude this section, there is a gap in the maturity models for the maritime industry. Especially a maturity model where different methods for estimation and planning are combined, are not presented. Because industry independent process models are already available, this thesis will create a method maturity framework specifically for the maritime industry.

2.3. Review of different time estimation methods from literature

The judgement of man-hours can be found in a broad range of industries, ultimately someone wants to know the duration of the project and how much it will cost. This section discusses different methods for estimating projects. Most methods concern the estimation of cost. Time and cost are linked because production hours can be translated directly into production costs.

2.3.1. Square–cube law

That different parameters scale differently is known for a long time. Galileo Galilei described the square-cube law in 1638 [15]. He states ”geometry teaches us that, in the case of similar solids, the ratio of two volumes is greater than the ratio of their surfaces”

The law states that the volume grows larger than the surface area. If the surface area doubles then the volumes increases X^3. For example, if the size of a block is multiplied with 2, the area of the cube increases with 2^2 and the volume increases with 2^3. It is not expected that there are such clear scaling factors for a vessel related to the amount of work. Different factors will influence the scaling, the design of the vessel changes but also the fact that the amount of tasks do not need to increases with the increased size. The number of tasks installing an engine stay more or less the same with increased KW, thus it is expected that the estimation factors will not be as predictable as in the square-cube law.

2.3.2. CGT method

One model that estimates the amount of work is the compensated gross ton (CTG) method [90]. This method uses the gross tonnage of a vessel to estimate the amount of work needed to build a ship. In other words, the amount of hours needed per GT. This method was originally created to compare the production efficiency of different countries. If the average construction time for a certain type of vessel is higher then the calculate CTG then it could give an indication that the the vessels are not produced efficiently in a country. This method is not perfect but could give an indication of the production efficiency of the country.

This method uses a simple formula to translate GT in CGT, as shown in equation 2.1. This formula contains three variables, A, B and GT. GT is the gross tonnage of the vessel. A and B are estimation factors, A controls the ship type and B denotes the influence of ship size. In appendix C the different estimation factors are shown. Factor A shows the difference between the ship types whereas B indicates the effect of size on a specific type of ship.

$$CGT = A \cdot GT^B \tag{2.1}$$

One ship type that is missing in appendix C is super yachts. In the original research, super yachts where placed under passenger vessels. The paper *Determination of the compensated gross tonnage factors for super yachts* [98] shows that this assumption is not valid. However, they estimate new values for A and B based on the production of 41 super yachts from various super yacht companies. From this analysis a new A and B value where found of $A = 278$ and $B = 0.58$. This shows that the production of a super yacht takes much more time then the production of passenger ships with $A = 49$. It was originally thought that a passenger ship was a good estimation for a super yacht which is clearly not the case. What needs to be noted is that the estimation was only done on 41 super yachts, which leaves a lot of room for uncertainty. For instance, the extremes had an $A = 76$ and $A = 1012$ which is quite a big difference. Another paper [40] did the same for naval vessel and found a lower spread of data points. T.Lamb[77] however commented that the paper was to optimistic and a large spread was still present. Other people also tried to estimate A and B values for special vessel types [117][86][21][110].

The CGT model with added super yacht values sounds promising but has a few drawbacks. Below, the three main drawbacks are given. The major drawback is that this model only gives an estimation on the total amount of work, it does not specify the scaling factors for the different process elements. The input is another drawback, as only GT is an input, but other specification such as length, beam, and KW are not included.

2.3.3. Parametric Cost Estimating Relationship

A parametric is a measurable characteristic of a system. These parameters show the relationship between a variable, such as GT, and a fixed output, such as painting time. These analyses are mostly done with regard to cost, because in projects cost is always a important factor. For instance Fokker uses cost estimation relationships for their price determination(al Jaberi, S. (2019, February 16), Personal interview). For the aerospace industry a lot of cost estimation relationship studies have been performed [11][81][116][99][28]. But for the maritime industry many reports also exist on the establishment of cost estimation relationships[108][13][138][41][63]. The main element in all reports is the way the relationships are established, they use regression analysis.

Regression analysis is a method to estimate relationships between data points. Most of the time, regression lines use historical data to create CERs, but neural networks and deep learning can also be used[12][132][80]. Figure 2.2 [61] shows a typical regression line, in this example the relationship is a simple linear relation. But also more complex relations are possible, these relations however also have limitations that need to be taken into account. Below these limitations will be further discussed.

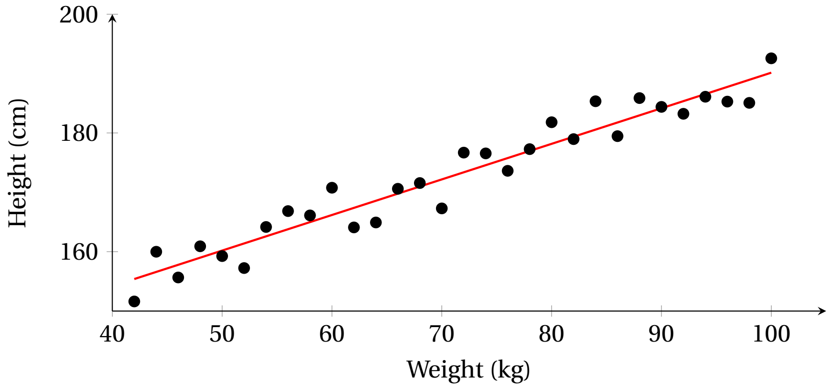


Figure 2.2: Graphical representation of a random regression line.

The first parametric cost estimations where suggested by Wright in 1936 [120]. He stated that equations could be made to predict the cost of aircraft over large production runs. After that the aircraft industry has used these relations to estimate production times and aircraft cost and, as stated above, Fokker is one of them.

Recommended are the following steps to develop a CER model[111], but these can also be applied for man-hour estimations.

1. Define the dependent variable.

   First define what the CER model will estimate. What parameter will be at the end of the CER model, this could be labour hours, cost, selling price. Also, what will be the level of detail? Will the total labour hours be estimated for the total production or for specific parts of the project?

2. Select independent variables to be tested.

   The next step is selecting independent variables, these are variables such as the time it takes to lay $1m^2$ of teak flooring.

3. Collect data.

   Collecting the data is the next step, this can be historical data or predictions made by experts. Because the data is essential, the data also needs to be reviewed to make sure it still applies to the current situation. Furthermore, data need to be comparable to each other, if not the data needs to be adjusted. An example of such an adjustment is inflation. If inflation is not taken into account, the price of old data could seem low. Changing the production methods, such as the usage of human versus robots, will also influence the outcome and thus needs to be accounted for.

4. Explore the relationship.

   During this step the correlation between the dependent and the independent variables must be determined. Various techniques can be used to determine dependencies. Such as, regression analyses, ratio analysis and moving average.

5. Select the relationship that best predicts the dependent variable.

   From the analysis above the relationship will be chosen that best depicts the relation between the two variables.

6. Document your findings.

> Last, document the findings. It is essential for the CER model that traceability is in order to verify and later validate the model. If the model does not predict new projects, the data will be checked. Even if it predicts the data maybe it was a lucky shot and it needs to be known how the CER elements where obtained.

There are limitations and pitfalls with CER. Because CER is data driven the quality and quantity of that data needs to be usable for the usage of the CER model, L.Liard[76] stated *"Models and Methodologies are not a replacement for Common Sense and Engineering Judgment"*. With two data points a trend line is possible, but will not give insight because the number of data points are too few. Determining the relationships can be prone to over-fitting or over-correlating. The first one is that estimation lines can be over-fitted to the data. Here the line will follow the points better but this could cause giving too much weight to noise or outliers. Over-correlating data means making correlations between variables that do not have a real correlation, but coincidentally show a trend line or factor between them. The next section will go in further detail into CER with the framework created by NASA.

2.3.4. Determining correlations

Using a parametric approach to estimate hours mean that correlations need to be established. A correlation means that there is a relationship between two variables. Correlations are used in all industries to predict and to argument why certain events will happen. One pitfall, stated in section 2.3.3, is that a correlation can be found between two non dependent variables. Meaning that looking at the data a correlation is presented but in real life there is no cause-effect. One must therefore evaluate the validity of the correlations. But how to asses correlations in the first place?

There are different methods to evaluate the presence of a correlation and the fit of that correlation. One could plot the data and visually look if trends can be seen but this is a subjective method. Different methods such as, Pearson's R, R^2, and Spearman's rank [82]. Each method will be discussed and a choice is made which method will be used to evaluate the correlation.

The Pearson's R method measures the linear correlation between two variables. With a value ranging from -1 to 1 with -1 indicating a perfect negative correlation and $+1$ a perfect positive relation. A value of zero indicates that according to the Pearson method no correlation is present, this does not mean that there is no correlation, only that there is not a linear correlation. The spearman's rank correlation differs that it is not linear[84]. Another method is, R^2, or sometimes called the coefficient of determination. R squared is an indication how well a model fits the original data[44]. It can measure how well a regression line, which represents the model, fits the data points. If a R^2 value of 1 is observed it means that the model represents the data perfect.

One question that arises during parametric analysis is, how many data points are needed? With a sample size of two points a trend line can already be made, this results in an R^2 of 1 because it will fit the data points perfectly. But one can understand that this data-set is to small because one additional point can mean this trend line is completely wrong. But what is the minimal data set needed? "David (1938) recommends the use of for Pearson correlations only if $n \geq 25$ "[26]. Thus a sample size of 25 is recommended. However, at RvLs there is not an abundance of data. The production of a vessel takes 3 to 4 years with around 2 vessels per year. This means that the sample size is limited, the current sample size is 19 which is lower than the recommended 25. Unfortunately the limited sample size cannot be changed but it is recommended to keep adding data over the year to improve the regression lines. Another factor to consider is the value of R^2. What is a good R^2 value? It depends[91][47], there is no direct answer. For one experiment on drug use within a country an R^2 of $0,10$ might be a good result. But for a lab test a R^2 of $0,99$ could be insufficient[1]. Table 2.3 shows the percent of standard deviation explained, e.g. a R^2 of 10% yield a 5% smaller error than a constant only model.

Table 2.3: Internal lead time representation for super yachts

R2(%)	Percent of standard deviation explained(%)
99	90,0
80	55,3
75	50,0
60	36,8
50	29,3
40	22,5
30	16,3
20	10,6
15	7,8
5	2,5
2	1,0

2.3.5. Cost Estimating methodologies by NASA

From aircraft to aerospace, NASA has a handbook in the estimation of cost. Called Cost estimating methodologies[6]. It describes four methods in estimating the cost, analogy, parametric engineering build-up and extrapolation using earned value management. Figure 2.3 shows each method placed on the corresponding phase, it shows that in each phase a different method or methods can be applied. This model has four phases, concept, design build and finally operations and support. This shows also the timeline, starting from rough sketches in the concept development phase to launching the product and giving operations and support. The next paragraphs discuss the four methods and present an overview with the strength and weaknesses of each method.

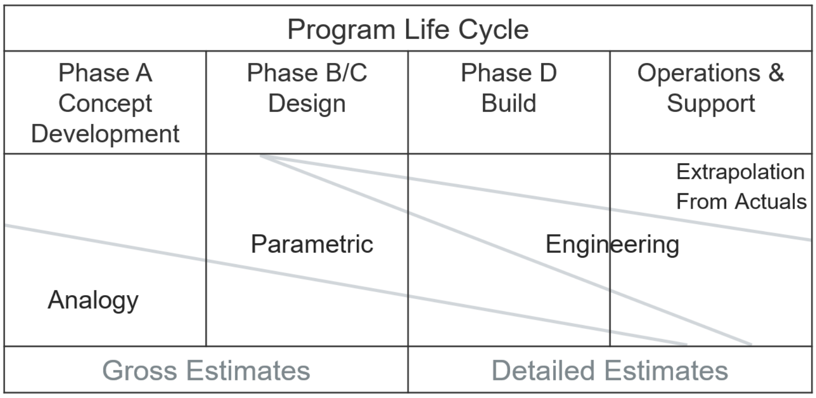


Figure 2.3: Use of Cost Estimating Methodologies by phase(NASA).

Analogy cost estimation uses the production of similar programs, or for us, vessels. New programs are mostly unique but use knowledge and systems from predecessors. The analogy methods uses these similarities to predict the new program cost. This method requires the help of estimators that will estimate the new cost by scaling old programs or coping cost of similar systems within the program. Because this method uses estimators, a level of subjectiveness is introduced. If the estimators make a prediction on old data, this prediction is mostly linear. Exponentials of other scaling formulas are more difficult to predict and thus less common for an estimator to use. This method, called "Black Book" by M.Ross[106], states that this method can produce acceptable results but become unreliable with increased sizes. Caprace and Rigo state that "The possibility of cost estimating belongs to a few experts. Besides this fact, the quality of estimations, based on the knowledge of experts, differs widely (variation on average ± 30%)." [30]. Thus a variation of 30% can occur which can be the different between a profit or a loss, assuming that a company has an average profit margin of 10%.

The next method is parametric cost estimation. This is in line with the CER method described in section 2.3.3, it uses statistical relationships from historical data combined with program parameters to predict the cost of the new program. Figure 2.4 shows the parametric cost modelling process NASA uses, is contains

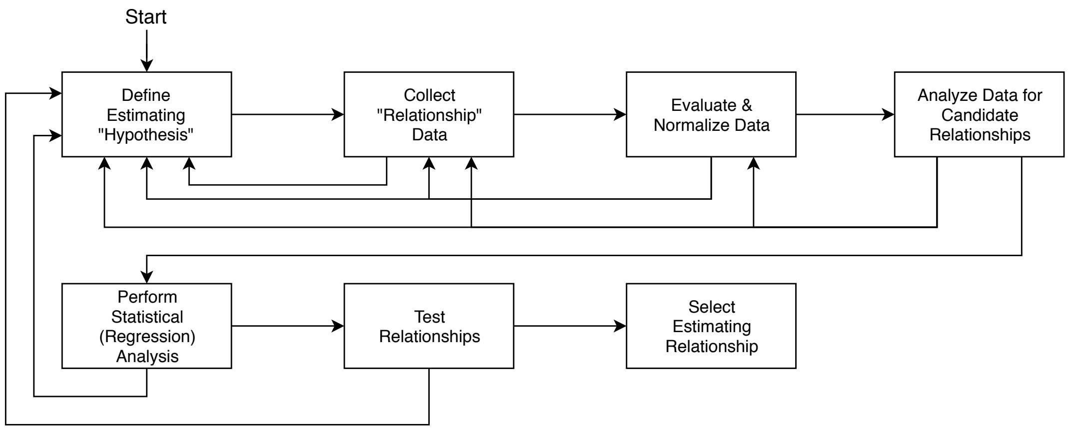


Figure 2.4: Parametric cost modelling Process(NASA).

similarities with the steps described in the previous section. The difference in the model is the inclusion of feedback loops to check if the estimation was correct. Parametric cost estimation has a few methods in determining relationships, such as ratios. But most of the time regression analysis is the primary method, if the correlation levels are low the estimates may not be accurate M.Ross[106], but this speaks for itself. If there is a relation between variables, the user must look into four reasons why there is a relation and to check if the relationship makes sense.

1. Chance.

   The first reason for a relation is chance. We are all prone to making conclusions on relations that in the end turn out to be just coincidence and do not have any real cause effect relation. For instance, that the biggest ships are always sold if a certain football club wins the tournament. This is just luck because the two are not related, if we assume that the buyers had no relationship with that football club.

2. Third set of circumstances.

   Maybe there is a relationship between two parameters but they are actually linked to a third parameter that causes both their behaviour. For instance, that it is dark in Australia when the sun is up in America. There is a relationship between the two but due to a third effect the ration of the earth. Thus generally it is preferred to look for this third relation ship to get a better understanding the whole system.

3. Functional relationship.

   This states if the relationship can be expresses in formula such as $L = \frac{1}{2}\rho V^2 C_l$. Which calculates the lift force, for parametric cost estimation such clear relations rarely exist.

4. Causal relationship.

   These are also formulated by a equation but gained from a regression analyses. These do not indicate a cause and effect but are made by the estimator which evaluated that there is a logical cause effect between the two parameters.

NASA created a clear step approach in obtaining the best cost estimation relationships, which in turn can be transformed to estimation relationship needed for this thesis.

1. Review the literature and scatterplots.
2. Select the independent variables(s) for each CER.
3. Specify each model's functional form (e.g., linear, nonlinear).
4. Apply regression methods to produce each CER.
5. Perform significance tests (i.e., t-test, F-test) and residual analyses.
6. Test for multicollinearity (if multiple regression).
7. See if equation causality seems logical (e.g., does the sign of slope coefficient make sense?).

8. For remaining equations, down-select to the one with highest R2 and/or lowest SE.
9. Collect additional data and repeat steps 1–8 (if needed).
10. Document the results.

The next method in the diagram of Figure is, engineering 2.3. This method is a bottom-up estimate, which means that every activity in the work breakdown structure is estimated on it total duration or cost. Adding these together will result in the total cost of the project. Performing this bottom up approach requires a level of detail in which all the task are known. That is why performing this analysis technique in an early stage is costly and with a great uncertainty because a lot of tasks need to be estimated.

The last method is, extrapolation from actuals, using Earned Value Management. This is more are tracking activity that tracks the added value which the user can compare by the expected to see if the project is still on track or is going over budget. This method will not be further elaborated because it is a tracking method and less an estimation method for future projects.

Figure 2.4 shows the overview of the three methods with their strengths an weaknesses. In chapter 3 the selection will be made which of these 3 methodologies is chosen.

Table 2.4: Table with strengths and weaknesses of the three estimation methods(NASA).

Methodology	Strengths	weakness
Analogy Cost Estimating	Based on actual historical data	In some cases, relies on single historical data point
	Quick	Can be difficult to identify appropriate analog
	Readily understood	Requires "normalization" to ensure accuracy
	Accurate for minor deviations from the analog	Relies on extrapolation and/or expert judgment for "adjustment factors"
Parametric Cost Estimating	Once developed, CERs are an excellent tool to answer many "what if" questions rapidly	Often difficult for others to understand the statistics associated with the CERs
	Statistically sound predictors that provide information about the estimator's confidence of their predictive ability	Must fully describe and document the selection of raw data, adjustments to data, development of equations, statistical findings, and conclusions for validation and acceptance
	Eliminates reliance on opinion through the use of actual observations	Collecting appropriate data and generating statistically correct CERs is typically difficult, time consuming, and expensive
	Defensibility rests on logical correlation, thorough and disciplined research, defensible data, and scientific method	Loses predictive ability/credibility outside its relevant data range
Engineering Build-Up	Intuitive	Costly; significant effort (time and money) required to create a build-up estimate; Susceptible to errors of omission/double counting
	Defensible	Not readily responsive to "what if" requirements
	Credibility provided by visibility into the BOE for each cost element	New estimates must be "built up" for each alternative scenario
	Severable; entire estimate is not compromised by the miscalculation of an individual cost element	Cannot provide "statistical" confidence level
	Provides excellent insight into major cost contributors (e.g., high-dollar items).	Does not provide good insight into cost drivers (i.e., parameters that, when increased, cause significant increases in cost)
	Reusable; easily transferable for use and insight into individual project budgets and performer schedules	Relationships/links among cost elements must be "programmed" by the analyst

2.3.6. Analogy

Their are limited papers about an analogical estimation. The paper *Improving and expanding NASA software cost estimation methods* [57] builds on the NASA methodology by using nearest neighbour estimation methodology to make estimations. They created a tool, where with high level parameters, parachute or thruster landing, estimation can be made. There are some papers on analogy concerning software[66][23]. But a overview is given by J.Keung[67] for different analogy methods for software, such as CBR and ace linear extrapolation. But in the end he came to the following conclusion *"No tool can replace the talents of a human expert, who is able to consider wider range of issues that lead to the success and failure of a software project."*. Meaning that even with analogy tools a good judgement is always key. From software to economics, the book *Analog Estimation Methods in Econometric*[48] says that if the sample size is low one must find sample that could represent that sample. For instance, super yachts and luxury cruise ships. If for luxury cruise ships more samples are know one can judge the effect of production hours of a super yacht based on that of luxury cruise ships, taking the known sample difference into account.

Analogy approaches for shipping have not been found, but due to the human affect methods from other industries can be used.

2.3.7. Parametric

The second phase mentioned in the NASA CER model is parametric. In this phase estimation are made based on previous data or ind industry standards. As stated, literature on parametric cost estimation is ready available, but man-hours estimation which is linked to cost is also available. For this thesis man-hours are needed, because of the planning, but because they are linked both estimation will be discussed. In literature also vessel specification estimation can be found, how to estimate the resistance in an early stage for instance. For this thesis it is chosen to discuss these in section 2.3.8 because they help to get more engineering knowledge. In this section both parametric cost and man-hour estimation methods for the maritime industry will be discussed, starting with cost.

In section 2.3.3 it was already stated that there are a lot of papers concerning parametric cost estimation, in this section a few papers will be highlighted. The paper on cost estimation is by H, Shetelig [115], identifies two methods, top down and bottom up approach in cost estimating. With the two methods he identified for each method a main problem. For the bottom up method the main problem is maybe loosing the contract. This problem can occur because calculating the price bottom up requires a lot of time because a high level of detail is required for this method, this is thus more an engineering approach. The top down approach could result in misjudging of the price because to little data is known and thus misjudging of the price. H.Shetelig states that between the two methods the parametric cost estimation method lies. Another article that looks into the top down and bottom op approach is a paper of V.Bertram [24], also using parameters from older vessels to determine the cost. The paper states the following key disadvantages of the top down approach that could be overlooked.

1. The approach uses only global information and is thus incapable of reflecting local changes or details of the design improving producibility.
2. The approach is usually based on weight. Any change, which increases weight, will automatically increase the cost estimate regardless of the real effect on cost. Extreme lightweight designs may drastically increase the number of required hours, while large frame spacing may increase weight, but decrease necessary man-hours. This is often not reflected in the formulae!
3. The approach is based on historical data, i.e. historical designs and historical production methods. In view of the sometimes revolutionary changes in production technology over the last decade, the data and formulae may sometimes be called ’prehistoric’. They do not reflect new approaches in structural design or production technology.
4. The approaches were probably based on inaccurate data even at the time they were derived.Shipyards are traditionally poor sources of cost information. The data are frequently skewed reflecting pressures of the first-line managers and other factors.

For instance the last point is directly felt during the gathering of data for this thesis, it became apparent that data is not readily available. These problem are also identified by M.Ross[106] and also states that managers lack the information in confidently make cost estimations. The paper presents a method to share cost and data among the ship engineers and managers to enable a deeper understanding of the technical data and thus increasing the cost estimation. It uses a Work Breakdown Structure(WBS) to estimate the cost, a more engineering approach, which will be discussed in the section 2.3.8. This was further described by W. A. Z. Wan Abd Rahman[131]. A study on this subject was done by M.Hur[58] and Rashwan [102] but came to the conclusion that for both method data is still the driver for accuracy. Rahman[101] compared these different methodologies, PWBS, neural, regression, etc. and came to the same conclusion that most methods still rely on company data to make their estimation and thus good company data is still valuable, *"No mathematical model can be made without shipyard expertise data and it can be concluded that the expertise data is still valuable in this shipbuilding industry."*. L. Bin[79] analysed three different regression models, linear, multiple and neural network. He came to the conclusion that the neural network was far better in the prediction.

A paper by P.Michalski[83], states that that the total building cost of a vessel consist of three things, material cost, labour cost and other shipyard cost. These shipyard cost consist of, ship equipment, hull construction and power plant and propulsion systems. In the paper he only looks at the unit costs per mass of these relative groups. The paper shows that all groups undergo the economics of scale, all the unit cost(such as hull construction) decline with the increased mass. Thus stating that the relative cost decline with he size of the vessel. Thus maybe also the hours needed, the next part will cover the man-hour estimation techniques.

There are also different methods to estimate the man-hours needed to produce a vessel. The book of Watson[133] presented several indication as shown in Figure 2.5 the problem is that these only indicate the ratio between the vessel types and cannot be used for an organisation specific, this is in line with the CGT method.

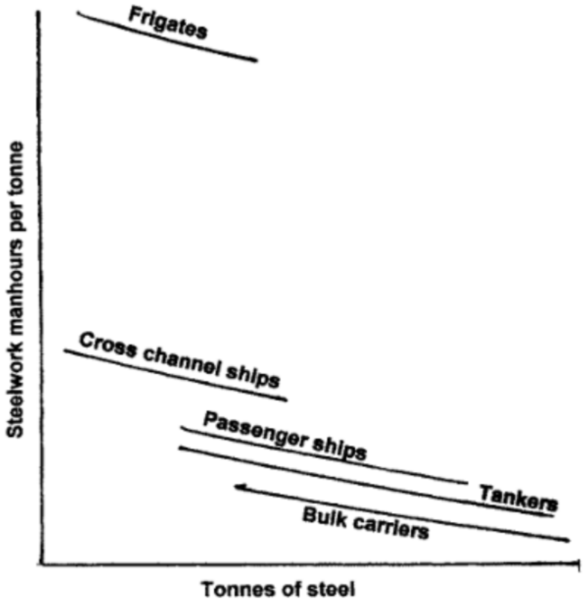


Figure 2.5: Manhours per tonne versus steel weight.

The paper by M.Ahmned[114] also uses weight for the man-hour estimation, where they state this is a good estimation method. B.Liu [29] extends this method by using factors on the range of vessel parameters, KW, GT, generator KW. And comes to the same conclusion that the using parametric data has a high accuracy.

The papers above give an indication of the different methods using a parametric approach, the next section will elaborate on the nest phase of the NASA framework, engineering.

2.3.8. Engineering

The next step in the NASA CER methodology is the engineering approach, different to parametric where estimations are based on vessel specifications an engineering approach sets out to reducing the engineering uncertainty. Creating more vessel details and specifications known in an early stage.

There are a lot of different ship estimation methods found in literature for different vessel parameters. Hull form, lightship, deadweight, propulsive, compartment, capacities, etc *M.Ross*[97], *Y.chen*[37], *E.Branch*[45], *C.B Barrass* [85], *J.S Carlotn*[33]. The ship parameters can be judged based on coefficients. But set out to increase the speed in which ship parameters are better judged and thus a higher accuracy for the hour and cost estimation are possible.

There are also cross over methods, that use parametric to estimation ship parameters. Which would result in early engineering knowledge where man-hour predictions can be based upon. Papers such as Harries [56]. They set out to identify different arrangements, this can be internal arrangement *Lee*[64], piping *Nienhuis* [89] and structural [103]. These engineering exploration models are not new and data back to 1977, *M.Eames* and *T.Drummond*[46] and *W. Nethercote* and *R. Schmitke*[88] made concept exploration models for naval ships. These conceptual models can aid in getting more engineering details in an early stage, in the next section it will be further elaborated how such a conceptual model, named rapid engineering, could aid in creating better estimations.

Caprace and Rigo present an additional method and that is the life cycle approaches. These are more holistic and start from the bird of the ship to her dead [30]. But these three methods are not sufficient according to Caprace and Rigo, they have developed a Feature-Based Costing(FBC) model. THe FbC model is based on a series of characteristics of the product, what they call product features. Products are described by a number of features such as hole, weld length, bevels, etc. The number of products can then be extracted from a CAD/CAM model, because these tools have advanced FBC becomes more accessible[51]. This tool is integrated with the CAD model thus let the engineering drive the estimation.

2.3.9. Rapid engineering

The engineering methods described above are concerned with estimating the vessel parameters is an early stage, from which better estimation can be made, because more vessel details are known. Another methods is creating whole ship designs in a early stage which result in better predictions because more vessels details are known resulting in better estimation.

A possible rapid engineer method is the packing approach, this is a method developed by J. van Oers[126], that creates vessel concepts based on an algorithm that optimises the building blocks that comply's with a set of requirements. With these requirements the algorithm generates a lot of designs which the naval architect can reflect on these designs. Because the packing approach is a method in generating designs it is not directly applicable in seeing the effect on the production times, but it could be a foundation for such a method.

The packing approach uses blocks that are predefined for instance, how much they weigh. Using the packing approach to could also be used to determine the cost of a vessel. One of the requirements for the super yacht could be the length and width of the vessel, the packing approach can then be used to pack the yacht. Two blocks would be identified, necessary systems and slack systems. The necessary system block would contain block which the vessel needs such as, engine room, crew area and bridge. Without these blocks then vessel would not be able to sail and are required by law. The slack systems are systems that do not fall in the previous category, these systems are more client driven. Blocks such as Jacuzzi and gym room are not necessary but are chosen by the owner.

All these blocks have specifications, one added specification could be production times. These production times can be obtained from historical data. The production times can be extracted from the model if all the block contain production times for that specific block. If a requirement is that the specified vessel size shall be maximised, the model would fill the volume with the blocks necessary and the slack blocks. With this the total amount of hours can then be extracted from the model.

The above described method is not yet implemented in the current packing approach. In the thesis of van Oers it is mentioned that the design could influence the production price, by decreasing the density of the systems within the ship, the size of the vessel could increase but the total production cost could reduce because the production space increases and thus the work efficiency could increase [54]. Other rapid engineering methods can also be used to increase the engineering knowledge such as the graph theory[35], where they described different methods to gain addition engineering knowledge in an earlier stage. Methods such as a holistic approach[95] can also be used for gaining additional engineer knowledge. Another approach by *P. de Vos*[43] uses network theory explore design options for energy distribution systems. Another form of rapid engineering could be, automated pipe routing[18]. The paper by W. Ruy[69] presented a method, using network theory, to automate pipe routing in the engine room. All these methods could aid in the rapid engineering.

2.3.10. Conclusion estimation methods

In this section literature was presented concerning estimation methodologies. The literature was structured around the CER framework created by NASA. For each element, analogy, parametric and engineer, literature was discussed what is currently present in the maritime sector. What became apparent during the literature study is that different methods exist in estimation man-hours, or cost, but all have the same bottleneck. The bottleneck is that all method from analogy to rapid engineering rely on fundamental information how much time it takes to perform a certain task. As stated in the section above, *"No mathematical model can be made without shipyard expertise data and it can be concluded that the expertise data is still valuable in this shipbuilding industry."*

In table 2.5 an assessment is given of the main methods based on the criteria presented in the beginning of the section.

Table 2.5: Table with summation and assessment of the different obtained estimation methods.

Method	Generic	Applicable	Scientific
CGT	The CGT method is generic, it has the A and B values for a broad range of vessels. Missing vessel types have been added.	The CGT method is simple to use and with little engineering knowledge it can be applied.	Papers on scopes on CGT are not cited a lot, ±20. However on Google 7430 hits are found on "Compensated Gross Tonnage". Assuming it can be said it is a known method.
Analogy	Analogy is a generic method because the expert making the judgement can come from any maritime sector.	The method is easily applicable, as long as there is an experienced estimator available. Analogical estimation can become difficult if no expert is present in the organisation.	Both analogical, parametric and engineering approach is a broad term where research can be divided upon. Therefore looking at the number of papers spoken in the section. Five papers have been discussed, analogy does not need to have a scientific foundation because an expert is mainly key.
Parametric	For a parametric approach the organisation can use it's own data, tailoring it to it own situation making it usable for the whole sector.	The method is broadly applicable but the bottleneck is the input, their are sector specific parameters but these could give unreliable results for a company.	12 papers have been discussed about the parametric subject, meaning it is not a unscientific method.
Engineering	Engineer method for engine power and propellers can be used general. But other technical aspects are harder to predict for all ship types. Therefore not all engineering methods are generic.	Using engineering estimation from literature to directly make estimations are difficult. But it could aid in getting engine kW from which a price can be gained but these are specific topics. Therefore it will be not used in the maturity model.	11 papers have been discussed about the parametric subject, meaning it is not a unscientific method.
Rapid engineering	Rapid engineering is still not used for all ship types but can be tailed to an industry.	The methods current available are not directly applicable, but could have great benefits because in an instance a lot of vessel engineering is know.	The papers discussed on rapid engineering like the packing approach have been sited a minimum of 35 times(Google scolar) thus there is a scientific foundation.

To conclude this section, four methods will be incorporated in the estimation maturity model, CGT, analogy, parametric and rapid engineering. The engineering approach will not be used, because it is deemed to specific for special cases. Also because these estimations need to be done at an early stage in the process elaborated calculations and engineering are not possible. Therefore rapid engineering, however limited in use, is incorporated because it can generate a design spectrum in a short amount of time.

2.4. Review of planning literature

Everybody has planned something in their life, maybe something small like a birthday party or an holiday trip. These are relative easy planning because the number of dependencies or stakeholders are small. But maybe a trip for two month to Australia will require more preparation and people might start writing things on paper to keep track. For organisations it is no different, one way or anther each organisation has a some sort of planning or road map to guide the processes. But as more tasks, dependencies, and stakeholders are involved a good planning can become essential to keep the project running smooth.

There are different methods to make, keep track and to improve the planning of an project. In this section the literature will be discussed on planning methodologies. The layout of the literature study was presented in section 2.1, as presented the planning literature will be divided into two main topics. Firstly a introduction will be made into the foundation of a planning, the project breakdown. After that the two topics are discussed, firstly planning uncertainty literature. Secondly the network analysis methodologies will be discussed. But first, the project breakdown.

2.4.1. Project breakdown

The first step when creating a planning is knowing which tasks need to be performed to finish the project. These tasks can be captured into a work breakdown structure(WBS), this commonly used method of presenting the task or work needed for a project. In section 2.3.7 it was already discussed that a WBS can also be used as a method for making bottoms op estimation. When the list of tasks is created the next step is to determine the relationship between the tasks

To get a clear image how tasks are linked and what the effect three questions are asked[19]:

1. What task must precede this task?
2. What task can be done in parallel?
3. What are the tasks that must follow this task?

When the tasks and their dependencies are known the next step is to create a network of the tasks, the next section will go into detail on current network diagrams and which one is the most suited for the problem of this thesis.

2.4.2. Network diagram

Knowing the task with their constrains and relations a network diagram can be made. Two network diagrams can be identified, activity on arrow and activity on node. Currently the activity on node are becoming more popular because it enhances the readability. Figure 2.6[128] shows an activity on node diagram, as shown each arrow contains an activity. What can be noticed is that compared to Figure 2.7[128] the readability of the activity on node is more easily.

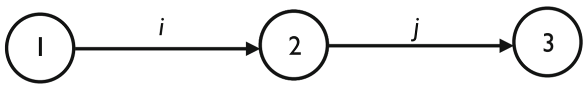


Figure 2.6: The AoA representation of activities *i* and *j*.

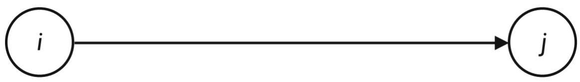


Figure 2.7: The AoN representation of activities *i* and *j*.

In Figure 2.8[17] an activity on node diagram is shown. The block for each activity contains two parts, earliest start and finish and latest start and finish. The difference between the earliest and latest start is called, the float. For elements on the critical path the earliest start and latest start are equal because delaying a critical activity will result in an increase in the total lead time of the project. An quick conclusion would be that the critical path has no float at all, but this is not true. For instance, a task had to wait on a specific water height, determined by the tide, if the activities before have a certain float because if they finish sooner they still have to weight on the tide and thus the total lead time will not change if the list of activities before are performed faster.

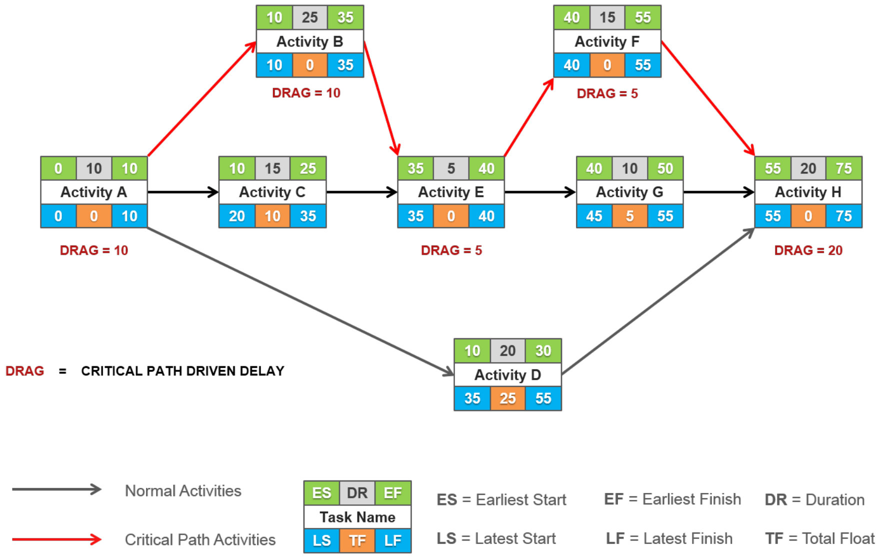


Figure 2.8: The AoN diagram with early and late starts.

Network diagrams as shown above can aid in the methodology for network theory, different research has been done using network theory as a foundation. The dissertation by *P. de Vos*[43] used edges and nodes to explore design for on board energy distribution systems to create designs in an early design stage, as discussed in section 2.3.9. *D. Reginter*[104] uses network theory also not for planning but to estimate, passages ways, electric and fire systems. *Cho, chung* and *Lee*[38] used the network theory for an automatic planning for block assembly in shipbuilding.

With the estimation, and network literature a planning can be made. But there is more to a planning than just creating it. The next section will concern with planning uncertainties and what method can be used to analyse these.

2.4.3. Uncertainty methods

The following section describes planning uncertainty methods. A planning is not 100% certain, maybe a shipment is delayed or work did not go as planned. There will always be a risk that the planning is delayed. But identifying or exploring possible uncertainty can aid a company to better react if a planning does not go to plan. The literature described below will focus on two parts, uncertainty modelling and risks, which create uncertainty. First, a uncertainty modelling technique PERT will be discussed.

2.4.4. Program evaluation and review technique

PERT is an analysing method to get insight in the minimum and maximum duration of a project. PERT was originally developed for the U.S. Navy special project office in 1958 to use in its nuclear submarine project[39]. PERT incorporates uncertainty in the project schedule. By using three time estimations, optimistic time, pessimistic time and the most likely time. This will give the possibility to make estimations with a certainty percentage. Because a percentage of certainty can be obtained, project schedulers can communicate this percentage to customers. For instance, there is a 80% certainty this project will be finished within X hours. Because it is not one fixed estimations but three estimations risk can also be incorporated, if a task has a high risk of delaying the pessimistic time will be larger, regarding the most likely time, than for a task with low risk.

As stated PERT uses the estimation of the optimistic, pessimistic and most likely time. The three times will be estimated by an estimator or chosen from historical data.

- optimistic time *(O)*

  This is the minimum time required to finish the activity, with this time estimation it is assumed that everything proceeds better than expected. This could be due to good weather conditions or worker morale.

- pessimistic time *(P)*

  The expected time when everything goes wrong, but excluding catastrophes. Such as the building catching fire.

- most likely time *(M)*

  The best estimation of the time needed to complete the task, is the most likely time.

With these three parameters the expected time can be calculated. With the PERT distribution more weight is given to the most likely time, see equation 2.2. Compared to the triangular distribution where all the three elements are weighted equally. The variance calculation is given by S^2.

$$T_e = \frac{O + 4 \cdot M + P}{6} \tag{2.2}$$

$$S^2 = \frac{(P - O)^2}{36} \tag{2.3}$$

Equation 2.4 gives the triangular distribution, comparing equation 2.4 and 2.2 the weighing factor difference for the *the most likely time* can easily be seen, 1 versus 4.

$$T_e = \frac{O + M + P}{3} \tag{2.4}$$

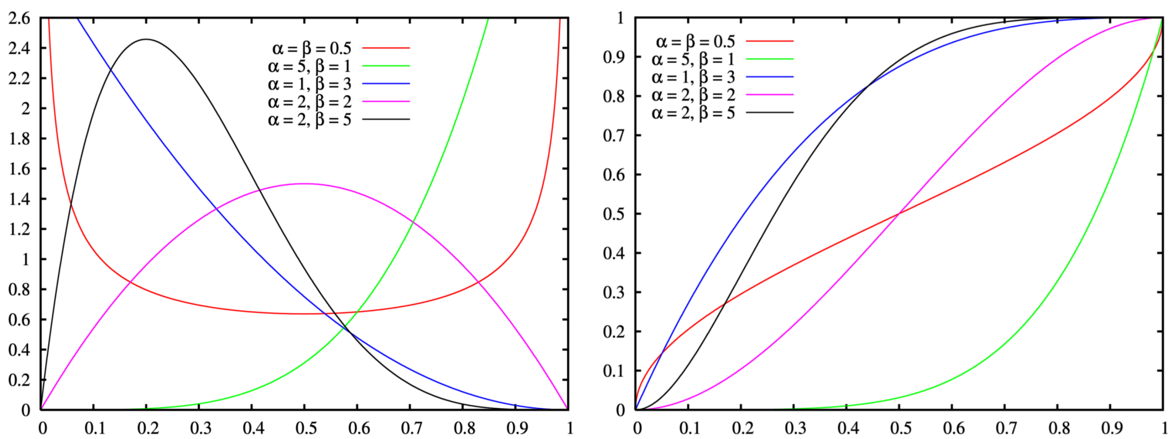
$$S^2 = \frac{O^2 + P^2 + M^2 - O \cdot P - O \cdot M - M \cdot B}{18} \tag{2.5}$$

The PERT is a special form of a BETA distribution which in term is family of the continuous probability distribution. The BETA distribution contains two parameters, α and β. To calculate these parameters from the three time indicators the following equations are used:

$$\alpha = \left(\frac{2(P + 4M - 5 \cdot O)}{3(P - O)}\right)\left[1 + 4\left(\frac{(M - O)(P - M)}{(P - O)^2}\right)\right] \tag{2.6}$$

$$\beta = \left(\frac{2(5 \cdot P + 4M - O)}{3(P - O)}\right)\left[1 + 4\left(\frac{(M - O)(P - M)}{(P - O)^2}\right)\right] \tag{2.7}$$

Figure 2.9[8] shows the Beta distribution, different α and β values are plotted to shows what the effect is of the different values. Figure 2.9aon the left shows the probability density function, what can be seen is that if P and O are the same the purple line is created. Thus an even distribution on the production completion. The black figures shows an BETA diagram that contains a longer p value, thus it is expected that the pessimistic value is longer then the time expected for the most optimal case.



(a) Probability density function

(b) Cumulative distribution function

Figure 2.9: Beta distribution

Figure 2.9b shows the cumulative distribution function, in essence this is the integral of the probability density functions. It shows the probability that the value on the Y axis will be less or equal than the value on the x axis. When looking again at the black and purple line, it can be seen that the purple line follows a symmetric patterns, because P and O are equal. And thus the value on the X an Y axis at $x = 0.5 = y$. Now looking at the black line the probability that Y is less then X increases. It can be read this way, the number on the x axis presents the day, thus the black line has a most likely time of completing the task of 0.2 days. Looking at the cumulative distribution it is expected that after 0.5 days the probability of the work being completed is ± 0.9. What is interesting is that the chance of the project actually finishing on the expected time is only ± 0.3. For the purple line it is logical that at 0.5 days a probability of finishing is 0.5 because the shape is symmetric.

Using the PERT method a estimation can be made concerning the probability of the real time a project will take. As explained above the probability of the project finishing on the expected time is, depending on the distribution, not 100% on the expected time, but less. This can create a planing with a number of certainty the project will be finished within this time.

One downside to using the PERT method in combination with a BETA distribution is the fact that three estimations are needed. These can be obtained from historical data or estimated by estimators. A benefit is that because a probability can be assigned a understanding takes place that calculated time is an estimation and thus not a fact. These estimates can be used as input for the expected timeT_e in a network diagram from which a critical path can be obtained.

2.4.5. Monte Carlo simulation

Manipulating the PERT estimates using Monte Carlo simulation can gain additional insight in risk and uncertainty in the schedule[73]. For instance, the probability of finishing the project within a certain time. Figure 2.10[87] shows a probability estimate, plotted on the X-axis is the project duration and the Y-axis shows the probability of completing the project on that time. When the project time increased the probability of completing also increases. This is a logical trend because when taking twice as long for a project it would increase the likelihood of completing it. These diagram can be made by using a Monte Carlo simulation.

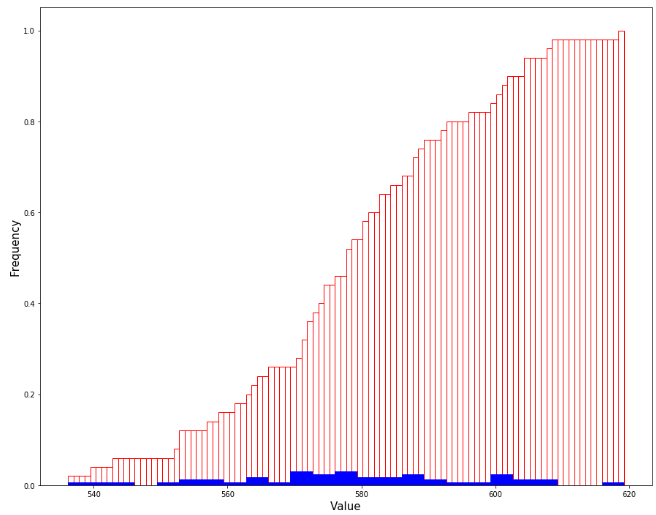


Figure 2.10: Monte Carlo simulation example.

The Monte Carlo method is a technique in which a process is simulated multiple times, with the inputs being randomly varied according to their given uncertainty for every individual run. By statistically evaluating the results of all runs the distribution and expected value of the results can be derived. That is why the Monte Carlo simulation is helpful with the PERT method, because there are three time estimations a time is selected within that range at the start of the simulation. Doing this n times gives a range of different completion times with corresponding. A simulation could select all the pessimistic time estimates and calculate the total time to complete the project, this is the longest duration with a completion certainty of 100%. Only selecting the optimistic values would cause the fastest production time. But the chance of this happening is low, approaching 1%. *M.R Duffly* [100] states these tools are not used broadly in ship production but says *"simulation-based project risk analysis will likely become a valuable tool for engineering managers"*, This is also concluded by other papers[71][70].

For a project the client might ask for a minimum probability of 85%, for big civil engineering project where the government(the client) asks for such a probability. The PERT method works best if there are multiple data points for a task, so it is possible to make a distribution and thus the estimation for pessimistic and optimistic.

2.4.6. Risks

Risk can be incorporated into a planning in different ways. A starting point is identifying which risks are presented by creating a risk register and identifying how to mitigate those risks. One such methods is the Failure Mode and Effects Analysis (FMEA)[94],*M.Ozkok* used this method to analyse the risks for the production of a casco. The effect of these risk are not directly incorporated into the planning. A risk method that is linked to the planning is the event chain methodology[42] it directly shows the implication of a risk, called an event, into the planning scheduled. Figure 2.11 shows the application of the event chain, the planning changes when an event is triggered, this mapping can see the event of such an event. The effect of these events can also be analysed by Monte Carlo simulation [78].

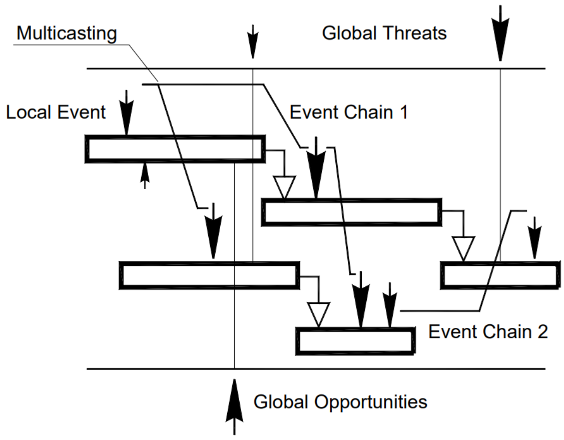


Figure 2.11: Event chain example

2.4.7. Network analysis

The following sections describe network analysis method that can be applied to further analyse the effect of changes or make better planning estimations. First critical path and critical chain will be discussed, followed by a section about network optimisation literature.

2.4.8. Critical path method

Now that the fundamental elements needed for the critical path are discussed, tasks, network and time estimation, the critical path can be made. The critical path is defined as *"The earliest possible completion time of the project is equal to the longest path in the network."*[128] and thus determines the overall lead time of the project. Decreasing the time in one of these activities would decrease the total lead time of the project. That is why companies are always looking out for the critical path or critical activities. If these are delayed to whole project will be delayed.

Figure 2.12[9] present an activity on node network diagram. The activity are indicated with the numbers and the corresponding time is placed right above the activity. Al activities need to be performed thus activity 7 cannot be skipped to get the the end, indicated by the number 11. Four routes can be identified in this example. To calculate the critical path in this example all the duration for each activity within a path are added. These added times result in the total time of the path. The path with the longest duration is, the critical path.

$$A = 1-2-3-6-9-11 \qquad C = 1-2-4-8-10-11$$
$$Duration = 22 \qquad Duration = 19$$
$$B = 1-2-4-7-11 \qquad D = 1-2-5-8-10-11$$
$$Duration = 19 \qquad Duration = 22$$

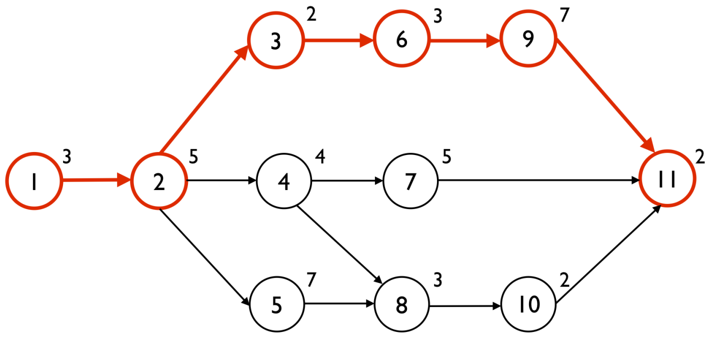


Figure 2.12: Graphical representation of a network with indicated critical path.

In this example two critical paths are present, route A and D. In a project multiple critical paths can be present, it is not limited by one path. This is a really simple example but gives the reader a clear example how the critical path can be determined. This example uses a single time per activity, here the T_e estimate from section 2.4.4 can be used. But is can also be extended, as explained in section 2.4.4 three time estimations per activity are used, to calculate the expected time(T_e). But these three times can also be used separately to investigate the effect if some activities are delayed or finished sooner. The critical path could shift if a task is delayed or finished sooner then planned. This could result in a schedule estimation where a level of certainty could be assigned to. A project owner could then communicate with the client the expected time with a certain percentage of certainty. This concept is also explained in section 2.4.5.

The critical path, as explained above, does not incorporate the capacity constraint. But this could be an important factor, craftsmen are scarce thus the amount of personal available is important factor for RvLs. A method that incorporates the amount of resources in calculating the critical path and thus the total lead time is the critical chain, the next section will elaborate further on the subject.

2.4.9. Critical chain

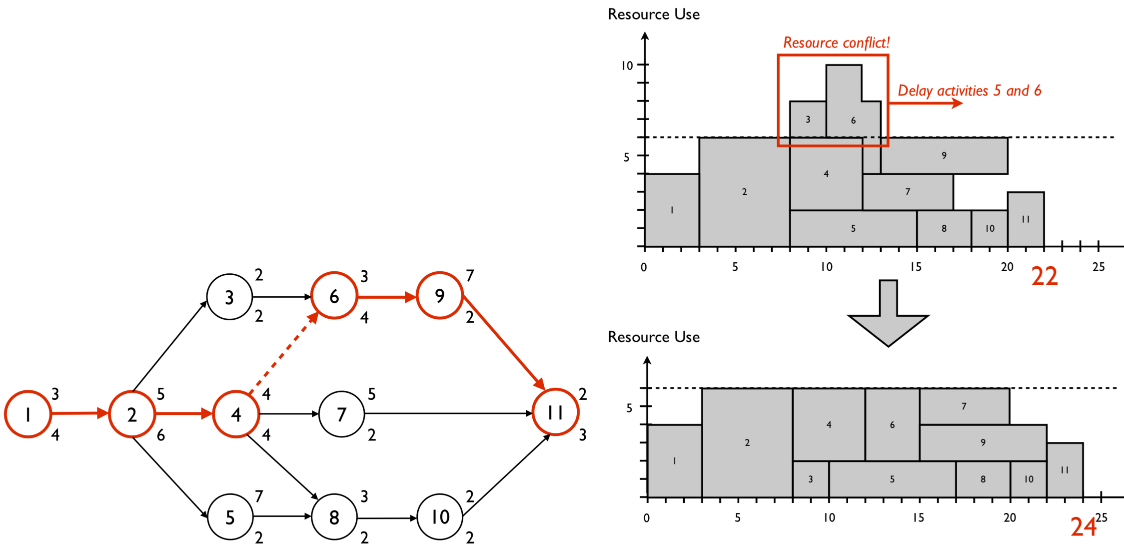
The critical chain method incorporates the resources needed in the network diagram[16]. In the other method the amount of resources are not incorporated, only the expected time, off course indirectly the estimated time is incorporated by the estimators when estimating the time needed for each activity. But when estimating the times separately it can be lost if the resources are still sufficient to perform the task also parallel. The critical chain emphasises the amount of resources in the schedule.

Figure 2.13b[9] gives a clear example how the critical chain works. Each activity from Figure 2.12 is represented by a 2 dimensional block, with resources needed on the y-axis and the time on the x-axis. The doted line indicates the maximum available resources. This figure simplifies that all the activities are bounded by the same type of resource. In reality a task is bounded by several resources, which would in mean multiple graphs need to be made to check for if there is no conflict of each resource.

Figure 2.13a[9] shows the new critical path, incorporating the maximum amount of resources a new lead time is obtained, in this example the time in increased to 24. Also the path itself changes, in Figure 2.13b the blocks 3 and 6 need be fall below the maximum resource level. This will cause the activities to shift to make room for activity 3 and 6, which results in a longer lead time. Figure 2.13a shows the new diagram where the critical path is shifted to $1-2-4-6-9-11$. The new critical path is not a chain of interlinked activities any more. A dotted line indicates a resource link between activity 4 and 6, this line will ensure that activities 4 and 6 are not scheduled simultaneously. Because 6 has to come after 4 an relationship is created and the critical path will follow this path.

The critical chain is a good method to get an insight in the effect of resources on the total lead time. It however adds an additional level of complexity by implementing all the resources in the model itself.

Another method is also called the critical chain. Goldratt states in his book, the critical chain, that for a project there should be a single buffer and not a buffer for every project[52]. Figure 2.14 shows two projects, the left side2.14a presents a conventional critical path planning with a float or buffer at the end of every task. What Goldratt states is that these floats needed to be combined to get an buffer at the end, he states that this approach will reduce the total lead time of the project. One reason is, following Parkisons law, that the task will require the time that is available. The new project planning will have the format shown in Figure

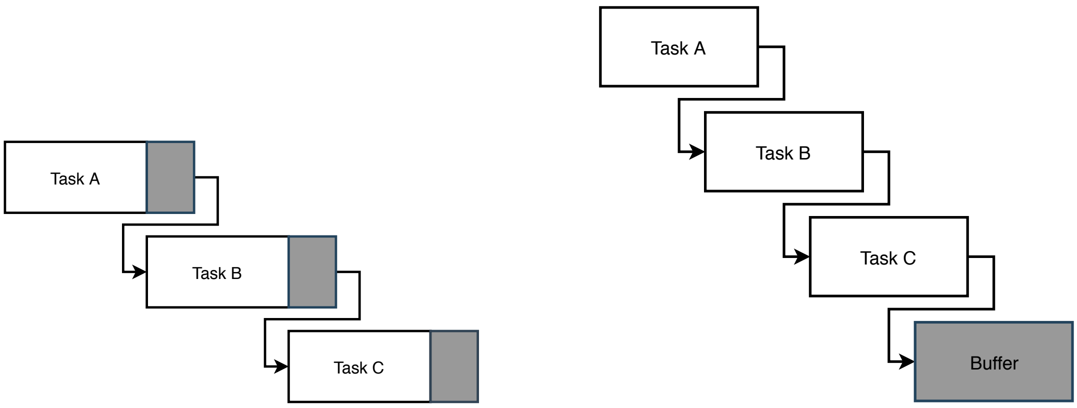


(a) New critical path diagram after resource compliance.

(b) Representation of a resource conflict.

Figure 2.13: Critical chain method

2.14b. One paper from Università Politecnica delle Marche(Italy) performed a case study of the critical chain on super yachts[25]. In which they state that using the critical chain method the % of lateness drops by 15%.



(a) Schematic of critical path

(b) Schematic of critical chain

Figure 2.14: Comparison between critical path and critical chain.

2.4.10. Planning optimisation

The past sections have focused on literature regarding network analysis, what the effect are of risks and network analysing methods such as the critical path. Making a planning can also be done automatically with the ability to optimise the planning. Different paper are written for planning optimisation, predominantly the outfitting phase. *Wei*[134] and *qin*[137] both use algorithms the create a planning optimisation. *Rose*[105] created the Integrated Shipbuilding Planning Method, the paper concluded that the method outperformed a manually generated planning because the workload was better distributed over the outfitting process.

Another paper looked at the planning process for ship building blocks[38] using network scheme to represent the process. But many more automatic planning and optimisation strategies could be thought of. One could implement smart routing used for small cities[121] to evaluate the flow of material in a ship and deal with possible bottlenecks such as doorways. What optimisation method would be the most useful for an organisation needs to be assessed by the organisation themselves, because most tools aid the current planners and still need company input for their correct workings[105].

2.4.11. Conclusion planning literature

Various method concern planning have been discussed, during the discussion of the literature it became clear that for different methods different levels of maturity is needed. Making a network diagram can be done using a simple project tool like Microsoft project, but for a PERT analysis the company already needs to be in the possession of production data to make these calculation with an low uncertainty. This example illustrates that different methods will need different levels of maturity.

Table 2.6 presents the different methods discussed in this section. For each method an assessment is given where it will be stated if the method will be used in the maturity framework or not. The framework will indicate possible planning methods corresponding to a maturity level, therefore methods will be excluded if they do not fit into the subject.

As presented in the table, all the methods described in this literature chapter will be used in the maturity model. The methods described in the literature studies are the most common planning methods, there are variations of the varies methods but for the maturity model these methods are sufficient. The planning optimisation is not an assessment of the current data,like the other methods, but focus on improving the planning. Continuously improvement is necessary in order for an organisation to grow and therefore it is important to incorporate.

Table 2.6: Table with summation and assessment of the different obtained planning methods.

Generic	Applicable	Scientific
network diagram Creating network diagram is applicable for all industries, thus also for the maritime sector, therefore it is generic and can be used for the production of different vessels.	Making an network are one of the first steps in creating a planning and thus applicable for the planning maturity model.	Books and papers using network theory have been cited over a 1000 times, therefore using a network is not a novel idea.
PERT and Monte Carlo To perform PERT or Monte Carlo an Organisation needs to submit their own data, but the method itself is generic and can be used for all sectors.	Application of the method depends on the data available of the organisation. Tracking your data depends on your maturity, therefore it will be used in the maturity model.	Monte Carlo and PERT is not a novel idea, together the first few papers on scopes contribute over 2000 citations.
Critical path and chain Both these methods use the network diagram to analyse which tasks are critical a if the resources are levelled, critical chain. As the network diagram they are not bounded to an industry and thus generic. Which means for this criteria it is applicable for the maturity model.	Using these methods needs more understanding then only creating a network, more expertise is needed. If this is available in the company in can be applied in the maturity model.	Critical path is well known with over 1000 citations concerning the subject, critical critical chain has less citation.
Event Chain The event chain methodology is an industry unspecific method to sea the effect of a risk on the planning, therefore is applies to the generic criteria.	The method is applicable if the risks have been mapped within the organisation. Having this risk registers depends on the maturity of the organisation. If these are know it is applicable, therefore it will be used in the maturity model.	On Scopus less articles are found concerning event chain, however on Google more then 47.000 hits has been found.
Planning optimisation Planning optimisation in literature are limited to outfitting and casco. But because the theory behind it is key it can be said the the methods are generic. Also optimisation techniques from other industries, like routing, could be used in the maritime industry.	The current methods cannot be implemented *out of the box* but once implemented could be applicable for the planners within the maritime industry.	Planning optimisation is not an out of the box solution, but needs to be developed for the specific case. Therefore it is less relevant what papers have written about is, but still a good starting point.

2.5. Conclusion literature study

In this chapter three topics where discussed, maturity, estimation and planning literature. The literature found has been assessed on three criteria, generic, applicable and scientific relevance. In short, generic means that the literature found needs to be useful for the whole maritime industry and not a specific vessel type. Applicable is if the method or literature can be applied, if a method is to abstract it is possible that it cannot be implemented. Lastly, scientific, the framework that will be created needs to consist of methods that are scientific accepted. With these three trade off criteria the literature has been assessed. The assessment can be found in the specific sections. Below the main conclusion on each subject are summarised answering the sub goals defined in 1.2.

2.5.1. Maturity

1. Identify current maturity frameworks from literature.

From the literature study into maturity models three conclusions can be drawn, firstly there exist mainly two types of maturity models, the first one is concerned with the process if process are well documented for instance. The second concern which methods to use for the maturity level of the company. The second conclusion is that there are no integral planning and estimation maturity models. Finally there are limited maturity models concerning the maritime industry.

To recap the conclusion stated in section 2.2.3, there is a gap in the maturity models for the maritime industry. Especially a maturity model where different methods for estimation and planning are combined, are not presented. Because industry independent process models are already available, this thesis will create a method maturity framework specifically for the maritime industry.

2.5.2. Estimation

2. Identify (man-hour)estimation methods from literature.

During the investigation of estimation literature three main conclusions can be drawn. Firstly, man-hour and cost estimation methods found in literature concern mainly vessel specific estimation factors, e.g. for a tanker or a cruise ship, and less methods that can be used for the whole maritime sector. Secondly, most estimation methods follow the analogical, parametric and engineering methods trend. The final main observation is that there are no specific guidelines when to use which method. The cost estimation method from NASA indicate a possible sequence of estimation methods. However, it does not directly state when certain methods can be used.

It is observed that there is not a framework where it states when certain estimation methods are usable and when not. This could result in choosing incorrect estimation methods for the estimation that need to be performed. As stated in the section 2.3.10 four estimation methods where chosen based on the trade-off criteria. The four methods are, CGT, analogy, parametric and rapid engineering.

2.5.3. planning

3. Identify planning methods from literature.

From the literature study for planning it can be concluded that planning is a subject that is not bounded to a single industry and that most methods are used over the whole spectrum. The second conclusion is that all planning methods discusses in section 2.4 can all be used in the maturity framework. The last conclusion is that there are a lot of methods that aid in creating a better planning, or give insight into possible uncertainties. What is missing however, is the sequence in which these methods should be used.

The literature study gave answer to sub goals one, two and three presented in section 1.2. What became clear is that there is a range of method available to make man-hour and planning estimations. What is missing is that there is not a framework where organisation can asses which methods to use to get the lowest possible level of uncertainty for the organisation. Using methods not suited to the organisation could lead to estimation with a higher uncertainty. This thesis will develop two maturity frameworks to aid organisations in making estimation with the lowest uncertainty for man-hour estimation and planning lead times.

3
Development of the theoretical maturity framework

Chapter 2 presented three main topics, maturity frameworks, estimation methods and planning methods. During the literature study it became clear that there is a broad range of estimation and planning methods. These methods range from simple methods, such as CGT, to more complex methods, e.g. the packing approach. This was the same for planning methods, ranging from analogy to Monte Carlo simulations. However, during the literature study it became apparent that there is not a method maturity framework available that aligns these methods to the maturity of an organisation. For instance, a company that just started does not have the data available to perform parametric estimations, based on old company data. Secondly the combination, or alignment, of estimation and planning methods is not existing.

This chapter will answer the following two researches questions, using the conclusions from chapter 2.

- *Develop a maturity framework to classify man-hour estimation uncertainty based upon the maturity of the organisation.*
- *Develop a maturity framework to classify ship production lead time estimation uncertainty based upon the maturity of the organisation.*

The chapter is structured as followed, firstly the theoretical model will be created that act as the foundation for both maturity frameworks. Secondly both frameworks will be presented in section 3.1.1 and section 3.1.2. These two sections are followed by a discussion about the frameworks. The second part of the chapter, section 3.2, will concern the theoretical models within the levels, giving the reader more insight in the different levels. Finally, section 3.3 present alignment between the estimation and planning framework.

3.1. Theoretical foundation

A theoretical model is created which will act as the foundation where the estimation and planning maturity framework will be based upon. As discussed in the literature study SPICE is often used as a foundation for new maturity frameworks. However, in this thesis SPICE is not used as a foundation. The reason why SPICE is not used, is because it acts as a foundation for process maturity frameworks, this thesis sets out to create method maturity framework. Where organisation can see directly which methods they can use based on their maturity. No method maturity framework foundation, like SPICE for process maturity frameworks, was found where the author of this thesis could build upon. Therefore, this foundation is newly created using the knowledge gained by the author during the literature study. The foundation has been discussed and re-evaluated by members of the TU Delft and employees of RvLs. The author of this thesis encourages people to re-evaluate and discuss the proposed maturity frameworks in order to improve it in the future.

The theoretical foundation contains three elements,1) the interaction between the maturity levels,2) the connection to estimation uncertainty and 3) nodes, input an output.

This theoretical foundation will be used to create the two maturity frameworks. The first theory is called the *The estimation pyramid*, the second theory is called *The planning pyramid*[1]. First the theory behind the framework will be explained followed by the specific maturity framework in section 3.1.1 and 3.1.2.

[1] Both names are created by the writer of this thesis, these are not industry standards.

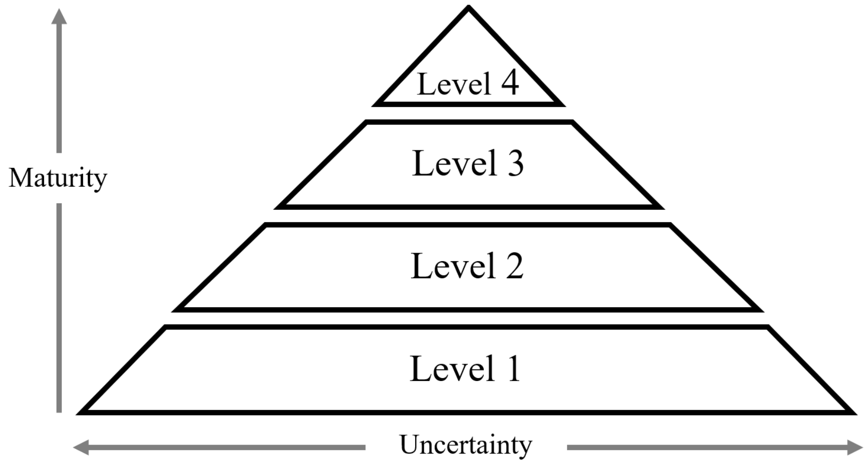


Figure 3.1: Representation of the theoretical pyramid structure.

In Figure 3.1 the basic layout of the model is shown, following a pyramid layout. The The bottom of the pyramid represents the first level of maturity, if the organisation grows in maturity it will move to the subsequent level, building the pyramid.

The maturity is linked to the uncertainty, the width of the X-axis indicates the amount of uncertainty. If an organisation gains maturity, and thus shift to a higher level, the width of the X-axis decreases and thus the uncertainty decreases[2]. This is results in the the first hypotheses of the maturity framework:

> *H1*
> *A higher maturity level results in a estimation with a lower uncertainty.*

The levels are designed in such a way that to reach a certain level the company needs to be able to perform the preceding levels. This can aid as a blue print for a company, if it wants to reach level *X* it first needs to be able to perform the preceding levels. If it is not able to execute the preceding levels the company may not be in a maturity state the perform are more complex level. For instance, if a company want's to create fully automated project schedules but is still not able to create a schedule by hand then if first needs to be able to perform such a task. Otherwise the deeper knowledge behind the schedule is not known and errors or mistakes by the automated projects cannot be spotted or fixed. Naturally there can be cross over but skipping a step is not recommended as explained by the previous example. This will be further elaborated in the discussion of the maturity framework in section 3.1.3.

The pyramid has three edges, two inputs and one output, shown in Figure 3.2. The first input are the *project specifications*.This input can contain multiple project specification($IN_{P,i...n}$ input, project, specifications), e.g. vessel dimensions but also interior dimensions, it depends for what purpose it will be used. This block is placed on the left side of the model. The input will not be directed to one specific block because the size of the pyramid can change depending on the maturity, the input will shift to the current maturity level of the company. The second input is the *Organisation input*($IN_{O,i...n}$ input, organisation, data) this input varies between the different levels. Increased maturity means that more knowledge is present withing an organisation, this increased knowledge will be used decrease the uncertainty. The last edge is the output($Out_{E,i...n}$ output, estimation, vessel parameters) these are man-hour estimation for different vessel parameters chosen by the user or a lead time. This edge is also not linked to a specific level but moves with the maturity.

An organisation will need to evaluate it's current maturity level, two type of evaluations will need to be performed. The first one, is if the organisation can deliver the required inputs for the specific level. This check is a simple yes or no, if the company cannot deliver the required input it has not reached that maturity level. In that case it first needs to obtain the required input data. The second evaluation is a judgement of the organisation capabilities, a level may require a certain discipline, like computer programming, if this discipline is not present in the company it first needs to be obtained before it can proceed to this level.

[2]The Figures in this chapter represent a schematic overview of the maturity pyramid, the relative width of the X-axis between the maturity levels is only a indication and might be different in real life. E.g. the uncertainty of level 1 could be twice as much as level 2.

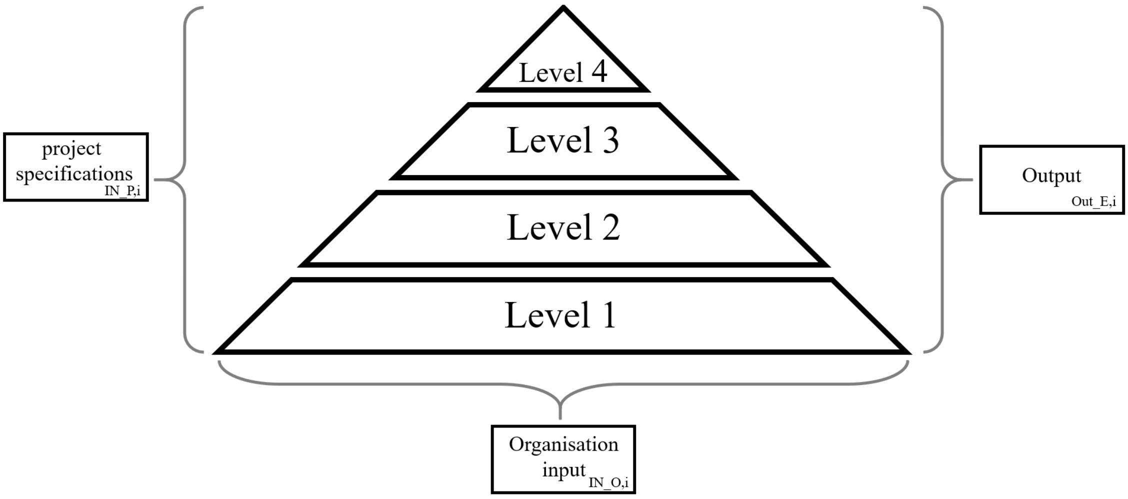


Figure 3.2: Pyramid model with corresponding edges.

In the following sections the two theories, *The estimation pyramid* and *The planning pyramid*, will be explained using the model described above.

3.1.1. The estimation pyramid

For the estimation pyramid four levels of maturity are identified, the different levels are presented in the itemise below and graphically presented in Figure 3.3.

Figure 3.2 presented the foundation of the maturity pyramid with three edges in this paragraph these edges will be disused with relation to the *estimation pyramid*. The pyramid has one input on the left, $IN_{P,i...n}$, this list contains specifications of the project such as, length, gross tonnage (GT), engine Kw. But that can depend on the company who will use this framework. The output of the framework, $Out_{E,i...n}$ are man-hour estimations. The depth of these man-hour estimation can depend on the organisation. In a high level estimation the *i* may stand for the total production hours, in a more detailed estimation the *i* could stand for the man-hours needed to complete a specific task. The last edge is the input from the organisations, $IN_{O,i...n}$, these inputs differ based on its maturity. E.g. a low mature organisation might not input production data. These inputs are shown in table 3.1.

The theory contains four levels of maturity, the order of the maturity levels is established by the writer of this thesis using the NASA CER framework as guideline and the finding obtained during the literature study on estimation methods. As explained, the levels work in chronological order, before level 2, *the analogical phase*, can be performed the organisation first needs to be able to perform level 1.

- Level 1 *CGT*
  The first level is the level where the lowest amount of maturity is needed. CGT is an easy method to estimate production effort.

- Level 2 *Analogical*
  In the the analogical phase an expert estimates the production effort based on his experience in building other vessels.

- Level 3 *Data driven*
  After the analogical phase the data driven phase can be used, this level uses parametric and a heuristics based on older vessels to estimate the new production hours.

- Level 4 *Rapid engineering*
  In the rapid engineering phase simulation models are used to speed up the engineering process. It brings engineering knowledge that normality is only obtained in a later stage earlier in the process. This additional knowledge will aid in determining the production effort.

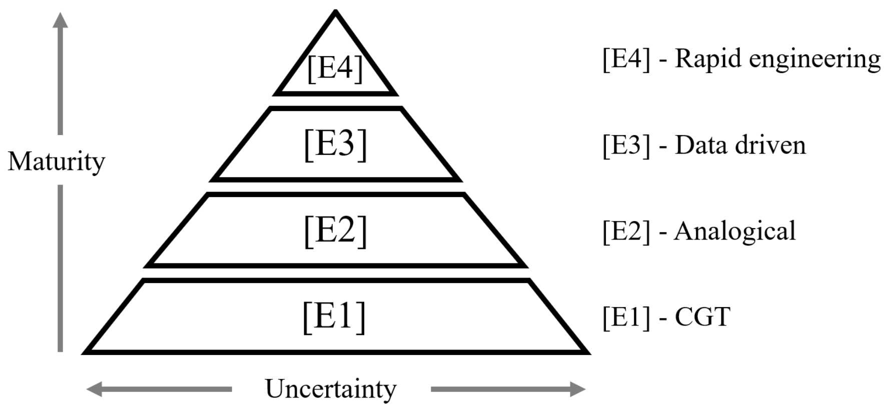


Figure 3.3: Graphical representation of the *estimation pyramid*.

3.1.2. The planning pyramid

For the planning pyramid six levels of maturity are identified, the different levels are presented in the itemise below and graphically presented in Figure 3.4. The order and type of maturity level have been created by the author of this thesis, based on the knowledge gained during the literature research. In section 7.1 the

Table 3.1: Table with the trade-off for each method.

level	Method(s)	Input(s)
level 1 *CGT*	• CGT method	• CGT values
level 2 *Analogical*	• Analytically • Expert judgement	• Expert experience
level 3 *Data driven*	• Parametric • heuristics	• Organisation data
level 4 *Rapid engineering*	• Automated design • Packing approach • graph theory • rapid prototyping	• validated simulation tools • Skilled simulation operators

order will be further discussed. As stated, the pyramid contains three edges, two inputs and one output. Project input ($IN_{P,i...n}$), are man-hour estimations from the estimation pyramid, and project characteristics. The organisational input($IN_{O,i...n}$ could be production times or experts experience. Lastly, The output edge, $Out_{E,i...n}$, is the planning with corresponding lead times. As with the estimation pyramid, a higher maturity level should result in a planning with better accuracy. E.g. the development of a realistic planning, which is less prone to the planning fallacy[49]. A higher maturity level could also result in a planning which is more risk robust, level 5. Or using optimisation to plan more efficiently, in level 6. From section 3.2.5 till 3.2.10 each level will be discussed in more detail, including, assessment criteria, model inputs and a proposed model.

- Level 1 *Analogical*
  The first level an organisation starts with is the analogical phase, in this phase an expert will judge the total duration of the project based on previous experience.

- Level 2 *Resource inclusion*
  With the inclusion of resource the lead time of tasks can be predicted with a higher certainty.

- Level 3 *Network phase*
  Creating a network planning all the tasks are linked to each-other which creates a network of the different tasks. Because the tasks are linked a critical path analysis can be performed in this stage.

- Level 4 *Data driven*
  If the company gains more data over it's lifespan more planning methods become available. With the data phase options such as PERT become available.

- Level 5 *Risk*
  Risk will give uncertainties, what happens if a component is not delivered on time? Knowing the impact and assessing what would happen will reduce the uncertainty of the planning. Methods such as event chain methods such as event chain can create more understanding into the effect of an event.

- Level 6 *Optimisation*
  The last phase is the optimisation. When all other levels are reached the next step is not only reducing the uncertainty but optimising the schedule in finding smart methods the reduce the risks or the lead time. Smart routing or scheduling could decrease the total lead time of the project.

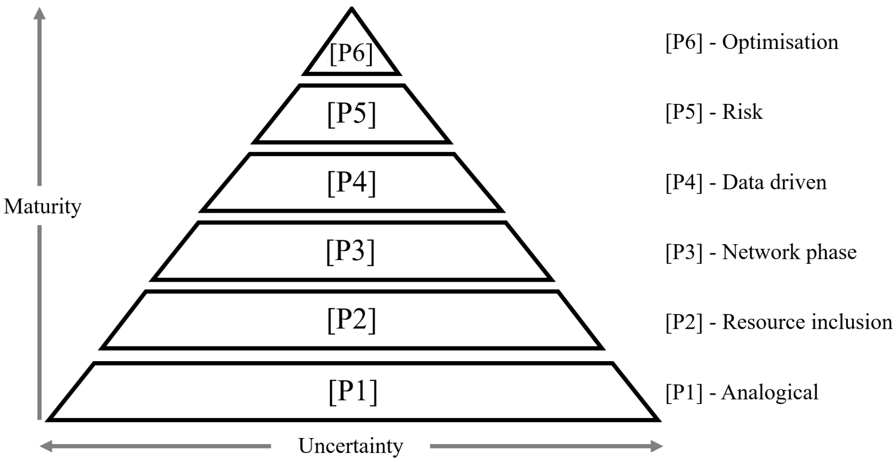


Figure 3.4: Graphical representation of the *planning pyramid*.

Table 3.2: Table with the trade-off for each method.

level	Method(s)	Input(s)
level 1 *Analogical*	• analytically • Expert judgement	• Expert judgement
level 2 *Resource inclusion*	• lead time	• resources • environment bottlenecks
level 3 *Network phase*	• critical path • critical chain	• network schedule
level 4 *Data driven*	• PERT • Monte Carlo	• Company data
level 5 *Risk*	• Event chain	• Risk assessment
level 6 *Optimisation*	• Smart routing • Production automation	• Validated simulation tools • Skilled simulation operators

3.1.3. The pyramid discussion

The effectiveness of *the estimation pyramid* and *the planning pyramid* can differ between organisations. The main reason for this difference is the quality of the organisation input. In this section a few scenarios are discuses that could happen with different input quality or a false maturity level.

Figure 3.1 shows the ideal situation, with the increased maturity the uncertainty should decrease. However the following hypothesis is defined.

> *H2*
> *Performing a maturity higher than the current maturity of the organisation increases the level of uncertainty.*

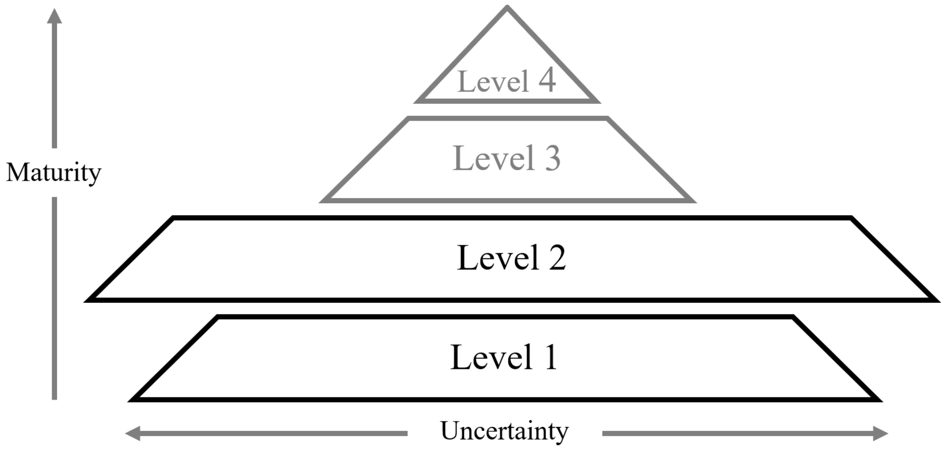


Figure 3.5: Uncertainty if the wrong maturity level is chosen.

To illustrate this hypothesis the following example is made, a company used to estimate their new project using a estimator that has been working at the company for over 20 years, his estimations have on average uncertainty of 15%. The company chooses to go to level 2 but did not document their data correctly which gave corrupt input data for level two, or did not have enough data points. This meant the uncertainty actually increased by chaining to a different level, Figure 3.5 illustrates this this difference. Figure 3.5 shows jump in uncertainty due to the new method, the uncertainty might decrease a bit but if the foundations are not sufficient it will never create a lower uncertainty then with the first level.

This example can be made for all the different levels, because with higher levels the complexity of the methods increase which increases the risk of making errors. The organisation using the framework should critically asses it’s maturity level before changing to a different level, changing to soon could give unreliable results. Ultimately these bad results could lead to the company not trying to increase it maturity because it thinks their current methods is the most reliable, missing out the benefits of a higher maturity level.

With higher maturity levels validation of the data and models become more important. Models can be seen as black boxes by the users, they cannot see how the simulation or the calculations take place. This means that when the model present the result they cannot see if they are correct or not. Because most models present a specific number a false sense of accuracy could be felt.

3.2. Theoretical model description

The previous section presented both the planning and estimation pyramid. Possible methods where stated which can be found within the maturity level, such as CGT method for level 1. In this section the level will be explained in more detail. First discussing the levels of *the estimation pyramid* followed by the discussion of *the planning pyramid.* Not all levels will be explained in the same level of detail, this is due to the fact that the higher levels become more complex and will be outside the scope of this thesis, but a good starting point for a sequel study for the refinement of the model.

The sections below are structured the same way, first a brief explanation will be given about the maturity level, secondly a table will be presented with the organisational input and the assessment criteria, finally a graphical description of the model[3] will be given.

3.2.1. Estimation-Level 1 *CGT*

Level 1 uses the CGT method described in section 2.3.2. For this level only little information is needed and every company should be able to perform this method. Figure 3.6 show the model needed to perform level 1, *Effort indication Production* in this thesis will be man-hours but other organisations might use a different output, e.g. machine running hours, length of welds. Table 3.3 gives a summary of the model input and the assessment criteria, these are defined based on literature study from section 2.3.2.

Table 3.3: Table with model input and criteria for estimation level 1.

Model input	Assessment criteria
• A and B values for ship type	☐ Engineer at organisation ☐ CGT values

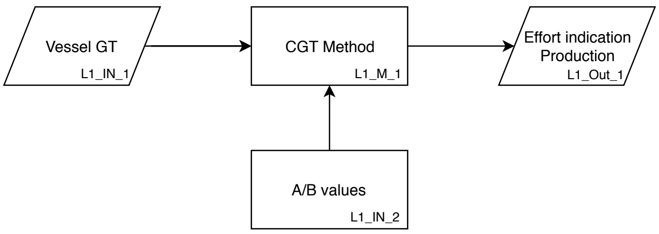


Figure 3.6: Schematic model of maturity estimation level 1.

3.2.2. Estimation-Level 2 model *Analogical*

The second level is the analogy level. This method is widely used in the industry. Figure 3.6 shows a schematic of an analogy approach in estimating the production times(*L2_Out_1*). The model is based on the current practices for analogy that is used at RvLs, an estimator uses the vessel specification and matches a reference vessel that has similar specifications(*L2_IN_2*). The expert will make an estimation for the new vessel based on the reference vessel and adjust time values accordingly(*L2_M_3*).

There are three assessment criteria to perform this maturity level, first the organisation needs to be able to perform the preceding maturity level, in this case the CGT method. Secondly the organisation needs an expert capable of making these judgement and there need to be some reference data to base his predictions on, these assessment criteria are also stated in the NASA cost estimation handbook[7]. Table 3.3 gives a summary of the criteria. In the table the necessary model input is also specified, the reference vessel. This input also corresponds to block *L2_IN_2*.

[3] All the models presented in this chapter are developed by the author of this thesis.

Table 3.4: Table with model input and criteria for estimation level 2.

Model input	Assessment criteria
• reference vessel data	☐ Perform preceding level ☐ Estimation engineer ☐ Data available of a reference vessel

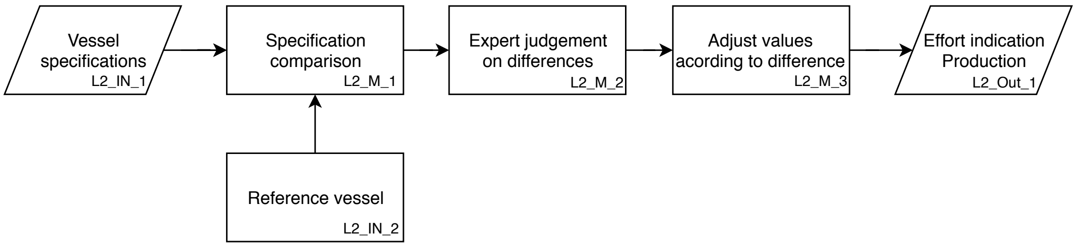


Figure 3.7: Schematic model of maturity estimation level 2.

3.2.3. Estimation-Level 3 model *Data driven*

The next step in the maturity level is a data driven approach, to perform this level a more elaborate model is needed, shown in Figure 3.6. The model consist of two parts, specification refinement(*L3_M_2)* and the conversion model(*L3_M_4*). During the early design of the vessel certain specifications are not acquainted. From reference data other specification can be estimated, to get a judgement of the sub level parameters(*L3_M_1*). Sub level parameters can be engine power(Kw) or the amount of floor space(M^2) for the crew area. The second part of the model is the parametric model, these are obtained from historical production data*(L3_IN_2)*. Both parts of model come together the conversion block(*L3_M_4*) where the specifications are translated in hours to give a time indication in the production phase(*L3_Out_1*).

To assess the suitability of estimation level 3 on a organisation, a set of particular assessment criteria have been defined as presented in table 3.5. The criteria are created by the author of this thesis, but are in line what is recommended by the *International Society of Parametric Analysts, ISPA*[92]. A key criteria is the minimum data points[4] to perform this level, in section 2.3.4 was stated that a minimum of 25 data points are needed. It needs to be noted that this is the minimum required amount of data points and that depending on the data still some scatter might be present. The data that will be used needs to have the same credibility, e.g. same unit or method the data was obtained. The last criteria is, usage policy and procedures, how to use the data driven level. User need to know how to appropriately use the model and know the resolution, e.g. results may be correct within a 10% range, the user must be aware of this error margin.

Table 3.5: Table with model input and criteria for estimation level 3.

Model input	Assessment criteria
• Organisational data • heuristic data	☐ Perform preceding level ☐ Data engineer ☐ Minimum of 25 data points ☐ Data should be are credible and verifiable ☐ Validated parametric model ☐ Usage policies and procedures

[4]The type of data points can be company specific, one might have GT over man-hours.

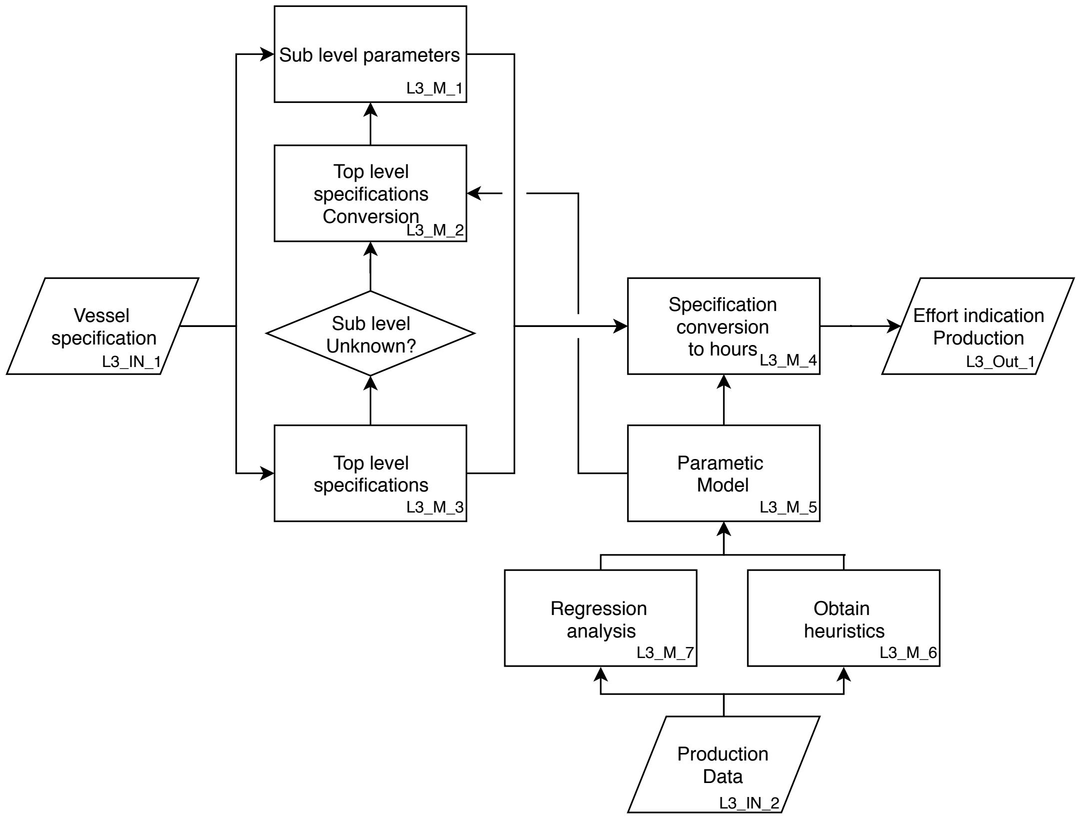


Figure 3.8: Schematic model of maturity estimation level 3.

3.2.4. Estimation-Level 4 model *Rapid engineering*

The last level is *Rapid engineering*, the key of this level is that more specification and data become available about the vessel. Normally this data only becomes available in a later stage if the engineers have designed the vessels in more detail. But by using smart algorithms, such as packing approach, more information becomes available and thus a better estimation can be made in the tender phase. Figure 3.9 present the schematic of the model. The model consist of two main parts, the rapid engineering model and the time estimation. The rapid engineering model *(L4_M_1)* is only indicated by a single block because the company will need to implement their model into this model. The output is a general arrangement (GA) /Layout of the vessel*(L4_M_1)*, this will be the input to the second phase, translation of GA/Layout into a time indication. This could be done based on industry production standard, such as weld time, and the parametric model for internal production times. Because two models are used it is important that both are validated, if the rapid engineering model is correct but the regression model from level 3 is never validated the outcome of level 4 might not be correct.

Table 3.6 indicates the model input and the assessment criteria for the organisation[5]. As stated before the rapid engineering model and the parametric model needs to be validated before the organisation can switch to the last level. As mention before it is not advised to skip a step in the pyramid, level 4 shows why this is important. If level 3 was skipped their would not be a validated regression model which would affect the accuracy in level 4.

[5]These criteria are established by the author of this Thesis, based on knowledge gathered during the literature study.

Table 3.6: Table with model input and criteria for estimation level 4.

Model input	Assessment criteria
• Historical data • heuristic data • industry production times	☐ Perform preceding level ☐ Model engineer ☐ Validated rapid engineering model ☐ Validated parametric model ☐ Usage policies and procedures

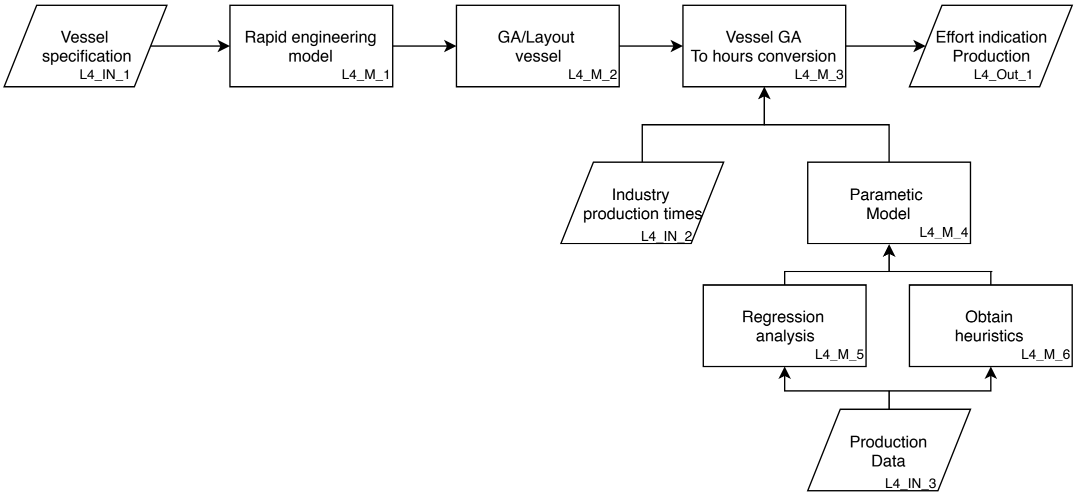


Figure 3.9: Schematic model of maturity estimation level 4.

3.2.5. Planning Level 1 model *Analogical*

The first step in the planning pyramid is the analogical approach. In this level an expert will receive the production time indication *(P_L1_IN_1)*. For instance, the total number of hours for the production of the teak deck. He will convert these total hours to a lead time based on his experience, workers available, suppliers, etcetera. He will then order the lead time's of the different task into a production sequence what in his mind will be the optimal production sequence. Finally he will create the planning, this could be in the shape of a Gantt chart.

Table 3.7 presents the input and the criteria needed to perform this maturity level. To perform this level only a Planning professional is needed and an estimation of the time required.

Table 3.7: Table with model input and criteria for planning level 1.

Model input	Assessment criteria
• Effort indication production	☐ Planning professional

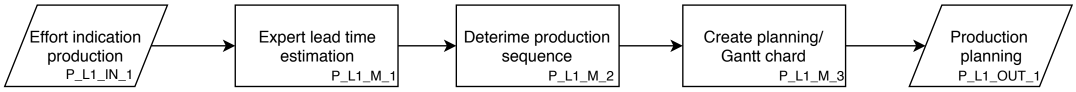


Figure 3.10: Schematic model of maturity planning level 1.

3.2.6. Planning Level 2 model *Resource inclusion*

The next level is the resource inclusion level, this is an addition to level one including of an automatic lead time calculation*(P_L2_IN_1)*. The steps following are the same to level one, thus a professional planner still needs to make the production sequence.

To perform this level, two more inputs are needed,*(P_L2_IN_2)* and *(P_L2_IN_3)*. Also a lead time calculation model needs to be present. These are both presented in table 3.8.

Table 3.8: Table with model input and criteria for planning level 2.

Model input	Assessment criteria
• Effort indication production • Resource availability • production constrains	☐ Perform preceding level ☐ Planning professional ☐ Validated Lead time model

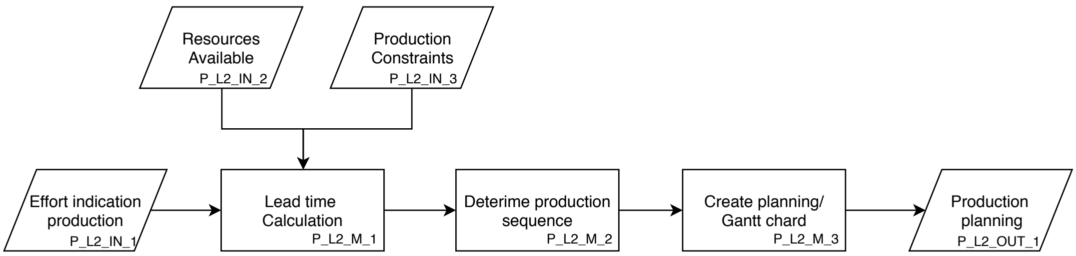


Figure 3.11: Schematic model of maturity planning level 2.

3.2.7. Planning Level 3 model *Network phase*

The next step in maturity is the network phase, in this phase the planning will be automatically arranged in a network schedule. This means that all tasks are linked to each other, this is especially beneficial during the project because if a task is delayed all depending tasks shift automatically. In block *(P_L3_M_2)* the lead time and a predefined network schedule are combined to create a planning. The predefined network, *(P_L3_IN_4)*, is a network of the different tasks all ready linked. The most projects follow the same production pattern and thus can the task sequence can be predetermined.

The addition to the previous level is a model that combines the network and the lead times, table 3.9 shows the criteria needed for this level.

Table 3.9: Table with model input and criteria for planning level 3.

Model input	Assessment criteria
• Effort indication production • Resource availability • production constrains • network schedule	☐ Perform preceding level ☐ Planning professional ☐ Validated Lead time model ☐ Validated network model

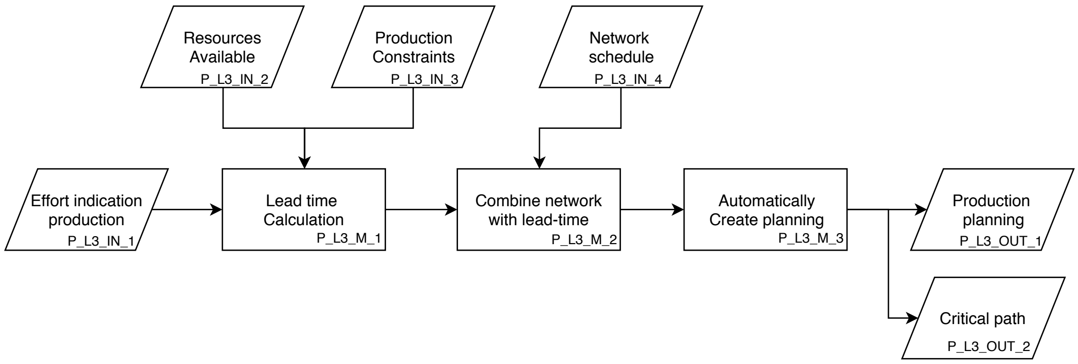


Figure 3.12: Schematic model of maturity planning level 3.

3.2.8. Planning Level 4 model *Data driven*

When a company has a lot of useful data it can be used to make better planning predictions, in section 2.4.4 techniques such as pert and Monte Carclo are discussed. The model presented in Figure 3.13 is amost the same as level three, there are two main differences the input and the Monte Carlo model. Level four can only be executed if the input data*(P_L4_IN_1)* follows the PERT methodology. This data can then be used in block *(P_L4_M_4)* to perform a Monte Carlo simulation where two outputs will be possible, planning distribution or different planning scenarios.

The main criteria for the data driven network is the amount of data points. Unfortunately no guidelines have been found on the number of data points or data fit needed to correctly perform a PERT simulation. It is expected that the same observation as for the minimum R^2 value holds(section 2.3.4), it depends on the situation. During the research it was found the pessimistic and optimistic values are mainly estimated by an expert. Further research in this topic is advised.

Table 3.10: Table with model input and criteria for planning level 4.

Model input	Assessment criteria
• Effort indication production • Resource availability • production constrains • network schedule	☐ Perform preceding level ☐ Planning professional ☐ Validated Lead time model ☐ Validated network model ☐ TBD data points ☐ PERT

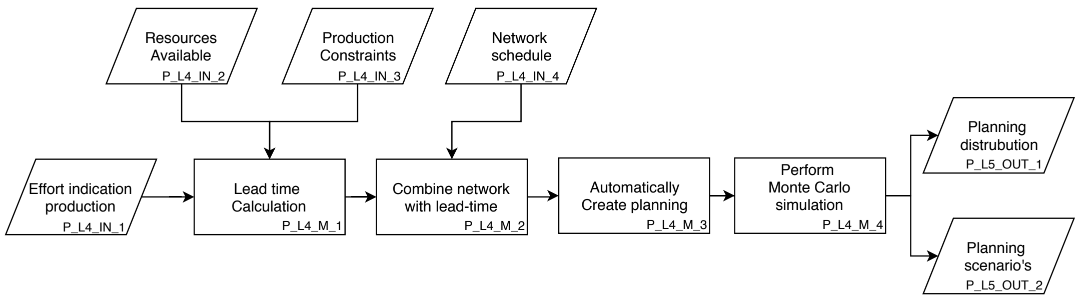


Figure 3.13: Schematic model of maturity planning level 4.

3.2.9. Planning Level 5 model *Risk*

During a project risks are always present, this could be a late delivery or rework that needs to be done. Section 2.4.6 describes a risk implementation method which can be used in block *(P_L4_M_4)*. The rest of the model contains the same elements as the level 4 method.

The additionally input required for the level 5 maturity is a risk register of the organisation, specifically a risk register for the planning.

Table 3.11: Table with model input and criteria for planning level 5.

Model input	Assessment criteria
• Effort indication production • Resource availability • production constrains • network schedule • risk register	☐ Perform preceding level ☐ Planning professional ☐ Validated lead time model ☐ Validated network model

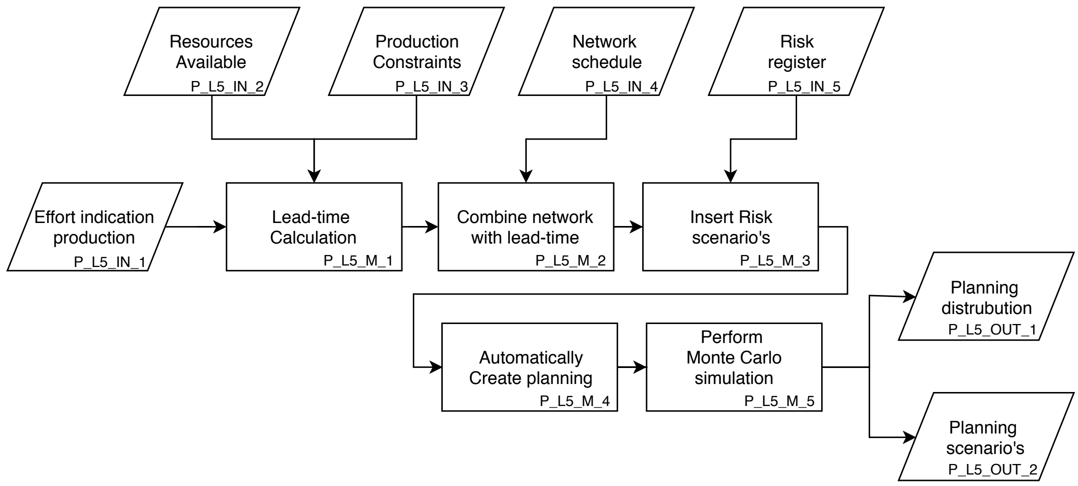


Figure 3.14: Schematic model of maturity planning level 5.

3.2.10. Planning Level 6 model *Optimisation*

The last level is the optimisation level, this level is different because it will use a optimisation model to come up with smart ways to perform the planning. One must think about smart routing, building schedules or optimised planning. Because this would depend based on the organisation preferences is represented with one block *(P_L6_M_3)*.

Table 3.12: Table with model input and criteria for planning level 6.

Model input	Assessment criteria
• Effort indication production • Resource availability • production constrains • task dependencies	☐ Perform preceding level ☐ Model Engineer ☐ Validated lead time model

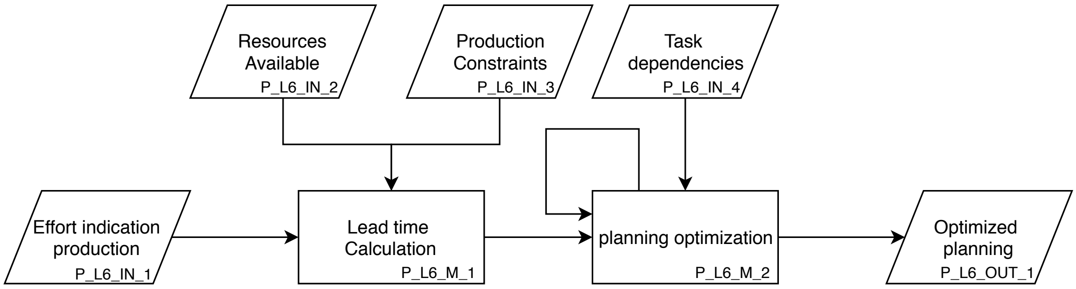


Figure 3.15: Schematic model of maturity planning level 6.

3.3. Level alignment

The two pyramids discussed in the above sections are linked to each other. This is due to the fact that the *estimation pyramid* is an input to the *planning pyramid*. If the maturities of these pyramids are not aligned the outcome could become unpredictable. For instance, if the estimations are based using the CGT method but the planning department is implementing *level 3 data driven* the results from that planning cannot be performed correctly, due to missing data, or unpredictable result could be obtained. It is advised that an organisation invest in the lower maturity level to align the maturity levels.

To prevent organisations from a misalignment in maturity levels, a matrix is constructed that shows which levels are compatible with each other and which levels are not advised. Table 3.13 shows the compatibility matrix. The compatible levels can seen, indicated by the grey cell. White cell combinations are not possible. This level alignment holds if the units and data type of the estimation and planning methods are compatible with each other, e.g. if estimations are made in dollars a direct alignment is difficult because for planning man-hours are needed, or estimations on man-hours are based on weight but the planning uses tasks. For both examples an alignment is prone to uncertainty because weight or dollars needs to be translated into tasks or man-hours, creating additional uncertainty.

Block [E3][P4] shows, D/E, a division for the compliance with level, the data driven estimation can be done if the requirement of 25 data points is met, however for the PERT and Monte Carlo simulation it is advised to use more data points(Data) for better results. If the organisation still want's to perform these methods it is advised to use percentages of the optimistic time, estimated(Est) by an export within the company.

Table 3.13: Table showing compatible maturity levels.

Estimation	planning					
	[*P*1] *Analogical*	[*P*2] *Resource inclusion*	[*P*3] *Network phase*	[*P*4] *Data driven*	[*P*5] *Risk*	[*P*6] *Optimisation*
[*E*1] *CGT*						
[*E*2] *Analogical*						
[*E*3] *Data driven*			*Est*/*Data*			
[*E*4] *Rapid engineering*						

3.4. Conclusion theoretical model

This chapter presented the theoretical frameworks for scaling and planning. The two models followed the same principle with on the y-axis the maturity and on the x-axis the level of uncertainty. The two frameworks created are the *estimation pyramid* and the *planning pyramid*. An organisation can use these frameworks in order to asses their current maturity level and look up which methods correspond to that maturity level.

For each maturity level an initial model is created, this will give the user a reference model where he or she can build upon. As stated previously the models might need to be altered to better suit the needs of the organisation. But still they give a good starting point. Therefore, the model should remain an organic framework. Which should improve over time when more insights are gather about the models and even about the different levels. In the future people might disagree with the current levels but that would only improve the model because with discussion more insights can be obtained.

In chapter 5 a case study will be performed to test the validity of the proposed maturity frameworks, ultimately answering the main research question of this thesis. But first chapter 4 will give the reader insight how RvLs build super yachts.

4

The production process of Royal van Lent

The writing of this thesis has been performed at Royal van Lent shipyards. The proposed *estimation pyramid* and *planning pyramid* will be tested using RvLs as a case study, to test the validity of the proposed maturity frameworks. This chapter discusses the current production processes at RvLs to give the reader insight into the company that will be used as the case study organisation. This will ensure that the reader has better understanding of the outcomes from the case study. This chapter will act as the answer to sub goal: *4. Map the current production and planning method of Royal van Lent shipyards.*

The first section explains the building process of a vessel from engineering until the ship is ready to be delivered to the client. After that a more detailed view of the production process at RvLs is given. The last section presents the current production planning at van Lent.

4.1. Vessel building process

As with any other project, designing and building a vessel from the ground up requires several steps. Figure 4.1 presents the different steps from start to finish. As shown, two phases, design and production, overlap each other because production can all ready start before the whole design is completed. Building the casco does not require that every little detail is known. The reason why they start earlier with the production is that an early start reduces the total lead time of the project.

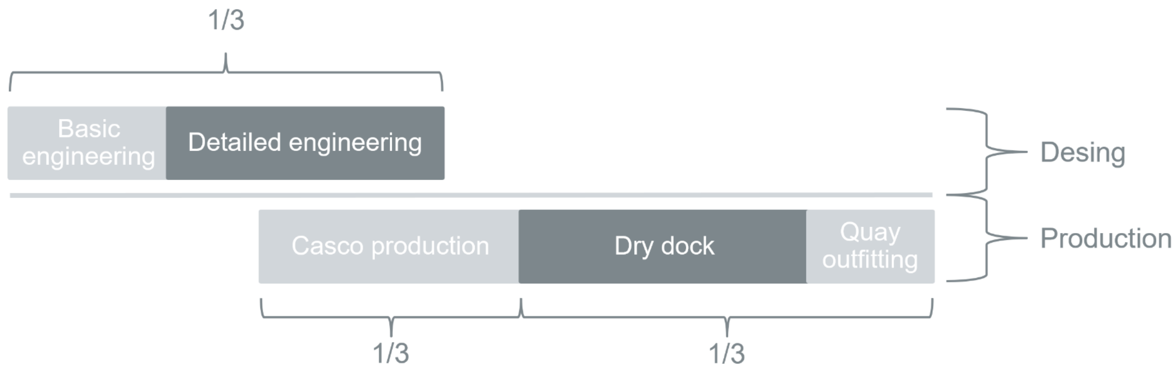


Figure 4.1: Schematic of the development and production of a vessel.

Within these two rows, five blocks are identified, starting at basic engineering. In this first block, *basic engineering*, the general arrangement is created and the preliminary sizing is determined such as length, weight and GT. When the basic engineering is done it goes into detailed engineering where the design will be finalised until the last nut and bolt. The way the design phase is performed can differ between companies, in section 4.1.1 the designing process at RvLs will be further elaborated.

The production row starts at the block *casco production*. In this phase the casco and the super structure of the vessel are build. As stated, these can be made before the final design of the vessel. This casco is then transported to the dry dock where the vessel will be transformed from casco to an almost complete ship. At the last step, *Quay outfitting*, little details are added such as the mast. Section 4.1.2 elaborates on the production process at RvLs. The diagram also shows the time indication for the different steps, these can change depending on the vessel but it gives an indication of their relevant durations. Starting earlier with the production of the casco can reduce the lead time quite significantly as it almost takes $\frac{1}{3}$ of the total time. The following section will go deeper into the design process at RvLs.

4.1.1. Ship designing process

If a customer wants to buy a vessel, he comes in contact with Feadship. This contact can happen in two ways, directly or via a broker. It has happened in the past that a client directly mailed RvLs with the request to buy a super yacht, but this is rare. Most of the times a broker is involved, he will show the client different companies such as Feadship, Amels and Lürssen. The companies' proposals are made to convince the client that he or she should buy a Feadship. The designers of the Voogt and the customer, or the customer team, come together to discuss the wishes of the client. This results in a preliminary drawing, appendix B shows such a drawing. These drawings do not offer great detail but are used to determine the price and planning. In this thesis this phase is called the *early design phase*. The price range of the super yacht is also determined in this phase, thus getting a good estimate is critical. If the client chooses to buy a Feadship, the basic engineering phase can start.

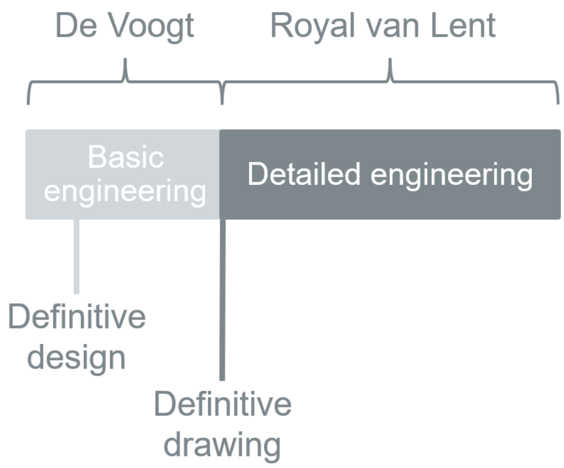


Figure 4.2: Schematic of the designing of a vessel.

Engineers at the Voogt further develop the design until the customer approves the design, which is then called the definitive design. The phase itself is called basic engineering. This design drawing is not the complete drawing, it only gives the look and feel of the boat. Cable routing and fuel lines for instance are not yet completed. Also hydrodynamic stability is verified in this phase because a design could cause the vessel to be top heavy and thus not stable, if this was discovered in the detailed engineering it would be more difficult to alter the whole design. Telling the customer halfway in the designing process that the vessel needs to change will result in a delay because work has to be redone but this will also dissatisfy the customer. In a business where word of mouth advertising is really important this needs to be avoided.

After the basic engineering phase, concluded with the definitive drawing, the detailed engineer can start. This phase is not performed at the Voogt but at RvL[1], detailed engineering is performed at the shipyard because here the communication between the engineers and the craftsmen is faster. Furthermore, a lot of engineering is outsourced to third parties that will do the engineering and production of that specific component, such as wiring. During this phase, as discussed in section 4.1, the fabrication of the casco will already start. How the production takes place at RvLs will be discussed in the following paragraph.

[1] During the sales phase both yards, de Vries and Royal van Lent, are in the running to produce the vessel. The portfolio of both companies will be checked which yard has time to produce the vessel. If both yards have space and time and both want to fabricate the vessel, then it comes down to the lowest price or customer preference.

4.1.2. Ship building process at Royal van Lent

In this section the production will be further elaborated. Figure 4.3 presents a schematic of different disciplines needed to produce a vessel. Three columns can be identified casco, dry dock, and wet. The production time line goes from left to right, thus the production of a super yacht at RvLs starts at the casco column and finishes when the vessel leaves the dry dock, indicated with the column *wet*. In the matrix two rows, internal and external, show disciplines that are carried out at an external location, not at the Kaag where RvLs is located. In the next paragraphs the different columns will be further explained.

The casco and the superstructure of the ship are not produced at the yard of Royal van Lent, but are constructed by third parties. To make this separation clear, these phases have been placed in the external block. This first phase consists of three blocks, building the super structure, casco, and the engine. Currently, the engine room is prepared when the casco is produced. At the writing of this document, Royal van Lent is also trying to get basic outfitting part of the casco building process. This would reduce hot work in the yard of Royal van Lent, unfortunately this is not yet fully implemented. The super structure is also constructed at a different company, because this company specialises in aluminium constructions. Once the superstructure and the casco are combined, the vessel can enter the dry dock.

Once the vessel is in the dry dock, the production for Royal van Lent really starts. In the dry dock, the vessel transforms from a bare casco to an almost complete vessel. Figure 4.3 shows that the interior is produced externally. Van der Loo, a company owned by Rvl, produces the interior.

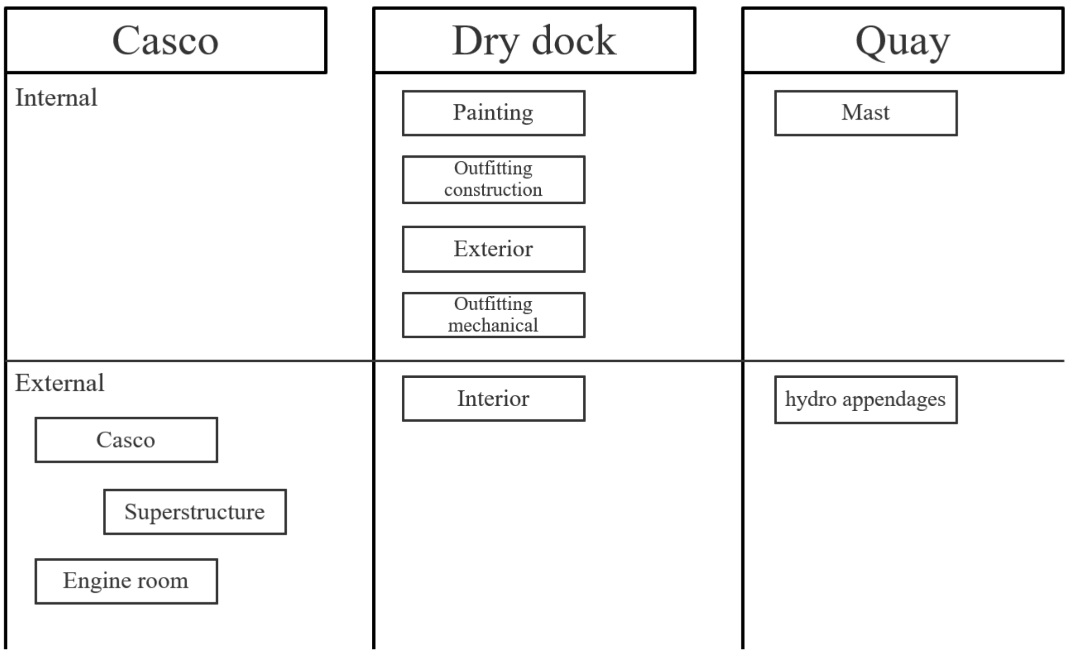


Figure 4.3: Schematic of the production of an vessel with indicated production locations, internal(RvLs) or external(third party).

After the dry dock phase, the vessel is moved quayside. In this stage outfitting can still happen if the vessel is not completed, which happens if the deadline was not achieved. But ideally in this stage only the mast and the hydro appendages, propeller and fins, are placed. The placement of the hydro appendages is done at an external party that has the ability to get the vessel in a large dry dock. At the new yard in Amsterdam this additional dry dock will not be necessary, because the water depth is sufficient. At the Kaag the vessel is raised with barges to reduce the draft of the vessel.

Once the vessel is completed, it will not be shipped directly to the customer. To check if all the vessel's requirements and specifications are met it will first undergo sea trails. During this time the crew of the super yacht will also check if the rooms meet the specifications and if they are satisfied they will mark off the rooms and personnel of RvLs is not allowed in anymore. After the sea trails the vessel will be handed over to the owner.

4.1.3. Company production structure

Four production divisions are present at Royal van Lent namely, construction, painting, and exterior and interior carpentry. In the list below the production divisions are discussed in more detail. This list only includes production departments, departments such as engineering and refit are not added because they are not responsible for a specific part of the production. Also this thesis will focus on production and not on engineering.

- Construction
  This department is responsible for all the construction elements of the vessel in dry dock, such as hatches and doors.
- Painting
  The painting department is responsible for all the painting and finish of the components of a vessel.
- Mechanical
  This department is responsible for all the mechanical systems such as hydraulic, ventilation and electrical systems.
- Carpentry exterior
  Carpentry is divided into two parts, interior and exterior. The exterior department is responsible for all the exterior wood, such as the teak flooring and banisters.
- Carpentry interior (Van der Loo)
  The interior is produced at Van der Loo, a production facility at an external location. All the furniture and interior is produced at this facility.

All these departments are overseen by a central planning department. RvLs uses a matrix structure, in which production departments are columns. The different projects, super yachts, are rows. This means that different projects can request the same resources, coordinating the resources over different projects is the responsibility of the planning department.

4.2. Current planning methodology

RvLs has a planning methodology using five depth levels[125]. These levels do **not** have any connection with the proposed levels from the *planning pyramid* and *estimation pyramid*. The levels RvLs uses, indicate the level of detail and the time reference. Level 0 shows the dock occupation, over a time frame of 5 years. Level 4 is the day to day planning like placing insulation in room *i*. The scope of this thesis corresponds to the level 2 project planning where month/weeks is the resolution.

Figure 4.4 gives an overview of the different levels.

Figure 4.4: Planning levels used at Royal van Lent

It first starts with level 0, this stage creates a high level planning which includes all the different projects. This planning also shows future projects where no contract is signed yet. The time frame of this planning is in years. It containing key milestones, such as production start and launching.

The next level, level 1, gives insight in a specific project. This planning gives an overview of the total project from start to finish with the main design and production steps described in section 4.1.2. This planning will give the departments a time frame with delivery dates. These deadlines are the input parameters for the next level, the project planning. This planning is not concerned with the different blocks within the ship, only with the disciplines needed to produce a vessel.

The project planning, level 2, uses blocks of the vessel to set deadlines for each specific block, appendix A gives a visual representation of how the vessel is spliced into blocks. Before this level, blocks were not used in the planning. Between blocks there are important dependencies. For instance, if a block undergoes hot work, the surrounding area cannot undergo insulation. Because one section can influence all surrounding sections, the planning is crucial to ensure that one section will not delay the other section.

In the department planning, level 3, each section is divided further in smaller tasks. The production department plans these tasks. The planning detail of this level is weeks/days. The level 4 planning is a day planning that is made by the foreman in the yard.

5

Framework case study on Royal van Lent shipyards

Chapter 3 presented two frameworks, the *estimation pyramid* and the *planning pyramid*. To test the validity of the proposed maturity framework a case study will be performed on Royal van Lent shipyards. This will answer the fifth sub goal: *Validate maturity framework using Royal van Lent shipyard data.* Performing the case study will also ultimately answer the main research question of this thesis.

This chapter has the following structure, first the case study methodology will be presented. Secondly, the current maturity of RvLs will be determined for the *estimation pyramid* and *planning pyramid.* Thirdly, models within both frameworks will be presented after that, the results from the case study will be discussed.

5.1. Case study methodology

As presented in section 3.3 the two frameworks are aligned, meaning that combinations of methods can be used, e.g. using the *Level 2, analogical* estimation in combination with the *level 3, network phase* planning. But also *level 3, data driven* estimation can be used with *level 3, network phase.* The question is, do higher maturity levels indeed deliver a lower level of uncertainty? That will be determined in this chapter. Figure 5.1 presents a schematic of the case study methodology, each block has a reverence number in the format, M_C _*n*, methodology, case study, block number.

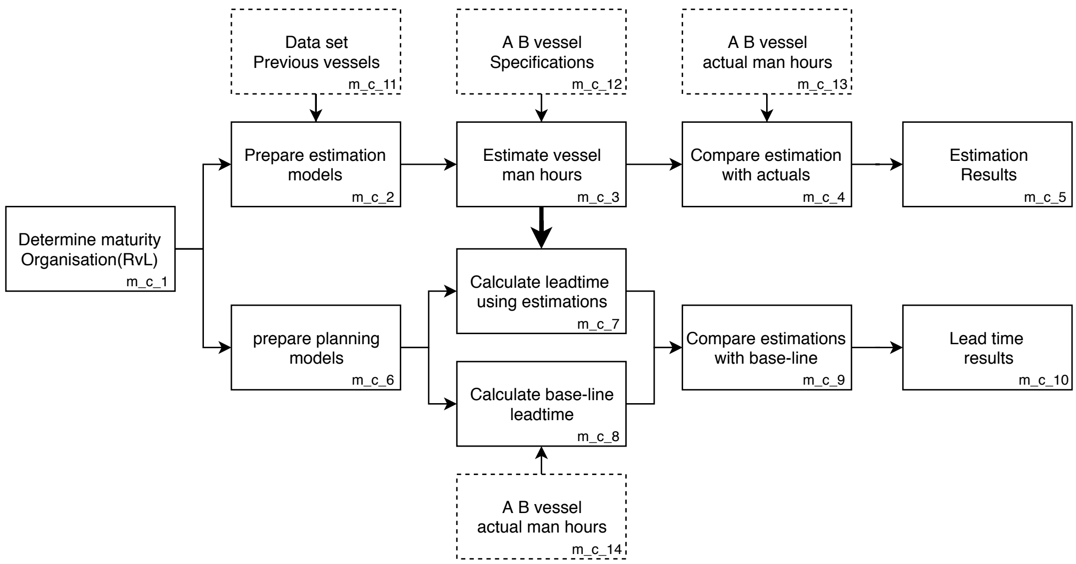


Figure 5.1: Schematic diagram representing the stricture of the thesis.

The first step in this case study is determining the current maturity of RvLs, *m _c _1.* When the current maturity level is established, the levels up until and preceding level will be performed. To test hypotheses [H2] that, performing a maturity level higher than the actual maturity of the organisation could result in a higher estimation uncertainty, one level above the current maturity level is chosen. Now that the maturity level is determined, the models for the estimation and the planning will be prepared, *m _c _2* and *m _c _6*. The models will be compared against each other, based on the estimation uncertainty. To test the level of uncertainty two test vessels have been taken from the original RvLs data set(*m _c _11*) these will be used as test vessels. In this chapter they are called Vessel A and Vessel B. Names and actual data cannot be disclosed due to the sensitive nature of these values. However, they are also not required for the discussion in this chapter. Table 5.1 presents the specifications of these two test vessels. The specifications of vessel A and B(*m _c _12*) will be the input for the estimation models, which will make an estimation of man-hours based on these specifications. E.g. the expert at RvLs will be given the specifications and a reference data set and be asked to estimate the man-hours for the vessels. The results of these estimations will be compared to the real man-hours needed to produce vessel A and B, as stated in block *m _c _4*.

Table 5.1: Specifications of test vessels A and B.

Yard no.	GT	Meter	engines	Propulsion power KW	Heli decks	pools & Jacuzzi's
TEST A	1052	61,2	2	2.984	0	1
TEST B	499	44,65	2	1.576	1	1

Yard no.	generators (EkW)	hatches and platforms	gangways	cranes & davits	lifts & elevators	m^2 Interior General
TEST A	550	4	1	2	2	212,3
TEST B	324	1		1	1	184,8

Yard no.	m^2 Interior Owner	m^2 interior Guest	m^2 Interior Tech spaces	m^2 deck covering	m^2 Interior crew	m2 outside furniture
TEST A	69,6	133,2	423,5	401,1	296,9	58,5
TEST B	41,1	54,5	127,3	280,9	133,6	32,6

In this thesis the uncertainty[1] will be quantified by a percentage that the estimation differs from the real value. This uncertainty will presented with sign (±), and thus not in absolute therms. This has been chosen because otherwise it is not visible if an over or under estimation is presented. Two different methods could present an uncertainty of 20% but one could always underestimate and the other could always overestimate, the reader could not see the the difference. Equation 5.1 shows the method used to calculate the uncertainty in %. The estimation are the man-hours estimated by the model, the real value the actual man-hour of the vessel. E.g. the estimation is 50 and the real value is 100 the uncertainty is −50%, an underestimation. If the estimation has the value of 150 the uncertainty has an over estimation of 50%.

$$\frac{Estimation}{Real} \cdot 100 - 100 = uncertainty(\%) \tag{5.1}$$

The next phase is evaluating the *planning pyramid*. The planning for Vessel A and B will be determined using the actual man-hours of the vessels. This data will act as a reference lead times,*m _c _8*. Unfortunately, the actual lead time data of the vessel A and B were not present at RvLs. Therefore the lead times will be estimated using the real man-hours. These calculated lead times will act as the baseline for the analysis.

The final step is combining the *estimation pyramid* and the *planning pyramid*. In block *m _c _7*, the man-hour estimations will be the input for the lead time models. The result of these estimation will then be compared(*m _c _9*) to the base-line lead times. Section 3.3 presented a level alignment diagram. There

[1] Deviation could also be a possible term, the author of this thesis has chosen to use uncertainty because deviation does not directly imply that the estimation could cause unknown effects. The term error could also be used during the case study because it is the different between the estimated and real value and not a range. However, in reality a fixed error is not expected but a range(uncertainty). Keeping the terminology consistent the term uncertainty is used.

it was stated that different methods can be used together, the hypothesis is that using the highest possible estimation maturity in combination with the highest planning maturity level, will result in the best estimated lead time. In the final block,*m _c _10*, the different combinations will be compared against each other on their lead time determination.

The next section will evaluate the current maturity of RvLs, as stated in block *m _c _1*.

5.1.1. Determining estimation maturity

The estimation pyramid contains 4 levels presented in section 3.1.1. As presented in chapter 4, Royal van Lent currently uses an analogical approach for its scaling estimations. Looking at table 3.4, presented in section 3.2.2, two assessment criteria are given to perform the *level 2, analogical* estimation. These criteria are, the availability of an estimation engineer[2] and data from a reference vessel, both these criteria are present at RvLs. Thus, RvLs has enough maturity to perform level 2. There is however a difference between the estimation and the logging of the hours, the hours are estimated for the total department, e.g. total hours expected for carpentry department. The logged hours are however filed under the vessel components, e.g. propulsion. A misalignment can occur because a vessel component contains hours from different departments, it is thus difficult translating vessel component hour to specific departments. In section 5.1.3 this will be further elaborated for the alignment with the *planning pyramid*.

The next level in the *estimation pyramid* is the data driven level. This level has three assessment criteria on which the company should comply to. Table 5.2 contains the summary of the three evaluation criteria. RvLs is investing in data engineers, parallel to the current data engineer the author of this thesis has the ability to perform a data analysis. For a parametric model with a low uncertainty sufficient data points are essential. Even though RvLs has been making vessels for 170 years only 19 data points per task are available. Also, for each task two different units are used, euros and hours. The amount of data points is below the advised minimum of 25 data points, combined with the difference in unit, RvLs is not able to perform level three. Lastly, the availability of a parametric model. Different attempts were made to create a parametric estimation model within RvLs. These models where never validated as they were deemed not accurate enough. Because no model is available the author of this thesis will create a new model.

Table 5.2: Assessment of the current estimation maturity level of RvLs using the level three criteria.

Assessment criteria	RvLs assessment
Data engineer	Achieved
Minimum of 25 data points	Not achieved, only 19 data points available.
Parametric model available	Not available, author will create a parametric model.

Based on the assessment of the level three criteria, RvLs is not yet mature enough to perform level 3 with a low uncertainty. Therefore it can be concluded that the current maturity of RvLs is level 2.

With level 2 the current maturity, up until level 3 models will be developed. To test hypothesis [H2] one level above the current maturity will be used in the assessment. In section 5.2 the models will be presented, these are based on the suggested models presented in section 3.2.3.

5.1.2. Determining planning maturity

The first step using the *planning pyramid* is determining the maturity level of RvLs. First the current methodology for planning will be assessed followed by the the proposed methods.

RvLs uses a mix of the first three levels, *L1,Analogical*, *L2,Resource inclusion* and *L3, Network phase*. During the creation of the planning the estimators per department get the task of estimating the amount of work needed by his department, this is mainly based on the general arrangement(GA) of the vessel and its size(GT). These hours are not used to determine the lead time time, but the the lead time is estimated analogical. RvLs currently has several planning professionals, who either work at the company for a longer time or are just hired. Level 3 maturity is performed by using Microsoft Project(MSP), with this planning software tasks can be linked in order to generate the critical path. This method is however not suited for this thesis because it is depended on MSP which is not as flexible and versatile as Python. RvLs thus uses a mixture of different techniques. The compliance for level three criteria are shown in table 5.3.

[2] Also called proposal engineer.

Table 5.3: Assessment of the current planning maturity level of RvLs using the level three criteria.

Assessment criteria	RvLs assessment
Planning professional	Achieved
Lead time model	Not available, author will create a lead time model
network model	Not suitable, author will create a network model

Looking at the assessment criteria presented in table 5.3, RvLs is able to perform the level three of the planning pyramid with input of the author. RvLs is not able to perform level 4, *Data driven*. This is due to the fact that the company does not meet the data point criteria. Therefore, it is expected that the organisation cannot perform the data driven level with a low uncertainty.

5.1.3. Level alignment

Table 5.4 presents the level alignment matrix. As determined, the current estimation maturity is *Level 2, analogical*, indicated in bold. The planning maturity was determined at *level 3, network phase*.

The estimated hours for level 2 *analogical* are on department level, but the planning will be created using vessel components. This will create a misalignment, it is therefore expected that level 2 *analogical* can result in an uncertainty in making planning estimations. Therefore the level 2 *analogical* will not be used in combination with level 3 *Network phase*. Because it does not meet the level alignment requirement, that the estimation parameters and build process parameters should align.

The maturity combination indicated[3] by the bold **X** will be analysed in this case study. E.g. the *level 3, data driven* estimation will be combined with the *analogical*, *resource inclusion* and *network phase*. These three combinations will be compared to another how the lead time estimation will change with different planning methods. Secondly, the effect of estimation techniques on lead time will also be compared. Because both *level 2, analogical* and *level 3, data driven* can use the *level 2, resource inclusion* the effect of a different estimation on the lead time can be analysed, resulting in the answer for the research question, *How to estimate ship production lead times with the lowest possible level of uncertainty.*

Table 5.4: Table showing compatible maturity levels with test indication.

Estimation	planning					
	[$P1$] *Analogical*	[$P2$] *Resource inclusion*	[$P3$] ***Network phase***	[$P4$] *Data driven*	[$P5$] *Risk*	[$P6$] *Optimisation*
[$E1$] *CGT*	**X**	**X**				
[$E2$] ***Analogical***	**X**	**X**	–			
[$E3$] *Data driven*	–	**X**	**X**			
[$E4$] *Rapid engineering*						

5.2. The estimation pyramid

This section presents the models of the *estimation pyramid*, indicated by block *m _c _2* from Figure 5.1. In section(5.1.1) it was determined that RvLs is currently in maturity level two. Therefore the three levels will be compared on the uncertainty of the estimation each method gives. The comparison method and the actual comparison will be done in section 5.3. In this section the three levels will be discussed and presented, starting with the CGT method.

[3] Although, [E2] and [P3] can be used together. However, it was found that for RvLs, the estimation parameters did not align making the combination not possible.

5.2.1. Level one CGT

Level one of the estimation pyramid is the CGT method. Section 2.3.2 discussed the CGT method in more detail, including the A and B values for super yachts.

Figure 5.2 presents the result for the CGT method. Three lines indicate the high, low and, mean A and B values. The paper stated that the data points used during the research covered to a GT of 3000, therefore Figure 5.4 goes up until 3000 GT. The the data set used in level 3 *data driven* contains vessels up until a GT of 2083GT, the yellow line *2083* indicates this vessel, in section 5.2.3 this data set will be discussed in more detail. Because the maximum GT of the data set is below 3000GT the CGT method can be used to make estimations in the 0-3000GT range. To see the difference between the high and low A B values the factor between them is presented in Figure 5.3. A factor of 1,5 can be identified, this could result in an estimation spread between the low and high A B values.

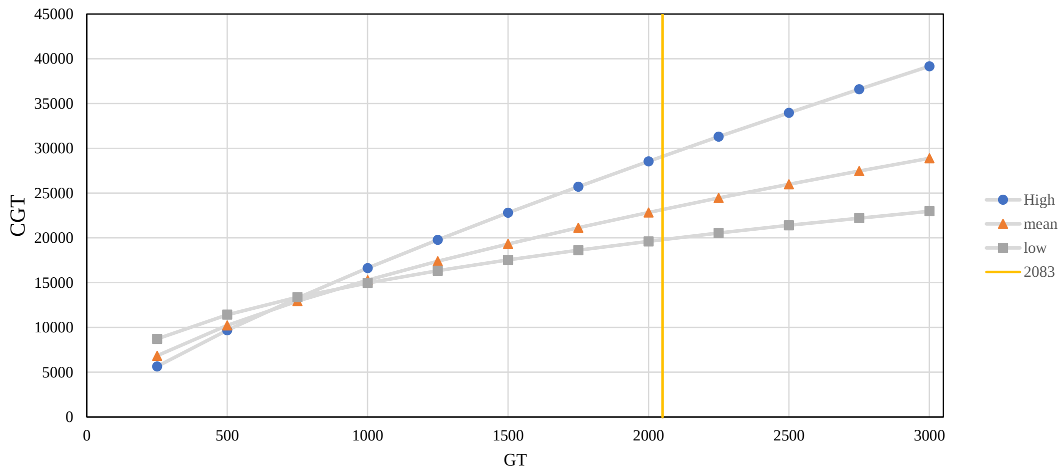


Figure 5.2: CGT man-hour estimation results for the RvLs data set.

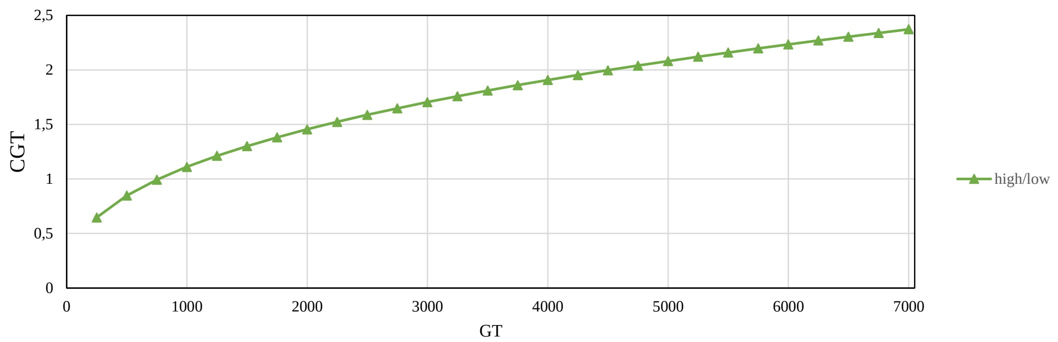


Figure 5.3: Factor between low and high CGT estimations.

Figure 5.4 shows the extrapolation of the CGT method, the blue line *3463* indicates the outlier that is removed from the data set.

The final step for the CGT method is determining the man-hours per CGT. For the three CGT estimations, high, medium and low, the mean will be used to estimate the man-hours for both vessel A and B. The man-hours per CGT is obtained by dividing the actual hours from reference data by the CGT estimation for that vessel. Because multiple vessels are present in this data set the mean is taken of the man-hours per CGT calculations. Due to confidentiality these numbers cannot be presented because the man-hours at RvLs can then be reversed calculated. What can be presented is the standard deviation of the fit. Table 5.5 presents the standard deviation for each CGT estimation, high, medium , low, with the corresponding standard deviation of the data. What can be seen is that the high CGT estimation has a standard deviation of only 0.9 man-hours per CGT. These standard deviations are small compared to the mean, unfortunately these cannot be presented due to confidentiality, but it is within 20%.

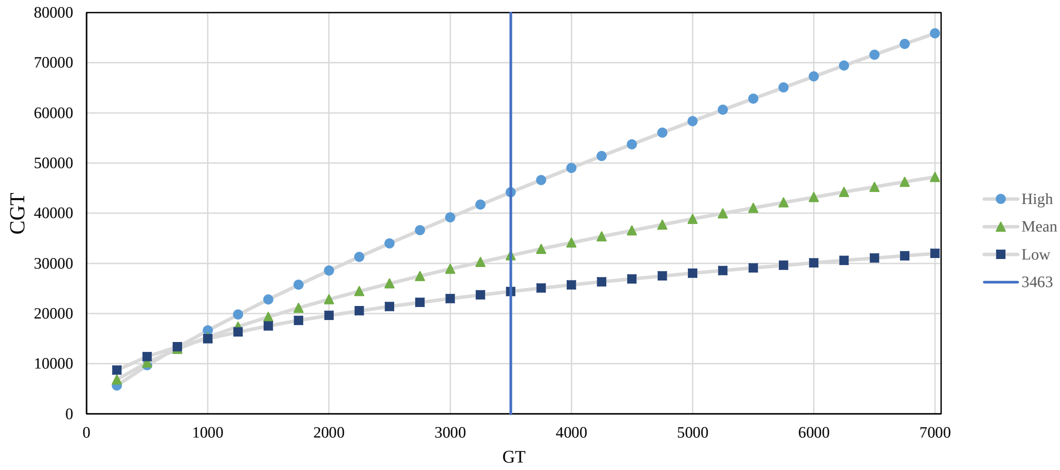


Figure 5.4: CGT man-hour estimation with extrapolated data points.

Table 5.5: Standard deviation of the man-hour per CGT estimation for high,medium and low A and B values.

CGT value	High	Medium	Low
Standard deviation σ	0,90	1,87	3,44

5.2.2. Level 2 analogical

Section 3.2.2 presented the theoretical model, this model aids as a guideline for an expert to make man-hour estimations. For this thesis the expert at RvLs has been asked to make a man-hour estimation for vessel A and B. Block *(L2_IN_1)* from Figure 3.7 indicates *Reference vessel*, the expert uses reference data to make judgements for a new build vessel. For this research the expert at RvLs has been given the same data set as the the data set used to train the model from level 3 *data driven*. The names of the vessels have been removed from the data set to ensure that the expert wont recognise the vessels. This is also the reason why the reference vessels have been called A and B to ensure the expert will not know the exact vessels. It is possible that he will recognise the specifications but it is unlikely that he will remember the made hours off all the vessels from the past by heart.

During the gathering of the analogical estimation it became apparent that there is a difference between estimations made and the logging of hours. Estimations are made based on the four departments of RvLs, the managers make an estimation for the man-hours their department expects. However, the hours are logged under the vessel components but these vessel components are not necessarily build by just one department. E.g. the carpentry(TIM) logs its hours under *Interior crew*, but mechanical(WTB) could also log hours under *Interior crew* for the instalment of a faucet. This results in not knowing how much of the logged hours for the *Interior crew* is carpentry and which is mechanical. This makes it difficult to compare the hours per vessel component and the estimation the departments gives.

It was possible for more recent vessel to find a distribution that clarified under which vessel components the departments logged their hours, presented in table 5.6. This was used to translate the total hours logged to hours per departments. It must be noted that this is a distribution from a recent vessel and thus could differ for older vessels. The total amount of hours($\sum hours$) is therefore deemed a better indication of the correctness of the estimation.

Presented in chapter 4 the production of RvLs is divided in 4 departments, carpentry(TIM), paint(PNT), construction(CNS) and mechanical(WTB). The man-hour estimation on an analogical phase can only be possible on this high level, the data driven level is capable of delivering a more detailed approach. In table 5.6 the second column present which department is responsible for which vessel component.

In section 5.3 the results of this estimation will be discussed, first the result versus the real values are discussed followed by the comparison of the three estimations methods, level one, two and three.

Table 5.6: Table with the vessel components the expert will estimate.

Code	vessel component	CNS	WTB	TIM	PAINT
VC_1	Casco	1			
VC_2	Superstructure	1			
VC_3	Piping mechanical systems	0,2	0,8		
VC_4	Propulsion	0,1	0,9		
VC_5	Construction mechanical systems	0,1	0,9		
VC_6	Electrical systems	0,15	0,85		
VC_7	Yacht equipment	0,85			0,15
VC_8	Exterior	0,45		0,55	
VC_9	Paint Ext				1
VC_10	Paint Int				1
VC_11	Interior		0,1	0,9	
VC_12	Interior owners		0,1	0,9	
VC_13	Interior guest		0,1	0,9	
VC_14	Interior public		0,1	0,9	
VC_15	Interior service		0,1	0,9	
VC_16	Interior crew		0,1	0,9	
VC_17	Interior captain, hospital and staff		0,1	0,9	
VC_18	Interior wheelhouse and ship's office		0,1	0,9	
VC_1 9	Interior technical spaces and stores		0,1	0,9	

5.2.3. Level 3 data driven

Figure 5.5 gives a recap of the model presented in chapter 3.2.3. Three parts can be identified in the model, the parametric model,specification conversion, and the conversion from specification into hours starting with specification correlation. In this case study it has been chosen not to include the specification correlation in the model*(L3_M_2)*, because the sub level specifications are known and also used for the analogical level. In appendix E the correlations between sub an top level specification are discussed, thesis but might give the reader some insight. One insight that was obtained is that the vessel specification overall correlated the best with the GT of the vessel so this might also be the case for the production hours. The next step is determining production correlations*(L3_M_5)*.

5.2.4. Production correlations

The next step is determining correlation between the vessel specifications and the production times, *(L3_M_5)*. In the data there is one vessel[4] that is an outlier, the volume(GT) is 1.75 times larger then the second largest vessel. To illustrate this problem two regression plots are made with and without the outlier, shown in Figure E.1. What can be seen is that the outlier creates the effect of better fitting data, the R^2 and adjusted R^2 drop when the outlier is removed. But including the data point could give a false sense of predictably of data points. For the sub level parameters the difference for the adjusted R^2 with and without the outlier is $92,4\%$ or $83,5\%$. Therefore it is chosen to do the analysis with and without the outlier in order to get more realistic results.

Table 5.6 shows the different production steps, also called vessel components, that will be used in this analysis. The term *piping mechanical systems* is used to indicate vessel systems such as fresh water system and HVAC, these are combined together to simplify the estimation model. In Appendix D the total list is presented and shows what systems follow under each category.

The correlation will be based on historical data gathered at RvLs. As stated in the paper of J.Pruyn [98] the companies that produce super yachts have different production procedures or even different quality standards. This means that it is hard to compare different companies. Therefore the production correlations that are found can not be used directly for other ship yards, however they can indicate the absolute effects.

The second step for the parametric model is finding correlations between the the vessel specifications and the production times. These correlations will be based on previous production hours of RvLs. In table 5.2 the Pearson's value and the R squared is presented of each production step with regard to the correlating

[4]Name known by author.

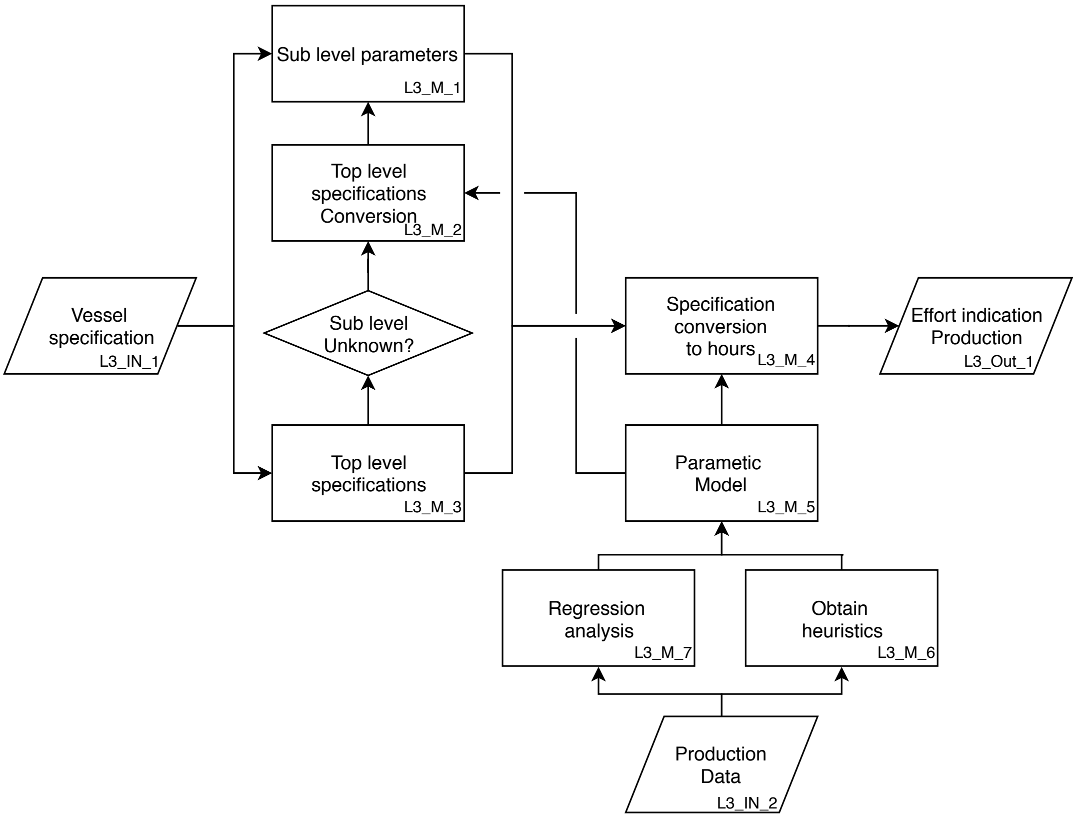


Figure 5.5: Schematic model of maturity level 3.

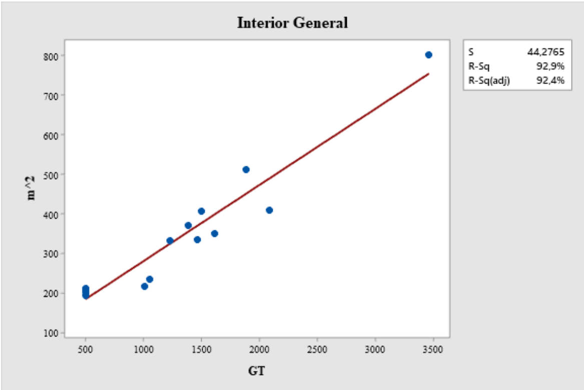
vessel parameter. The first note is that for this analysis only linear regression is used, other methods such as logarithm and exponential regressions fits have been evaluated but linear regression fitted the best. The second choice for linear regression is to reduce the change of over fitting the data creating a false sense of predictability.

The first step is choosing which vessel parameter correlates with which vessel component. These correlations are based on two factors, the first factor is the amount of correlation(R^2 and Pearson) and the second is the logic of the combination. For instance, there was a strong correlation detected between the engine KW and the amount of time it took to build the guest interior, these correlations where not chosen, but an explainable correlation is then opted. In the next section the correlation will be discussed.

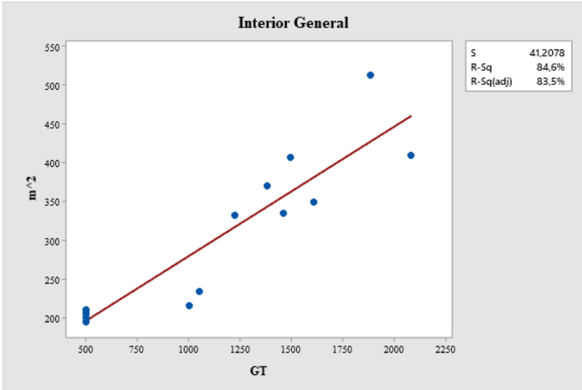
Table 5.7[5] presents the correlation between vessel component and the vessel specifications. In the column *correlation* the vessel specification is stated which correlates the best, based on the criteria described above, correlation level(R^2)and correlation logic. In this paragraph the interesting points will be highlighted. The first observation is that the most components correlate with GT, this is logical because it best represents the total volume in the vessel and most components scale logically with the volume. E.g. a larger volume means a larger casco. The second observation is that the average of R^2 is 0.74 which means that only 50% of the standard deviation is explained. This means that the model with a R^2 of 0,75 only yields errors 50% smaller than a constant only model on average. The last observation is that production tasks not always have the best correlation with the specific room dimension, for example the hours needed to produce the guest interior did not have the highest R^2 with the actual size of the guest interior, GT has a R^2 of 0,94 and with the m^2 it is only 0,76. This difference could have the following reason, customers who buy larger vessels are willing to spend more on the quality and finish of their guest interior. Graph E.7 shows that the price per m^2 increased with vessel GT, thus a vessel of 2000GT payed more per m^2 than a vessel of 500GT.

At RvLs two data types are logged under the vessel components, cost and internal man-hours. The man-hours are the internally logged hours that employees of RvLs made on that specific vessel component. The cost is the price RvLs payed to third parties. E.g the casco is produced at NMC, this organisation sends invoice

[5]The following abbreviations are used in this table, all have unit m^2, Int=interior, Int gen= interior general, Int tech = Interior technical spaces, Int crew = interior crew, deck cov =deck covering, Int guest = interior guests



(a) Regression analysis with outlier.



(b) Regression analysis without outlier.

Figure 5.6: Evaluation outliers.

Table 5.7: Table with the correlations between production hours and vessel parameters

Vessel component	Correlation	R^2	Pearson
Casco	GT	0,90	0,95
Superstructure	LOA	0,67	0,81
Piping mechanical systems	GT	0,88	0,92
Propulsion	KW	0,73	0,85
Construction mechanical systems	Int gen	0,65	0,80
Electrical systems	LOA	0,54	0,75
Yacht equipment	LOA	0,88	0,94
Exterior	GT	0,91	0,96
Paint Ext	GT	0,60	0,78
Paint Int	GT	0,61	0,79
Interior	Int gen	0,78	0,76
Interior owners	GT	0,66	0,81
Interior guest	GT	0,94	0,95
Interior public	Int gen	0,81	0,90
Interior service	Int tech	0,67	0,84
Interior crew	Int crew	0,85	0,92
Interior captain, hospital and staff	Int crew	0,69	0,83
Interior wheelhouse and ship's office	Int tech	0,58	0,77
Interior technical spaces and stores	Int tech	0,67	0,82

to RvLs for services provided, the completed casco. For this thesis it has been chosen only to use the internally logged man-hours and leave out third party costs, two reasons resulted in this choice, unknown data and cost correlations.

The amount of hours third parties spend on the vessel component has not been logged, only the total amount of cost is known. Within the cost three parts are present, a profit margin of the organisation, labour cost and material cost. The actual hours spend on the casco is the labour cost divided by an hour rate, the hour rate is also unknown for the data set. Equation 5.2 shows the explanation in equation form, the problem is that 4 estimations need to be made in order to obtain the total hours, the validity of the estimations are questionable. But more importantly, they are expected to be different for all vessel components. It is expected that the company producing the casco has different profit margin, material cost and hour rates than the company responsible for the engine. Estimating all these factors for all the components is expected to have a high uncertainty.

$$man_{hours} = \frac{Price_{total} \cdot \frac{100}{100+margin_{profit}} - cost_{material}}{Rate_{hours}} \tag{5.2}$$

Looking at the correlation between the vessel specification and the vessel components, presented in table 5.8[6]. the average R^2 is only 0.64, which corresponds to a percent of standard deviation explained of 0,41%. This low number is mainly due to the low interior correlation, if the interior correlations are left out an average R^2 of 0,87 can be observed, with a minimum of 0,64. The interior has low correlation with an average of only 0,43.

In this thesis the choice has been made not to include the cost in the total analysis and method comparison. This choice has been made on the two problems described above, the man-hour determination and the low correlation. The man-hour determination has the highest weighing factor for not including this in the analysis. The effect of removing this data from the model will be further discussed in chapter 7 because it is known that leaving this data set out of the model will influence the validity for RvLs.

Table 5.8: Table with the correlations between production cost and vessel specifications.

Vessel component	Correlation	R^2	Pearson
Casco	GT	0,89	0,95
Superstructure	LOA	0,30	0,36
Piping mechanical systems	GT	0,97	0,98
Propulsion	KW	0,97	0,99
Construction mechanical systems	tech	0,94	0,96
Electrical systems	LOA	0,87	0,93
Yacht equipment	GT	0,84	0,92
Exterior	LOA	0,87	0,93
Paint Ext	LOA	0,64	0,80
Paint Int	NA	NA	NA
Interior	Int gen	0,76	0,58
Interior owners	Int tech	0,61	0,78
Interior guest	Int gest	0,29	0,54
Interior public	Int gen	0,37	0,67
Interior service	deck cov	0,27	0,53
Interior crew	Int guest	0,48	0,69
Interior captain, hospital and staff	Int tech	0,19	0,43
Interior wheelhouse and ship's office	Int crew	0,62	0,79
Interior technical spaces and stores	Int tech	0,29	0,54

5.2.5. Leave one out cross validation

To compare the different maturity levels, it is necessary to validate the data driven model. However the validation of the model requires another approach then the standard method. Usually N samples are left out of the model for the regression analysis in order not influence the model, otherwise the model will estimates a vessel for which the production data is already included in the model. With the model validation for this thesis there is one problem.

The problem with the validation is the comparison for which the model is designed for. Hypotheses [H2] states that, performing a maturity level higher that that of the organisation could results in worse results. Therefore it is expected that the parametric model would not give results with a low uncertainty. But during validation this would seem as an incorrect model. But in reality the model could be correct and the hypothesis deemed true, that estimations with low uncertainty cannot be made with small company data set, $N < 25$.

Leave one out cross validation is used to validate the model. This method is used in machine learning if the data sets are small, the whole sample size will train the model leaving one sample out of the training set. The model uses the training set to make the model, after that is done the validation sample is placed back in the training data set and another set is removed for validation. Figure 5.7[113] shows the concept of removing one data set out of the training set and repeating this for the whole data set.

This method is implemented to validate the parametric estimation model, one vessel is removed from the training set and then tested against the model. Then this data set is put into the training set and another is removed. This has been done for 50% of the data points to evaluate if the model is correct and validated with

[6]NA = Not available

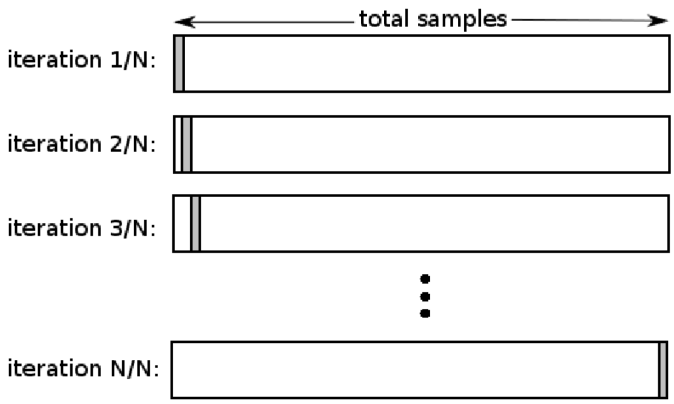


Figure 5.7: Leave one out cross validation sample shift.

a small sample set. But the most important factor is that the model is still validated even if the error might be present. If the model then gives large errors the model itself is correct but the company data is not sufficient to train the parametric model. This results in an estimation where large errors can be present.

Figure 5.8 shows the plotted errors. On the X-axis are the different vessel components, casco, etc. , the numbers correspond to the numbers in table 5.6. On the Y-axis is the error for different vessels[7]. One can see that there is an even spread in errors above and below the X-axis. This indicates that the error is it not bias in positive or negative direction.

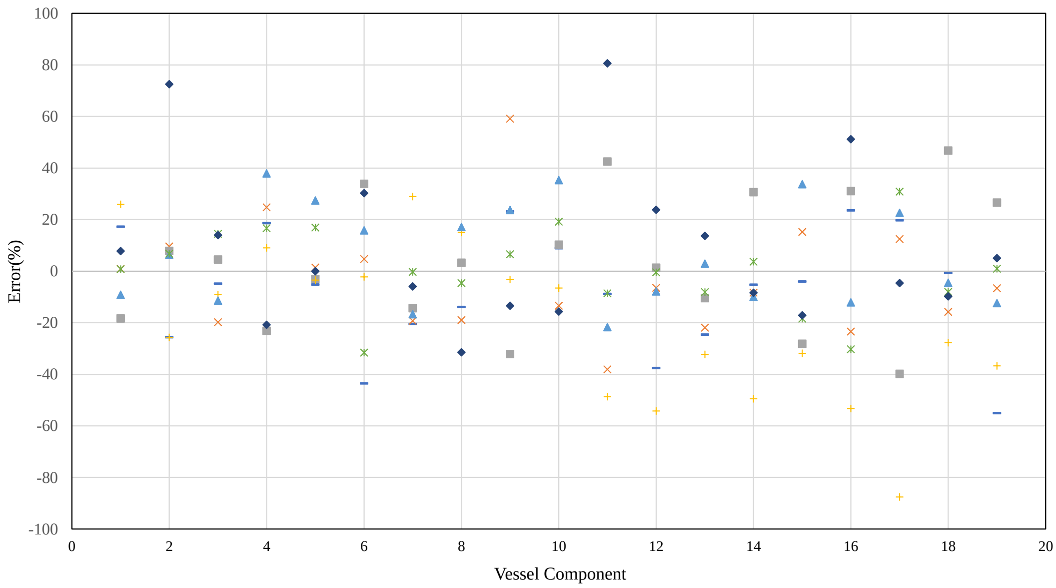


Figure 5.8: Figure showing the error in percentage for the cross validation

The mean of the error is -3,99 with a standard deviation of 19,6%, this means that 68,2% of the errors are within this standard deviation. Thus an average error of around 20% can be expected using level 3 the data driven method. The errors for the test vessels A and B will be further discussed in the comparison analysis in section 5.3.

When looking at Figure 5.8 it can be seen that the error spread increases after point 10 on the x-axis, VC_10 paint. The vessel components after 10 are the interior hours, crew, owner, etc. This is an expected spread because the interior is customer specific. One might ask for a more lavish interior and another for a sleek standard interior, this means that the level of interior finish differs and thus the hours spread.

[7]No name is stated for the vessels due to discretion.

Two conclusion can be drawn from Figure 5.8, the first conclusion is that by using the cross validation method, the sum of errors is around zero, meaning that the model is not skewed in over or under estimating vessels man-hours. The second conclusion is that large errors can be detected in the estimations. This could be due to the small data set and the fact the super yachts are one of a kind. Using leave one out cross validation it is determined that the model is correct and can be used in further analysis, but that estimation errors will be present.

5.3. Estimation pyramid level comparison.

The goal of the maturity model is to asses the level of maturity a company has and which corresponding methods it can implement to get the lowest uncertainty possible. As stated, implementing methods not corresponding to the maturity level can result in higher uncertainty. To test this a case study is performed at RvLs, firstly the current maturity level of RvLs has been assessed, resulting in the level 2 maturity *analogy*. To asses the claim of the maturity level that selecting the wrong level could result in a lower uncertainty the data driven model has been implemented. In this section level 1 *CGT*, level 2 *Analogy*, and level 3 *data driven* will be compared to asses the maturity framework. Firstly the method of assessing the levels will be discussed in the next paragraph. Secondly the results from the test will be compared against each other.

To asses the different methods two vessels have been removed from the data set, these vessels will be used to test the uncertainty of the different levels. In the list below the test method will be described.

- Level 1 CGT
  For the CGT method the total amount of hours for both test vessels will compared to the estimation the CGT method gives, this result in an error percentage. This error will be compare the total real hours of the vessels A and B and the CGT estimation.
- Level 2 analogy
  To obtain the uncertainty for the analogy level the specifications of the two reference vessels will be presented at the experts of RvLs, they will make an estimation based on their knowledge and current estimation practices. The difference with the actual hours is then the error.
- Level 3 data driven
  For the data driven level the two vessels will be implemented in the model, this will result in the man-hour estimation for both the vessels. The difference with the actual hours is then the error.

The error of each level will be compared to each other to asses which method resulted in the estimation with the lowest uncertainty.

5.3.1. Level 1, *CGT*

Table 5.9 presents the CGT methods estimation compared to the real total amount of hours for vessel A and B. The real hours of reference vessel A and B are compared to the hours calculated using the CGT method. In the paper *Determination of the Compensated Gross Tonnage factors for Super Yachts*[98] three AB values are presented, high, medium and low. The real hours for reference vessel A and B are compared against these three estimations.

Table 5.9: Table presenting level one,*the three minute rule*, estimation for for vessel **A** and **B**

Vessel A	high	medium	low
Vessel GT	1052	1052	1052
CGT	17297,6	15733,1	15267,5
Percentage (CGT(hrs) \Real(hrs)) (%)	-1,3	0,0	3,3
Vessel B	high	medium	low
Vessel GT	499	499	499
CGT	9667,9	10208,1	11414,0
Percentage(CGT(hrs) \Real(hrs)) (%)	9,3	28,5	52,9

The correctness of the estimation between vessel A and B differs. One can see that for vessel A using the CGT method results in a maximum error of only 3,3% if the low values are used. If the medium values, the advised values of the paper, are used an error of $0,0\%$ can be seen. For vessel A the estimations are therefore judged to be good. For vessel B the estimations have a higher error, the medium CGT estimation has an error of $28,\%$ and the low value an error of $52,9\%$. The CGT method thus over estimates the amount of hours needed to produce vessel B. These large errors for vessel B, compared to the small error for vessel A, could be due to the slope of the CGT curve. Looking at Figure 5.2 it can be seen that below 750GT the low estimations give a higher CGT value than the high CGT values. This means that the high CGT values give a low CGT value, this can be seen in table 5.9, these are the calculated CGT values without incorporating the man-hours per CGT. This will increase the error because for the low CGT values the man-hours per CGT are higher than for the high CGT values.

Using the CGT method could lead to results with a low uncertainty, but if these low uncertainties are correct needs to be further investigated. It could be unsuitable for vessels below 750GT but suitable for vessels above.

5.3.2. Level 2, *analogical*

Before presenting the results of the analogical estimations two comments need to be made, the first one is that the level of detail for the analogical estimation can only be done for the four departments at RvLs. The second comment is that RvLs has recently changed its building strategy. This could mean that the current estimators are influenced with this new mindset, the experts where informed that A and B are old reference vessels so they would estimate it in the old manner. However, this new strategy could still influence the estimation.

From vessel B the original estimations are known, unfortunately these are not available for vessel A. These original estimation are also shown in table 5.10. As stated in section 5.2.2 the estimation of hours and logging of hours are done differently at RvLs, hours for estimation are done on department level but the logging of these hours is done under the vessel components. The discussed translation matrix of department hours to component was based on data available of a recently build vessel. This could cause an uncertainty in the correctness of the data.

Table 5.10 presents the estimation uncertainty for vessel A and B. For carpentry(TIM) and mechanical(WTB) relatively high errors for the estimation can be seen, this could be explained due to the original logging method. Therefore, the total amount of hours gives a better representation of the accuracy of the estimation because all man-hours have been summed, meaning it is not dependent where the data is logged. When looking at the total hours, the original estimation for vessel B and the estimation for vessel A are below $2,5\%$. For the new estimation for vessel B a higher error could be seen, a possible explanation is that vessels of 500GT are not build anymore at RvLs and are therefore harder to estimate for the current estimators.

Table 5.10: Table presenting level two,*analogical*, difference(%) between estimated and actual man-hours for vessel **A** and **B**.

Vessel	**A** expert	**B** expert	**B** original
CNS	-16,3	6,5	-20,1
WTB	55,0	170,0	30,9
TIM	-46,9	-32,4	-0,9
PAINT	31,4	9,0	6,4
$\sum$ Difference (%)	1,1	19,6	2,3
Mean (%)	7,6	7,8	2,7
St deviation σ (%)	37,4	65,9	14,6

The estimated hours are based on departments, the logged hours are based on vessel components. This creates a discontinuity in the *estimation pyramid* and the *planning pyramid.* It is stated that the data types should match between the pyramids. Therefore in this case study it is not possible to combine *level 2 analogical* with planning level *3 network phase.* Level 2 *resource inclusion* will be performed but it can be expected that results with a high uncertainty are present.

5.3.3. Level 3, *data driven*

Section 5.2.3 presented the level 3,*data driven*, estimation model. In this paragraph the estimations for vessel A and B will be compared to their actual values. Table 5.11 presents the estimation for vessel A and B. The real numbers are not presented due to confidentiality. The distribution is presented, this the the percentage(%) of that vessel component compared tot the total amount of hours.

The two columns stating *difference*, presents the difference between the estimation and the real man-hours for the reference values in percentage. It can be seen, that for vessel A the maximum outliers are for construction mechanical systems with a difference of $-61,9\%$ which is a factor difference of 2.6. The other outlier is the interior services man-hours which is overestimated with $39,2\%$, a factor of 1,4. A mean error of $-7,9\%$ with a standard deviation of $17,1\%$ The estimations for vessel B show larger outliers, for the superstructure an over estimation of 126% can be seen a factor for of 2,3. The captain interior is under estimated with $43,1\%$. The estimation has a mean error of $14,9\%$ with a standard deviation of $25,1\%$. The model under estimated vessel A and over estimated vessel B, vessel A is better estimated with a mean and standard deviation lower then vessel B.

Table 5.11: Table presenting level three,*data driven*, estimation for reference vessel **A** and *B*.

Vessel parameter	**A** Distribution(%)	**A** Difference(%)	**B** Distribution(%)	**B** Difference(%)
Casco	11,8	2,4	12,5	24,1
Superstructure	1,6	-41,6	2,4	126,0
Piping mechanical systems	11,8	-13,6	10,7	33,2
Propulsion	1,6	-23,2	1,9	19,1
Construction mechanical systems	2,9	-61,9	3,1	22,8
Electrical systems	0,5	-35,8	0,5	-17,6
Yacht equipment	2,9	1,9	2,4	32,2
Exterior	7,3	11,4	6,7	0,3
Paint Ext	22,8	-3,3	22,7	-20,6
Paint Int	3,2	26,1	3,1	46,2
Interior	10,9	-9,5	15,8	57,8
Interior owners	2,7	14,0	2,6	-1,2
Interior guest	3,7	-13,2	2,8	-9,3
Interior public	8,3	-0,1	6,2	14,9
Interior service	1,3	39,2	1,5	11,9
Interior crew	3,8	8,6	2,7	32,5
Interior captain, hospital and staff	0,6	-15,3	0,4	-43,1
Interior wheelhouse and ship's office	1,5	-7,9	1,3	9,1
Interior technical spaces and stores	0,7	-10,2	0,7	-10,5
	$\sum$ difference (%)	-7,8		10,8
	Mean (%)	-7,9		14,9
	St deviation σ (%)	17,1		25,1

5.4. Conclusion estimation pyramid

Tables 5.12 and 5.13 present a recap of the estimated hours in comparison to the real hours for vessel A and B. In the previous sections the individual results where presented, therefore this section focused on the relative performance. From table 5.12 and table 5.13 the following observations can be made. The CGT method had the lowest and highest estimation difference, meaning that it could posses a high uncertainty. This is inline with the hypothesis that level 1*CGT* gives the highest uncertainty. The second observation is that the *analogy* estimate for vessel A is more precise than the data driven level. This is only the case for the original estimation of vessel B. The new estimation had a higher uncertainty then the *data driven* maturity, but this could be due to the fact that 500GT is not build anymore. The σ is worst for both analogy estimation but this was due to the logging. Looking at the table it can be said that the data driven level does not give a lower uncertainty than level 2 *analogy*. Corresponding to hypothesis[H2]: *Performing a maturity higher than the current maturity of the organisation increases the level of uncertainty*. This is based on one case study and therefore it is recommended to perform this analysis on more organisations to see if this statement still holds.

Table 5.12: Table presenting the the three estimation levels with error(%) for vessel **A**

Maturity	CGT High	Medium	Low	Level 2 Analogy	level 3 Data driven
$\sum$ Difference (%)	-1,3	0,0	3,3	1,1	-7,8
Mean (%)	–	–	–	7,6	-7,9
St deviation σ (%)	–	–	–	37,4	17,1

Table 5.13: Table presenting the the three estimation levels with error(%) for vessel **B**

Maturity	CGT High	Medium	Low	Level 2 Analogy	Original Analogy	level 3 Data driven
$\sum$ Difference(%)	9,3	28,5	52,9	19,6	2,3	10,8
Mean (%)	–	–	–	7,8	2,7	14,9
St deviation σ (%)	–	–	–	69,0	14,6	25,1

5.5. The planning pyramid

In this section the planning pyramid will be assessed using RvLs as case study. In section 5.1.1 the current maturity of RvLs has been established. It was found that RvLs used a mix of the first three planning maturity levels, with the highers being level 3 *network phase*. Level 4 *data driven* is not possible due to the lack of data. This sections follows the layout discussed in the methodology section 5.1. Firstly, the method for level 1,2 and 3 will be discussed and the baseline lead times will be calculated. After that the three levels will be compared to each other in section 5.6 where the base line will be compared to the lead time calculated using the estimations, from section 5.2.

5.5.1. Level 1 Analogical

The total lead time(TLT) at RvLs is mainly sales or customer driven(B. de Leeuw, 2019). This means that the total lead time is not based on the man-hour estimation needed to produce the vessel. The lead time is judged by an expert, of course this is bounded by a certain amount, by the reference lead times from RvLs. Therefore, the level 1 analogical planning will not use the estimation for the *estimation pyramid*.

Table 5.14 presents the lead times for different vessel lengths. RvLs uses standard lead times for different vessel lengths. In the table it can clearly be seen that the lead time is not linearly linked to the GT[8] of the vessel. A vessel that is three times as large will not have a lead time three times longer.

Table 5.14: Internal lead time representation for super yachts.

LOA	GT estimated(14W)	Lead time
60	1030	±3 Years
70	1500	±3 Years
80	2000	±3 Years 6 months
90	2700	±4 Years
100+	3500	±5 Years

The lead time will be estimated for test vessels, A and B. Table 5.15 presents the outcome, not surprisingly the lead time for both vessels is 3 years even if the GT of vessel A is twice as large as that of vessel B. In the right two columns the lead time for casco and dry dock are stated. RvLs uses the three way rule, that engineering, casco and dry dock all represent $\frac{1}{3}$ of the time. There is overlap in these phases but the lead time of the phase is $\frac{1}{3}$ of the total lead time.

Table 5.15: Lead time estimation for vessel *A* and *B*.

Vessel	GT	LOA	Lead time	Casco	Dry dock
TEST A	1052	61,2	±3 Year	±1 Year	±1 Year
TEST B	499	44,65	±3 Year	±1 Year	±1 Year

These lead times presented in table 5.15 will be compared to the results from maturity level 2 *resource inclusion* and level 3 *network phase*, this compassion is discussed in section 5.6, it is known to the writer of this thesis that the level of detail differs between the methods and that the analogy part is at a higher plannings level.

5.5.2. Level 2 Resource inclusion

Level two of the *planning pyramid* includes the resource inclusion. Figure 5.11 presents the level 3 model, the level 2 resource inclusion is also present in this model. Block *(P_L3_M_1)* represens the lead time calculation. In this section a planning will be made using level 2. In section 5.6 the different levels will be compared to each other.

The lead time model needs two inputs, as shown in Figure 5.11. Resource availability*(P_L3_IN_2)* and production constraints*(P_L3_IN_3)*. To calculate the lead time, needed in block*(P_L3_M_1)*, equation 5.3 can

[8] These GT estimations has been based on a vessel with 14 meter width, corresponding to the Kaag Dock, in the Amsterdam Dock vessel can be build are wider and thus a higher GT.

be used.

$$L_{Time} = \frac{Hours_{total}}{Workers_{total}} \tag{5.3}$$

Shipping companies today are not only reliant on their own resources, third parties are hired if additional personnel is needed. Therefore the resources are variable for RvLs, if there are no other constraints this would mean that with an infinite amount of workers a vessel will be produced in an infinite small amount of time. This would not be the case due to production constraints. For instance, their is a maximum amount of workers that can work efficiently in one room, adding more craftsmen will not increase the productivity because they will hinder each other.

For the model it is chosen to set the amount of resources to infinite and compute the lead time based on the production constraints. The main reason is because of the variability of resources, additional personnel can be hired, but the constrains are fixed. It needs to be noted that the resources can also become the bottleneck, but for this thesis it is assumed that the resources are unlimited[9].

For this thesis the production bottleneck for the lead time calculation is set to the floor area needed for one person to still work efficiently. The ARBO law states that $4m^2$[127] is needed for one person to work efficiently. It is known by the author of this thesis that there are more physical production bottlenecks present. For example, hallways can become a bottleneck, only a certain amount of workers can flow efficiency through a hallway, but also the flow of goods into the vessel can be restricted by the limited amount of vessel entrance points. In section 7.1 this topic will be further discussed. Equation 5.4 incorporation the floor-area bottleneck into the lead time equation. For the lead time calculation the floor area is used and not the volume because it is assumed that personnel will not work above each other in the same room.

$$\begin{aligned} Workers_{total} &= \frac{Area_{m^2}}{Workarea_{m^2}} \\ L_{Time} &= \frac{Workarea_{m^2} \cdot Hours_{total}}{Area} \end{aligned} \tag{5.4}$$

The area restriction bottleneck directly influences the total lead time. Therefore, different scenarios are made to see the effect. These scenarios are made because if the the real bottle neck is $8m^2$ instead of $4m^2$, the lead time will double. Equation 5.4 shows that the amount of $Workarea_{m^2}$ is in the numerator.

Because the bottleneck is the amount of floor space, the total lead time of bigger vessels does not need to increase with larger size. Because the floor space also increases more personnel can work on larges vessels. Looking back at equation 5.4 if the amount of work doubles but the vessel floor space also doubles the total lead time will remain constant.

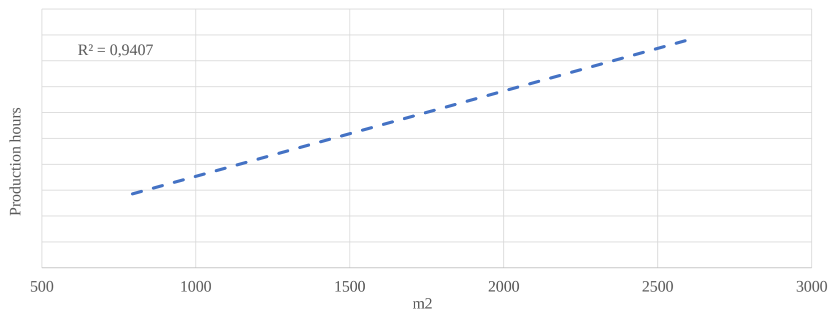


Figure 5.9: Graph showing the linear correlation between the vessel floor space and man-hours.

Figure 5.9 shows the floor area of the vessel versus the amount of production hours. On the axis the m^2 floor space of the vessels and on the y axis the total amount of hours spend on the vessel based on historical data[10] it shows that the floor space and the amount of hours needed to produce the vessel have a linear correlation. This means that, based on equation 5.4, the lead time will remain the same for the increased

[9]It has been observed at RvLs, that during the production works becomes less efficient because a lot of personnel works in one room. Meaning that they have to work around each other. The inefficiency factor is difficult to estimate and therefore the production bottleneck is set at a floor area.

[10]The separate data points and the values on the Y axis have been removed due to confidentiality, the m^2 range on the axis has not been changed.

vessel size. This is also enforced by Figure 5.10 which shows the total hours divided by the total interior m^2, which gives a constant hours per m^2[11].

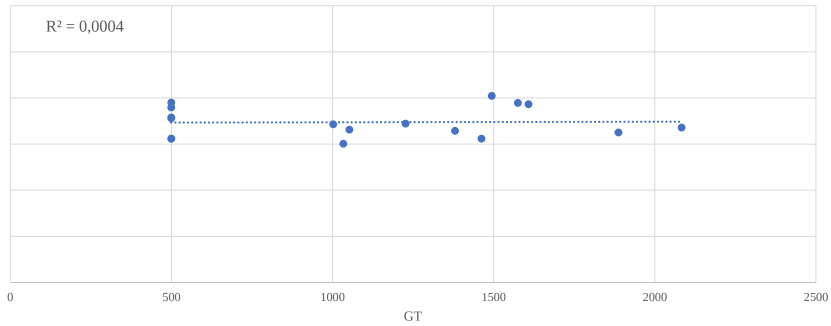


Figure 5.10: Graph showing constant man-hours per m^2 for different vessel sizes

For vessels A and B the lead times are calculated based on three scenario's, these scenarios are the craftsmen per m^2, the three scenarios are $4m^2$, $8m^2$, $12m^2$. The lead times calculated per vessel component are presented under the three scenarios. Table 5.16 presents the lead time per vessel component for vessel A and table G.6 for vessel B. In the paragraphs below the columns will be explained in further detail.

The different vessel components are the same as the vessel components in presented section 5.2.3. The different vessel components cannot be produced simultaneously, the casco has to be finished before the interior can start. Therefore, the different vessel components sequence needs to be established. Three different production phases are identified at RvLs, casco production at NMC, outfitting at RvLs and lastly the installation of the interior at RvLs. In the second column of table 5.16 and G.6 indicate the phase of the vessel component. It is known that there is overlap in the production times but for level 2 this level is sufficient, level 3 will take into account the different production stages between the vessel sections.

To calculate the lead time for each vessel component equation 5.4 is used. It is assumed that the total $m2$ stays constant over the three phases. It is difficult to predict how many workers each vessel component can occupy, therefore is is opted to equally divide the total area over the vessel components and use that area to calculate the total lead time for each component. Equation 5.5 shows the method in equation format.

$$Leadtime_{hours} = \frac{vesselcomponent_{manhours} \cdot N_{vesselcomponent}}{\sum craftsmen} \tag{5.5}$$

The last three columns in table 5.16 and G.6 present the three floor area scenarios. Because it is assumed that the next phase cannot start before everything is completed the total lead time of that phase is the longest activity. Table 5.18 gives an overview of the total lead time[12] of vessel A and B. It needs to be known that the shipyard has 46 production weeks per year, which means that a lead time of 3 years corresponds to 138 weeks. A workweek of 5 days with 7 hours per day is assumed.

Three conclusions can be obtained from this analysis. The first conclusion is that although vessel B is twice as large as vessel A, 499GT vs 1052GT, the lead is actually shortened by a factor of 1,2. This is due to the fact that more personnel can work on the vessel simultaneously. Vessel A can accommodate 1,86 times more craftsmen which means that for this instance the lead time is shorter than for the smaller vessel. The second conclusion is that the lead time for the casco and superstructure production is not realistic. This is due to the fact that the casco and superstructure are produced at an external location by a different company. Therefore no hours are registered, the decision not to include euro's is discussed in section 5.2.3. The third conclusion is that the $4m^2$ bottleneck is to optimistic, the lead time would be just over a year. For vessel A this would mean that 400 personnel is constantly working on the vessel, in a discussion with RvLs this number is deemed too high and 150 was more realistic for vessel A, resulting in a lead time of 148 weeks. In section 5.6 the results of the different maturity levels will be compared against each other.

[11]The Y-axis values are removed due to confidentiality.
[12]Total lead time=TLT

Table 5.16: Table with the vessel components base line lead times(days) for vessel A.

	User m^2:	4	8	12	16
	$\sum$ craftsmen:	399	150	133	100
Vessel component	Phase	LT	LT	LT	LT
Casco	1	141	375	423	565
Superstructure	1	34	91	102	137
Piping mechanical systems	2	668	1776	2004	2672
Propulsion	2	99	263	297	396
Construction mechanical systems	2	367	974	1100	1466
Electrical systems	2	34	91	103	137
Yacht equipment	2	141	374	422	562
Exterior	2	321	853	963	1283
Paint Ext	2	1153	3064	3458	4610
Paint Int	2	124	330	372	496
Interior	3	665	1769	1996	2662
Interior owners	3	132	350	395	526
Interior guest	3	237	631	712	949
Interior public	3	456	1213	1369	1826
Interior service	3	53	141	159	213
Interior crew	3	191	508	573	764
Interior captain, hospital and staff	3	36	96	109	145
Interior wheelhouse and ship's office	3	89	238	268	358
Interior technical spaces and stores	3	44	117	132	176

Table 5.17: Table with the vessel components base line lead times(days) for vessel B.

	User m^2:	4	8	12	16
	$\sum$ craftsmen:	214	107	71	53
Vessel component	Phase	LT	LT	LT	LT
Casco	1	140	279	419	558
Superstructure	1	14	29	43	58
Piping mechanical systems	2	446	892	1338	1783
Propulsion	2	91	181	272	362
Construction mechanical systems	2	141	282	422	563
Electrical systems	2	34	67	101	134
Yacht equipment	2	100	199	299	398
Exterior	2	370	739	1109	1478
Paint Ext	2	1585	3170	4754	6339
Paint Int	2	117	234	351	468
Interior	3	623	1246	1869	2492
Interior owners	3	166	333	499	666
Interior guest	3	189	379	568	758
Interior public	3	336	671	1007	1342
Interior service	3	83	165	248	330
Interior crew	3	128	256	383	511
Interior captain, hospital and staff	3	40	79	119	158
Interior wheelhouse and ship's office	3	72	145	217	290
Interior technical spaces and stores	3	47	93	140	187

Table 5.18: Table with the base line total lead times per phase and work m^2 for vessel A(1052gt) and B(499gt).

m^2:	4(A)	8	12	16	4(B)	8	12	16
phase 1 (Days)	141	375	423	565	140	279	419	558
phase 2	1153	3064	3458	4610	1585	3170	4754	6339
phase 3	665	1769	1996	2662	623	1246	1869	2492
phase 1 (weeks)	4	11	12	16	4	8	12	16
phase 2	33	88	99	132	45	91	136	181
phase 3	19	51	57	76	18	36	53	71
TLT	56	149	168	224	67	134	201	268

5.5.3. Level 3 network phase

Figure 5.11 gives a recap of the level three planning maturity model. In level 2 block *(P_L3_M_1)* has been developed presented in section 5.5.2. The next step is to create the network model that combines the lead time calculation with the network diagram, as stated in block *(P_L3_M_2)*. In this section the level 3 planning maturity will be performed. First the network will be created that represents the construction of a super yacht at RvLs, block *(P_L3_IN_4)*. After that the lead time and the network will be combined. Finally the results will be presented of the level 3 planning. In section 5.6 the three planning levels will be compared. But first the creation of the network will be discussed.

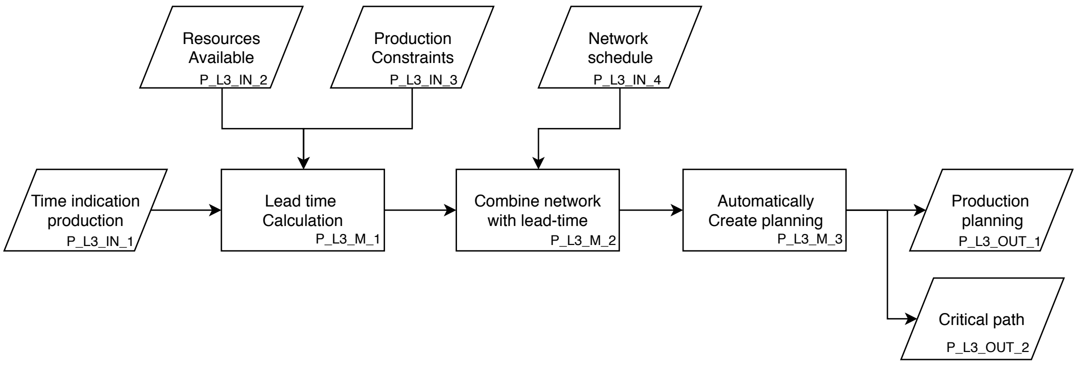


Figure 5.11: Schematic model of maturity planning level 3.

Combining lead time of tasks and its relationship to other tasks, or the network, results in a planning. Every planning is in essence a network of different linked tasks. The difference between the network of level two and level three is that level 2 only concerns the major phases, casco, outfitting and interior. In level three level of detail will be increased and the tasks are linked to perform the critical path analysis. The next step is to chose the level of detail for the network. E.g. a network can have a level of detail where the placement of every nut and bolt is included or can have low level of detail where only the three main phases, casco, outfit, interior are included.

For the planning of the casco the sections are used shown in Figure 5.12. The numbers indicate the individual sections and the colours the area type, e.g orange[13] is the owners deck. If the casco is brought to RvLs this changes to different floor area's. In this thesis it is chosen to keep the section division for the whole planning and not switch to specific floor area's, this method is chosen because the floor area's for the different sections already need to be estimated to calculate the lead times.

For this simulation the ten colours will be used as the sections of the vessel. Each section needs to go to a predetermined path(tasks) till completion. The different tasks are, casco, hotwork, paintint, outfit, paintext, interior[14]. For sections also superstructure, engine and special are included. Special means, super yacht specific building tasks such as a beach club or helipad. Table 5.19 presents the tasks needed to make a complete section.

The tasks presented in table 5.19 also influence the work possible in the adjacent sections, if hotwork takes place interior painting cannot be done in the sections adjacent to it. This creates dependencies between the sections, the network model links all the dependencies to each other using the Python package *NetworkX 2.3* [10] Figure 5.13a shows the representation of the network created for two sections.

Figure 5.13b shows the the building process of the two adjacent sections but then in the Gantt chart format. The dotted line represents the shift from casco builder to the the RvLs yard. Before the casco moves to RvLs all sections need to be done and conserved. This was not visible in the original network but clear with the Gantt chart. Because the tasks are linked, the total lead time, and corresponding critical path, can be obtained. The constraint that interior can only start when the other tasks are completed is no longer needed for level 3. The start of the interior production is only constrained by the task of the section itself and the adjacent section, so no longer of the entire vessel. It is constrained by the adjacent section because, e.g. painting cannot start if the adjacent section still has hotwork to be done, it will ruin the paint work.

[13] If this paper is read in grayscale, Orange is block 905 and 904.

[14] Hotwork = All tasks related that need some form of heat, e,g, welding cable trays. Paintint = Paint interior, also called conservation because the internal surfaces get a protective coat of paint. Paintext= Exterior painting.

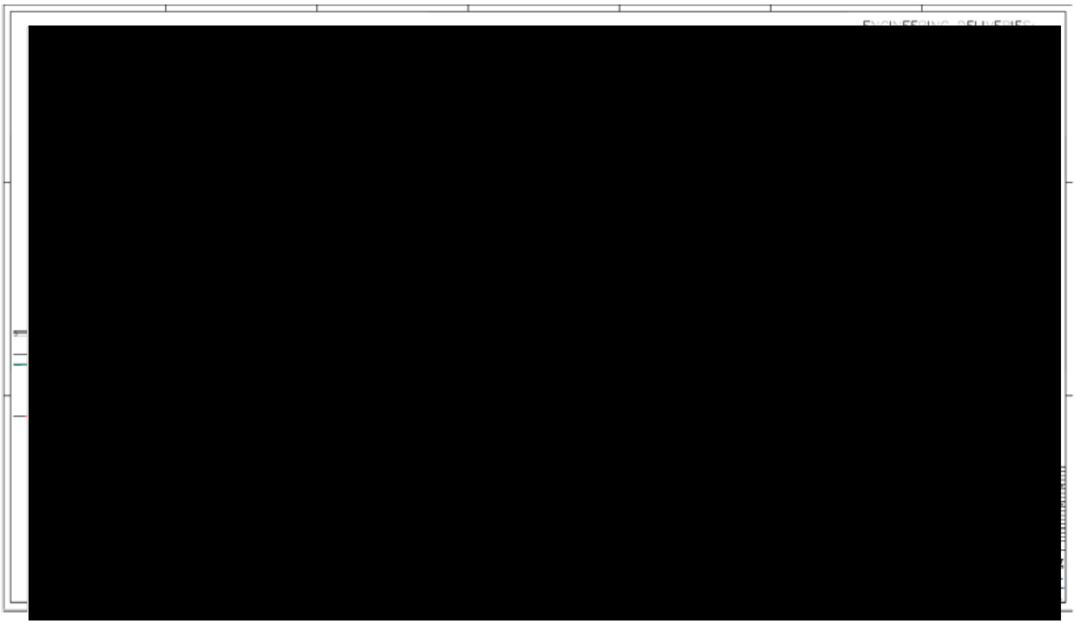

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Figure 5.12: Section division at Feadship.

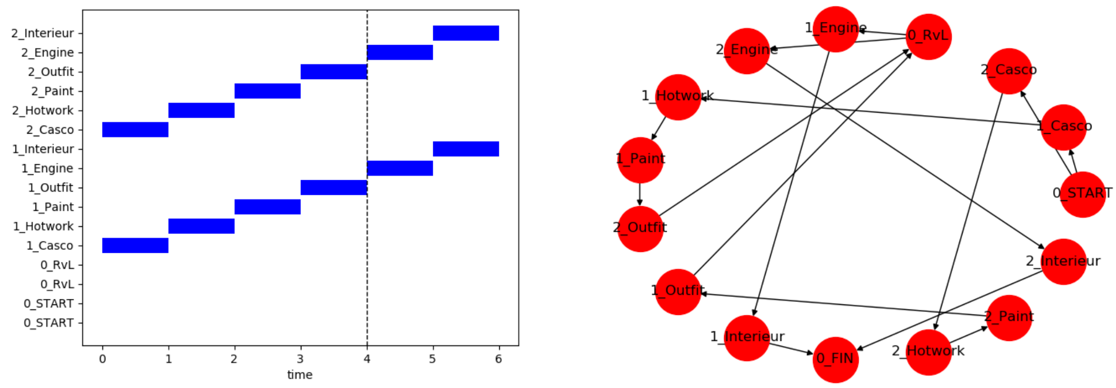
Table 5.19: Table with the tasks section combination matrix.

	1 Light blue	2 Yellow	3 Green	4 Pink	5 Black	6 Red	7 Blue	8 Orange	9 Purple	10 Forrest green
Casco	X	X	X	X	X	X	X			
Super structure								X	X	X
Hotwork	X	X	X	X	X	X	X	X	X	X
Paint int	X	X	X	X	X	X				
outfit	X	X	X	X	X	X	X	X	X	X
engine				X						
Special				X		X				
paint ext	X	X	X	X	X	X	X	X	X	X
Interior	X	X	X	X	X	X	X	X	X	X

The lead times for each section are presented in appendix F, the lead times are obtained using the lead time model from level 2 but then on a section basis. The lead times for 4, 8 and 12 m^2 constraint are calculated as can be seen in the appendix. These lead times are the input of the network model, in this model the total lead time(in weeks) and the critical path are calculated. Table 5.20 presents the total lead times of the three different scenarios for test vessel A and B for level 3 network phase.

Table 5.20: Table with base line lead times(weeks) for level 3 *data driven*.

Vessel **A**	4,0m^2	8,0m^2	12,0m^2	Vessel **B**	4,0m^2	8,0m^2	12,0m^2
Phase 1	19,3	38,7	58,0	Phase 1	14,9	29,7	44,6
Phase 2	36,0	71,9	107,9	Phase 2	37,2	74,5	111,7
LLT	55,3	110,6	165,9	TLT	50,9	101,8	152,7



(a) Visual network representation of the example project. (b) Gantt chart of the example project

Figure 5.13: Network and Gantt chart of the example project.

5.5.4. Planning pyramid base-line comparison

In this section the base-line results of each maturity level will be compared to each other. Tables 5.21 and 5.22 present the total lead time, in weeks, for each maturity level for vessel A and B. For the analogical and the network inclusion 2 lead times are presented, the casco phase and the RvLs phase. For the resource inclusion there is a third phase, namely interior. The resource inclusion contains this addition phase because interior cannot start before the other tasks are completed, with the network phase this is incorporated by the network dependencies. Therefore stating only Phase 2(RVL) is correct.

Table 5.21: Base line lead time(weeks) estimation comparison between maturity levels, vessel **A** 1052GT.

	[P1] analogical	[P2] resource inclusion	[P3] network phase	[P2] resource inclusion	[P3] network phase	[P2] resource inclusion	[P3] network phase
m^2	-	4,0	4,0	8,0	8,0	12,0	12,0
Phase 1	46	4,0	19,3	10,7	38,7	12,1	58,0
Phase 2	46	32,9	36,0	87,5	71,9	98,8	107,9
Phase 3	-	19,0	-	50,5	-	57,0	-
TLT	92	56,0	55,3	148,8	110,6	167,9	165,9

Table 5.22: Base line lead time(weeks) estimation comparison between maturity levels, vessel **B** 499GT.

	[P1] analogical	[P2] resource inclusion	[P3] network phase	[P2] resource inclusion	[P3] network phase	[P2] resource inclusion	[P3] network phase
m^2	-	4,0	4,0	8,0	8,0	12,0	12,0
Phase 1	46	4,0	14,9	8,0	29,7	12,0	44,6
Phase 2	46	45,3	37,2	90,6	74,5	135,8	111,7
Phase 3	-	17,8	-	35,6	-	53,4	-
TLT	92	67,1	50,9	134,1	101,8	201,2	152,7

Three observations are made based on table 5.21 and 5.22. The first observation is that the $4m^2$ area constraint is to small, when looking at the guidelines by RvLs the vessels are then produced too rapid. A constraint of $8m^2$ predicts a realistic image. The second observation is the lead time of both vessels have the same order of magnitude, for the $8m^2$ constraint a difference of 3 months can be observed, a difference of $\pm 10\%$. This indicates that although the vessel is twice as large the lead time will not increase significantly.

For the $4m^2$ criteria it the larger vessel is even faster. The final conclusion is that level three *Network phase* estimates a shorter lead time, this is logical because in level three interior can start if the surrounding sections enable it. In maturity Level two, the interior had to wait till all the mechanical systems where build. The next section will focus on the effect of the estimations on the total lead time.

5.6. Pyramid level alignment comparison

In this section the pyramid alignment will be discussed, table 5.23 presents a recap of the level alignment. In this section level 2 *Resource inclusion* and level 3 *network phase* will be discussed. Level one *analogical* will not be discussed because that level does not use direct hours as a lead time determination. Thus it will remain the same 3 years for all the estimation methods, for both vessel A and B. First the level 2 *resource inclusion* is discussed, followed by level 3 *network phase*.

Table 5.23: Table showing compatible maturity levels.

Estimation	planning					
	[$P1$] *Analogical*	[$P2$] *Resource inclusion*	[$P3$] ***Network phase***	[$P4$] *Data driven*	[$P5$] *Risk*	[$P6$] *Optimisation*
[$E1$] *CGT*	**X**	**X**				
[$E2$] ***Analogical***	**X**	**X**	–			
[$E3$] *Data driven*	–	**X**	**X**			
[$E4$] *Rapid engineering*						

5.6.1. Resource inclusion

In this section the three estimations levels, CGT[E1], analogical[E2] and data driven[E3] will be compared against the base line calculation, indicated by row *Est/Base*. Table 5.24 presents the comparison for vessel A and 5.25 for vessel B, the tables only show the scenario $8m^2$, in Appendix G the other scenarios are shown in table G.3(vessel A) and G.4(vessel B). The CGT values used in this table are for the medium A and B values, appendix G.1 presents the lead time values for the high and low A and B values. Appendix G also presents the lead time calculations for the data driven and the analogy levels.

When looking at the tables, 5.24 and 5.25, three observations can be made. The first is that CGT is not a suited option to estimate the lead time of a vessel. After comparing them with the base line a difference of ±66% can be seen, this was expected because the estimation itself had the same amount of error. The second observation is that using the estimation input of level 3 *data driven* the difference with the base line is respectively −5.0%(Vessel A) optimistic or 3.0%(vessel B) pessimistic estimation, for scenario $8m^2$. This is a smaller difference than for the man-hours estimation. Third it can been seen for analogy that for vessel A, that although the original estimate was better, the total lead time was not closer to the base line than the parametric model. It is thus important that when making lead time estimations knowing what the actual vessel component hours are is superior than knowing the total amount of hours more correctly. For vessel B the two analogy estimations are presented, the original estimation[15] and the new estimation. The old estimation had a better accuracy on the total man-hours, however the lead time has a big difference, 10% for the $8m^2$ scenario, there the parametric model had a better fit.

What overall can be concluded for the level alignment for level 2 *resource inclusion* is that having a good man-hour estimation is not sufficient in the calculation of the lead time. The CGT method had an uncertainty of less then 1% for the total man-hour estimation, however translating those hours into a lead time deemed unreliable. This holds true for the expert judgement as well. The original estimation for vessel B was within 2,5%, the lead time is off by 10,2%. In that case the parametric model scored better, 2,9%.

[15] O=original estimation

Table 5.24: Lead time(weeks) for resource inclusion Level 2 with the three estimation techniques, for vessel A.

m^2	8,0	8[E1]	8[E2]	8[E3]
Phase 1	10,7	-	11,1	11,0
Phase 2	87,5	-	115,0	84,7
Phase 3	50,5	-	32,0	45,7
TLT	148,8	50,3	158,1	141,4
Est/Base (%)	-	-66,2	6,3	-5,0

Table 5.25: Lead time(weeks) for resource inclusion Level 2 with the three estimation techniques, for vessel B, With Analogy Original.

m^2	8,0	8[E1]	8[E2]	8[OE2]	8[E3]
Phase 1	8,0	-	13,1	6,5	9,9
Phase 2	90,6	-	98,7	77,5	71,9
Phase 3	35,6	-	31,3	36,4	56,2
TLT	134,1	45,8	143,1	120,5	138,0
Est/Base (%)	-	-65,8	6,7	-10,2	2,9

5.6.2. Network phase

The second alignment is level three *network phase* with level 2 *analogical* and level 3 *data driven*. Tables 5.26 and 5.27 present the lead times for vessel A and B, respectively. Looking at scenario $8m^2$ the error between the baseline and the and parametric estimation is larger compared to the method above, errors $-8,5\%$ and $+2,5$ for vessel A and B, respectively. What is interesting is that the estimation error showed a mean error of $-7,9\%$ for vessel A and a mean of $14,9\%$ for vessel B. What can be seen is that the error between the man-hours and the lead time for vessel A remained constant, but for vessel B the error reduced. The analogical estimations are not included in the network phase, the reason is that the analogical results from section 5.6.1 are deemed to not reliable because of the hour translation. The analogy estimation maturity is deemed immature to be used in combination with maturity level 4 *network phase*.

Table 5.26: Lead time(weeks) for network phase Level 3 with the two estimation techniques, for vessel A.

m^2	4,0	4[E3]	8,0	8[E3]	12,0	12[E3]
Phase 1	19,3	17,8	38,7	35,6	58,0	53,4
Phase 2	36,0	34,4	71,9	68,8	107,9	103,2
TLT	55,3	50,6	110,6	101,2	165,9	151,8
Est/Base (%)	-	-8,5	-	-8,5	-	-8,5

Table 5.27: Lead time(weeks) for network phase Level 3 with the three estimation techniques, for vessel B.

m^2	4,0	4[E3]	8,0	8[E3]	12,0	12[E3]
Phase 1	14,9	19,4	29,7	38,8	44,6	58,3
Phase 2	37,2	34,5	74,5	69,0	111,7	103,4
TLT	50,9	52,2	101,8	104,3	152,7	156,5
Est/Base (%)	-	2,6	-	2,5	-	2,5

5.6.3. Conclusion maturity alignment

Tables 5.28 and 5.29 present the results of the level alignment. The tables present the difference between the total lead time of the base-line and the calculated total lead time using the estimation methods. As stated, the analogical planning does not use man-hours as input, therefore the alignment is indicated with a "-". What can be seen is that the CGT method has the largest difference, 66% with the base line planning for level 2 *resource inclusions*, for both both vessel A and B. The analogical estimation performs constant with a difference of 6% for both vessels, this difference with the base-line could be explained by the method of hour logging. Level 3 *data driven* underestimates the lead time for vessel A and overestimates for vessel B. This is inline with the original estimation. To estimate the lead time, the CGT method is not a suited option. The difference between level 2 *analogical* and level 3 *data driven* is small, but one can say that to make estimations with the lowest possible uncertainty it is key the estimators need to estimate the vessel components and not just the departments. Because for level 2 *resource inclusion* the data driven level performed the best, even though the original estimation uncertainty was not better. Unfortunately the network phase could not be compared to the analogical, but as shown for the resource inclusion it did not perform better.

Table 5.28: Table showing difference between base-line and estimated man-hours for vessel A

Estimation	planning					
	[P1] *Analogical*	[P2] *Resource inclusion*	[P3] ***Network phase***	[P4] *Data driven*	[P5] *Risk*	[P6] *Optimisation*
[E1] *CGT*	–	$-66,2\%$				
[E2] ***Analogical***	–	6.3%	–			
[E3] *Data driven*	–	$-5,0\%$	$-8,5\%$			
[E4] *Rapid engineering*						

Table 5.29: Table showing difference between base-line and estimated man-hours for vessel B

Estimation	planning					
	[P1] *Analogical*	[P2] *Resource inclusion*	[P3] ***Network phase***	[P4] *Data driven*	[P5] *Risk*	[P6] *Optimisation*
[E1] *CGT*	–	$-65,8\%$				
[E2] ***Analogical***	–	6.7%	–			
[E3] *Data driven*	–	$2,9\%$	$2,5\%$			
[E4] *Rapid engineering*						

6 Conclusion

Dock space is a valuable asset of ship builders, it dictates how many vessels can be produced at a location. Scaling up requires large investment costs in the production of a new dry dock. Optimising this dock space means more vessels can be produced faster. To investigate dock optimisations, the first step is investigating the certainty of the lead time estimations. Because knowing the lead times with a high certainty, means improvements can be better assessed. Another aspect of optimising is the dock occupation. The dock space is reserved years before the actual vessel is build. But because of the lead time uncertainty, lead time contingency is implemented giving extra dock time. Improving this certainty means that vessels can be reserved closer behind the finish deadline of the preceding vessel. Therefore, less dock time is reserved for unforeseen delays and can thus be used for the production of new vessels. Royal van Lent shipyards wanted to investigate which methods are needed to reduce the uncertainty in its lead time estimations, in order to optimise the dock space. But this question is not only applicable to RvLs, The maturity framework proposed in this thesis is applicable to the entire maritime sector.

The main research question of this thesis was:

How to estimate ship production lead times with the lowest possible level of uncertainty?

To answer this main research question sub goal where defined that aid in finding the answer to the research question. First the sub goals will be answered, followed by the two research objectives. Lastly the main research question of this thesis will be answered.

1. *Identify current maturity frameworks from literature.*
   From the literature research into maturity frameworks it was found that these frameworks can be classed in two categories[32], process and method maturity models. The method maturity framework was opted as the basis for the solution of this thesis. The major reason is that their currently is no method maturity framework available. For method maturity frameworks there is not a basis like SPICE[107]. Therefore, it was chosen to develop a new maturity framework based on literature found for planning and man-hour estimation. This selection is based on the three literature selection criteria. Generic, is the method suitable for different organisations in the maritime industry? Applicable, can it actually be used? Scientific, is the method valid and commonly accepted by the community.
2. *Identify (man-hour)estimation methods from literature.*
   This thesis focused on man-hour estimations. Most literature concerning estimations in an early design stage focusses on estimating the cost, also called cost estimation relationships[6]. Three main estimation methods where identified: analogical, parametric and rapid engineering. A fourth method was found specially for the maritime industry, CGT. These four estimation methods where selected to be used in the maturity framework. This selection is based on the three literature selection criteria, generic, applicable and scientific.
3. *Identify planning methods from literature.*
   For the literature study it was chosen to widen the approach with research into planning methodologies, and not only specific to lead times. These two topics are linked to each other and most planning analysing methods aid in better understanding the lead time, like PERT and critical path[50][19].

From the literature two main subject where found, network and uncertainty analysis. Network analysis covers the linking of task and duration. Creating the ability to preform critical path[19] or network optimisations[129]. The uncertainty methods are methods like, PERT, Monte Carlo, event chain[39][87][42]. Based on the literature criteria it was chosen to incorporate the methods described above.

4. *Map the current production and planning method of Royal van Lent shipyards.*
The current production and planning methods of Royal van Lent shipyards are mapped to better understand the current practices. RvLs uses four planning levels for the depth of their planning(these levels do not have any relation with the levels proposed in the maturity framework). This thesis focused on the year/months lead time of estimation of RvLs. Another important aspect is that RvLs does not make the casco in house. This means that the total lead time is also depicted by a third party, for the analysis this third party was left out because only the information provided by RvLs is known.

5. *Validate maturity framework using Royal van Lent shipyard data.*
The proposed maturity framework, called the *estimation pyramid* and *planning pyramid* has been tested on validity using RvLs as case study organisation. Firstly the current maturity of RvLs was determined, based on that maturity the first three maturity levels of the *estimation pyramid* and *planning pyramid* were compared to each other based on uncertainty. The maturity framework was tested with two test vessels, A and B. The different maturity levels will estimate the lead time and man-hours of these two vessels. These were compared to the actual estimations of the vessels. The results of the two pyramids and the alignment will be discussed below under the two objectives.

To aid the process of answering this question the following two sub research objectives where created. First the answers to the sub research questions will be presented followed by the answer to the main research question.

> *Develop a maturity framework to asses man-hour estimation methods based upon the maturity of the organisation.*

The development of the maturity framework of man-hour estimations resulted in the creation of the *estimation pyramid*. In this maturity framework four maturity levels are identified: CGT, analogical, data driven and rapid engineering. During the creation of the maturity frameworks two hypotheses where stated. H1) A higher maturity level results in an estimation with a lower uncertainty. H2) Performing a maturity level higher than the current maturity of the organisation could increase the level of uncertainty.

To test the validity of this framework and test corresponding hypotheses a case study was performed at RvLs. Three maturity levels where compared against each other, CGT, analogy and data driven. The following can be concluded. The CGT method has the highest uncertainty of 28,5% for the case study. The preceding level *analogy*, gives a lower uncertainty in the estimation, corresponding to hypothesis H1. Level 3 *data driven* did not perform better than level 2 *analogy* which is in line with hypothesis H2. The mean error for the *data driven* level was the highest, and a large estimation spread was seen during the leave one out cross validation, ±20%. However, RvLs is not fully mature in their level 2 *analogical* method either. The difference between the parameter of estimation, departments, and logged, vessel components, first need to be aligned to improve the analogy estimation.

> *Develop a maturity framework to asses ship production lead time estimation methods based upon the maturity of the organisation.*

The development of this maturity framework resulted in the creation of the *planning pyramid*, for this pyramid six maturity levels were identified: analogical, resource inclusion, network phase, data driven, risk and optimisation. Three maturity levels were compared to each other, *analogy*, *resource inclusion* and *network*. From the analysis became clear that RvLs does not use man-hour estimations for their *analogy* phase. Secondly, for maturity level *resource inclusion* $8m^2$ per craftsmen is deemed a good starting point in calculating the production lead time. During the analysis of level 2 *resource inclusion* it also became clear that the lead time does not increase with vessel size. The last conclusion for the *planning pyramid* is that the network phase is deemed to present the lead time with the lowest uncertainty, because sections are only depended on the state of the adjacent sections and not the whole vessel, this is in line with hypothesis H1.

The *planning pyramid* uses the input of the *estimation pyramid* and alignment matrix was presented. Three conclusion on this alignment are presented below, which will lead to answering the main research question of this thesis.

Firstly, it was concluded that there needs to be a correct alignment between the estimation of man-hours and the determination of lead times, also called the pyramid alignment. During the research conducted it was found that the estimations were not made on vessel component level but on the total hours of the department. During the pyramid alignment comparison it became clear that although the experts man-hour estimation had the lowest uncertainty(1,1%), the actual lead times where less correct than level 3 *data driven*. Respectively 6,3% versus -5.0%. Comparing that to the man-hour estimation for the *estimation pyramid* an uncertainty of 1,1%(analogy) vs -7,8%(data driven) were found. It can be seen that a man-hour estimation with a low uncertainty does not result in a low lead time uncertainty, if the estimation parameters are not aligned.

Secondly, a higher planning maturity resulted in a lead time with a lower uncertainty, for level 1 *analogical* no man-hour inputs where needed and thus the lead time is not based upon the required amount of work but on the vessel length. Level two *resource inclusion* used man-hours as input for the lead time, which gives the ability to asses the lead times of the same sized vessels but with other man-hours estimation, a more luxurious interior for instance. The final investigated maturity level, level 3 *network phase*, gave additional insight in the actual production steps of the vessel due to the network phase, meaning the critical path could be obtained and thus the total lead time.

Finally, what can be concluded is that CGT can only be used as a first indication and that it is advised to increase the maturity to level 2 at minimum. Increasing the estimation maturity from level 1 *CGT* to the estimation of an expert, level 2 *analogical*, significantly reduced the lead time certainty, -66,2% versus 6,3% for vessel A. With the above presented conclusions the main research question can be answered:

How to estimate ship production lead times with the lowest possible level of uncertainty?

Estimating lead times with the lowest possible level of uncertainty is achieved by selecting the correct estimation method corresponding to the maturity of the organisation, and by aligning the *estimation pyramid* and *planning pyramid* based on maturity and estimation parameters.

7

Discussion, recommendations and further research

In this chapter the discussion, recommendation and further research is presented.

7.1. Discussion

The discussion is comprised of three elements, discussion of the proposed maturity frameworks, after that the results will be discussed and lastly the application will be discussed.

7.1.1. Method

1. Additional level *Estimation pyramid*
   For the estimation pyramid on level was left out in the maturity levels, the social effect.

   - Level 4/5 *Social effects*
     The last level are social effects, with the change in size social aspects can also become a role. The learning effect of the process can speed up the process

   This was originally added to the maturity levels, because social effects, like the learning effect[93], where not taken into account into the framework. Some company's like Fokker, take this effect into account for the production of aircraft components(S. al Jaberi 2019). Another social aspect has the opposite effect, the Ringelmann effect[135]. This effect explains that if the group size increases the individual members become less efficient, thus with more personal the total output is less than the sum of the individual output.

   The reason these are left out of the framework it that these can also be captured by level 3 *data driven*, because these effect should become apparent in the data. However, the literature study did not studied these effects further, but it is recommended to further investigate these effects if they indeed need to be placed in the maturity framework.

2. Maturity level order *planning pyramid*
   Section 3.1.2 presented the six level of the planning pyramid. As stated, the levels and the order of these levels are created by the author of this thesis. The choice is up for discussion. One element of discussion is the fact the network phase is stated in level 3, but most plannings, are a series of tasks linked together with a certainty amount of duration. And therefore a network is needed. In level 1 their is actually already a network, the two phases. The author of this thesis has chosen to shift it to level 3 because the methods critical path need level one and two to function correctly. Thus it is known that level 1*Analogical* and 2 *resource inclusion* have a network, but not suitable for network analysis.

   The second discussion is Level 4 *data driven* and level 4 *Risk*, the order could be the other way around. First identifying risk and then looking into planning, because it could be possible to identify risks before the data driven level is possible. The author has chosen to first perform the data driven level because incorporating the effect of an pessimistic value for PERT already includes an expected risk. Level 5 *risk*, is more focused in assessing the direct impact a risk has on the planning, using event chain. The author however advises organisation to always take in account risk, e.g. delays, late deliver, hazards, etc. into account. This could be in the form of a contingency time buffer in your planning.

7.1.2. Results case study

1. Translation from vessel components to departments
   The translation from vessel components to the vessel departments was done based on study into a recent vessel. Their it was investigated under which vessel component they logged their hours. This could be an unreliable translation because build method have changed over the time. This could explain why there is a large uncertainty for the department estimations. These values should be read with an critical mindset and the author is aware that this translation could have induced the uncertainty.

2. Data points
   The first point of discussion is the number of data points used in this thesis, only 15 reference vessels could be used for the parametric model of this thesis, because of the low number of data points only linear correlations where found where discrete or exponential relationships might be presented.

   The second part is the type of data points, this thesis was restricted to the system coding of RvL, where scaffolding or transportation hours are not a separate data point.

3. Correctness of data
   RvLs is currently going into a transition phase where the company is improving their hour registration, during the research it became apparent that in the past production hours for the same tasks where not always logged under the same system code. This could mean that the original data contains a error margin, the percentage of false logged hours are not known. It is expected that the majority is logged correctly but one should be aware of a possible error margin.

4. One expert used in research
   In this thesis only one expert did an estimation on the two reference vessels A and B. The writer of this thesis is aware that this is a small sample but because the organisation only had one proposal engineer the sample size could not be increased. Therefore it is also recommended in section 7.2 to test the proposed framework in different organisations.

5. Cost removal
   As stated in section 5.2.4 the cost of third parties are not translated into man-hours. This choice was done because three assumption needed to be made, profit margin, material cost and labour cost. These are unknown for each system code and it is expected to differ between components. E.g. it is expected that an invoice of the engine placement has a larger percentage in material cost, the engine, than a labour intensive task like polishing the anchor box.

   The removal has an influence on the results. The casco and super structure are entirely build by a third party which is left out with this decision. But because this has been left out for all the maturity levels the relevant comparison is still valid.

6. Vessel component simplification
   Vessel components hours have been combined for two reasons. Firstly, not all the data points have been logged under the same system code. Combining the system codes increases the change of giving a more accurate amount of hours. The second reason is that the level of detail in the number of different vessel components is not in line with the accuracy of the actual data. the scope of the different system codes for each vessel are not logged. This could mean that for one vessel a percentage of piping is logged under *engine* instalment and for a other vessel entirely under *piping*. Combining the different vessel components therefore reduces this uncertainty but decreases the level of detail. One might discuss if some of thesis combination are not valid, but because they have been done consequently for all the maturity levels the comparison is still valid.

7. Lead time bottleneck
   For the lead time bottleneck the amount of workers per m^2 had been chosen, in reality more lead time bottlenecks are present in the manufacturing of a vessel. such as third parties but also the times it takes for paint to dry. The writer of this thesis is aware that more bottlenecks are present, a few bottlenecks will be discussed. Identifying all possible bottlenecks is beyond the scope of this discussion. One

possible bottleneck are the walkways and corridors, if a room is large but has only one door the flow of people and goods are restricted by this door instead of the room itself. Another bottleneck are the entrance points in the actual vessel, these entrance points also change during the production. From large possible entrance points during the casco build to only the cabin door. That is the reason why most of the time the engine is all ready been placed in the casco, in a later stage it cannot fit thru the entrance points. Other bottlenecks are, paint drying time, transport, output of suppliers, etc. Super yachts bottlenecks can also change depending on the customer. E.g. if a customer wants a pearl coating this needs to be painted in one go meaning that all other exterior work needs to be finished, for other vessels this is not necessary creating a difference in bottlenecks. Assuming their are infinite number of workers, is also a point of discussion. At one point the number of personal available will be issue for ever larger vessels, if in the same year the competitions like Oceanco, Lürssen, Amels, etc. build a large vessel the number of craftsmen could be a bottleneck and could lead to an increase of lead time. Assessing the effect of market competition on the number of available personal and thus lead time was deemed outside the scope of this thesis. This could be a real bottleneck in real life.

7.1.3. Application

1. The application of the maturity framework
   The lack of a maritime estimation and planning maturity framework might indicate that their no need for such maturity frameworks. The author of this thesis argues that these maturity frameworks should be a starting point when selecting estimation or planning methods. Before someone selects a parametric model for his or her research it should first asses if this method is the best starting point for his estimation problem. Using the maturity framework could aid in placing his problem in context.

   Industry specific maturity models are more common in other industry like healthcare[34]. The development of a maturity framework for the maritime industry might create the opportunity to have a foundation of discussion between the maturity of the different companies in the maritime sector and share techniques how one can increase maturity. And get to a stage where rapid engineering can become more used instead of theoretical application, stated by *Van Oers, B.J* in this thesis on packing approach[126].

7.2. Recommendation

In this section the recommendations for the model and for RvLs are discussed. Firstly recommendations are given to improve the framework and corresponding models. The recommendation discussed below are for the current model, in section 7.3 further research is stated that can be used to further develop and improve the model. Secondly recommendations are stated that will help RvLs in making better estimations.

1. Hours within cost
   As stated in the discussion hours within the cost of third parties are not used in the analysis of this thesis, making estimation where company decisions are based upon it is advised to implement these into the model.

2. Implement additional lead time constraints
   It is recommended to further analyse the different lead time constraints in the model. For now using m^2 bottleneck is sufficient, but for a more in dept analysis into lead times it is advised to map the other production constraints.

3. Third parties
   For the scope of this thesis third parties have been left out into the model. However third parties are an important factor in the production of super yachts. Company's like Oceanco are even entirely build by third parties. Therefore it is recommend to include these into further lead time estimations. It is important to set a scope for third parties, when they are included or not.

4. Implement machine learning
   The parametric model is currently made by hand, but identifying parametric estimation can done using simple machine learning tools for phyton such as Scikit[3], the leave on out cross validation was already a first approach in implementing this technique. The benefit is that the estimation can made more quickly.

The next enumerate is for RvLs specific, these are recommendations how to improve the estimation process.

1. Log external hours
   It is recommended for RvLs to log external hours made by third parties on the vessel. This serves two purposes, the first is that further estimations on man-hours can also be made for third parties. As stated the casco is produced at a third party, it gives insight what the actual hours of production are. The second benefit is a controlling aspect, if the third party needs twice as many hours as estimated RvLs has information to support the discussion.

2. Improve estimations constantly
   It is advised to create a integral estimation data base that updates at a short interval. The interval of estimation updates should be faster then the current lead times of a super yacht, three to 5 years. E.g. the man-hours needed to place $1m^2$ of teak deck can be updated in a shorter interval. This can directly be used in new vessel estimations and the effect of building techniques can directly be analysed.

3. re-evaluate estimation on predetermined intervals
   Currently, man-hour estimations are not re-evaluated during the project. It is unknown within RvLs what the average estimation error is, for cost and man-hour estimations. Knowing these margins the level of contingency can also be determined more accurately.

4. Shift to data driven maturity
   Relying on the experts opinion is not wrong, it is however advised to shift to the data driven maturity level. People have the tendency to under estimate a planning, called the planning fallacy[49]. Making data driven decisions can aid in reducing this fallacy. And making more realistic estimations.

5. State vessel independent tasks
   The yachts build at RvLs are all custom, that means that a planning or estimation cannot be used directly for another vessel. This means that estimations are hard to make, therefore it is advised to identify standard tasks. E.g. a crew cabin, takes X amount of hours. If a vessel needs more crew cabins this standardises task can be multiplied. Another example is interior floor or wall production times, it is expected that with larger vessels the room area increases in size[*discussion at RvL*]. If the hours per m^2 is known the estimation can be made without a reference vessel with similar rooms sizes.

7.3. Further research

This section will present further research that can help improve the model or validate the correctness of the framework.

1. Study outbound estimation
   Study the applicability of the proposed *estimation pyramid* and *planning pyramid* for outbound estimation. In this thesis it is tested on an inbound estimation as a first validation of the maturity framework. The next step wound be to test it on the outbound performance, when making the outbound estimation the reader needs to realise that the maturity of the organisation needs to be re-evaluate because the current amount of data points might not suffice for the new vessel. Making bigger vessels is an outbound estimation, but building different types of vessels could also be classified as an outbound estimation. RvLs would be less mature for the production of a 60 meter bulk carrier then a 60 meter yacht. Appendix H presents the application of the *estimation pyramid* on the estimation of man-hours of a large super yacht, one early conclusion could be that CGT should indeed only be used as a first estimated but that a uncertainty is always present.

2. Study in accuracy range for maturity level
   In the petrochemical industry, their are frameworks where based on project knowledge an estimation uncertainty range can be determined. For instance, in the early phase a range of $\pm 50\%$ cost spread could be expected, and with increased level of knowledge this will decrease. Figure 7.1[118] presents such a model, where the different classes indicate a level of engineering completion. It would be an interesting subject to make these estimations for the maritime industry, what are the expected uncertainty's with a certain amount of engineering knowledge, currently no data is available on this subject to the writers knowledge.

3. Data point reduction research.
   For this thesis the number of data points where limited. But if a large sample size is present the effect of reducing the sample size could be studied when a sample size is deemed to small to make predictable estimations.

4. Application of maturity framework on other organisations
   To further improve the estimation and planning pyramid the framework will need to be tested on other organisations. That way the model can be improved even more an could aid as a guideline for estimations within the maritime sector.

5. Research estimate errors for man-hours in maritime industry
   No research was found that investigated the amount of error margin of estimation on the maritime industry. How many times and by how much, do a project go over budget or are under staffed in the maritime industry. For the IT sector research has been done in the amount of cost overrun[119]. This could be also performed for the maritime sector.

6. Research lead time calculation errors for the maritime industry
   Estimating a lead time does not mean the project actually has that lead time, everybody has read the news that construction projects delay, a famous one is the Sydney opera house what was delayed by ten years[20], Trigunarsyah[122] even stated that only 47% construction project are finished on time. For the maritime industry these figures are not mapped, it would be an interesting further study in the actual lead times and how they differ from the estimated lead times.

7. Improve model with third dimension
   The current maturity framework only has two dimensions, level of maturity and the level of uncertainty. But as mention previously(Figure 7.1), having more project knowledge can reduce this level of uncertainty. This level of knowledge can only be gained if more engineering takes places which means more time spend on the engineering of the project. This means there is a third dimension, time. How time affects the uncertainty can be researched in more detail.

8. Optimise dock space
   As presented in the introduction of this thesis RvLs is looking for ways to optimise its dock occupation. But it first needed to evaluate how to make lead time estimation with the lowest possible uncertainty. Because this has been performed in this thesis a further research will be actually optimising the dock space.

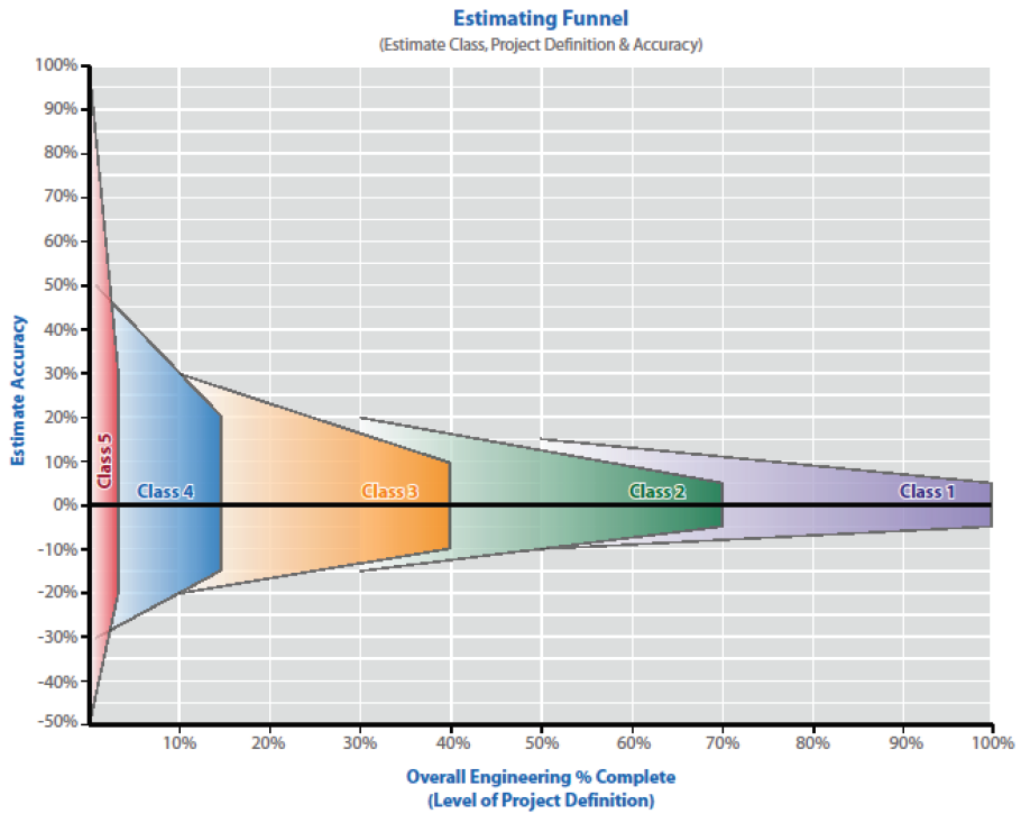


Figure 7.1: Schematic of estimation accuracy for different engineering completion classes.

A

Vessel blocks

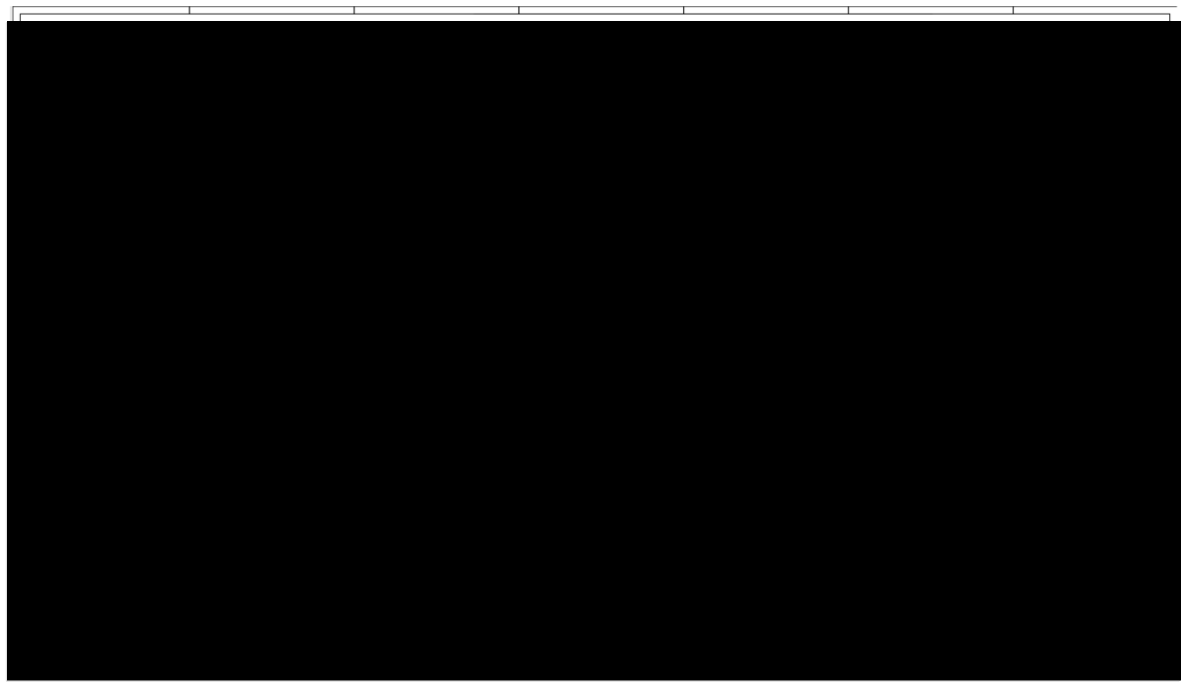


Figure A.1: Block indication.

B
Early design sketch

Figure B.1: Early design sketch

C

Vessel used in the CGT model

Table C.1: A B parameters for each vessel type.

Ship type	A	B
Oil tankers (double hull)	48	0.57
Chemical tankers	84	0.55
Bulk carriers	29	0.61
Combined carriers	33	0.62
General cargo ships	27	0.64
Reefers	27	0.68
Full container	19	0.68
Ro ro vessels	32	0.63
Car carriers	15	0.70
LPG carriers	62	0.57
LNG carriers	32	0.68
Ferries	20	0.71
Passenger ships	49	0.67
Fishing vessels	24	0.71
NCCV	46	0.62

D

Componend devision

Table D.1 presents the simplification of the system codes. The names in bold correspond to the vessel components the expert and the simulation have to estimate, table 5.6 with estimations can be found in section 5.2.2.

Table D.1: Table with component division under main components.

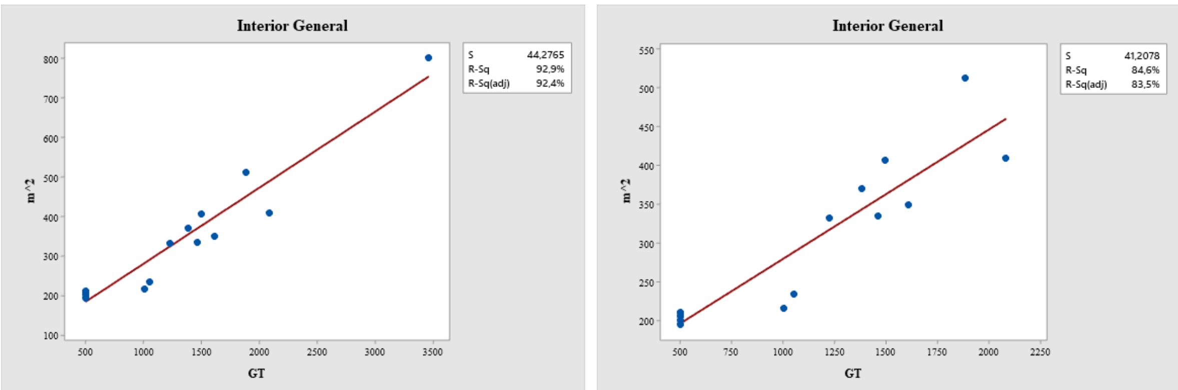
System code	Vessel component	System code	Vessel component
	Casco		**Yacht equipment**
2000,00	Hull & Superstructure	6000,00	Yacht equipment
2200,00	Hull construction	6100,00	Boarding equipment
2800,00	0.5 x Hull & Superstructure additional items	6200,00	Hatches and Platforms
	Superstructure	6300,00	Cranes and davits
2400,00	Superstructure construction	6400,00	Foremast
2600,00	Mast	6500,00	Miscellaneous yacht equipment
2800,00	0.5 x Hull & Superstructure additional items	6600,00	Lifts and elevators
	Piping mechanical systems	4600,00	Helicopter facilities
3000,00	Mechanical systems	4900,00	Jacuzzi's, pools, sauna & steam showers
3100,00	Bilge & drainage system	8500,00	Tenders and toys
3200,00	Firefighting system		**Exterior**
3300,00	Fuel oil system	8000,00	Exterior
3400,00	Cooling system	8100,00	Deck covering
3500,00	Fresh water system	8200,00	Outside ceiling
3600,00	Black and grey water system	8300,00	Deck equipment and fittings
3700,00	Lubrication oil system	8400,00	Life saving equipment
3800,00	Compressed air system	8600,00	Outside furniture
3900,00	Ventilation and air conditioning system	8700,00	Anchor and mooring equipment
	Propulsion	8800,00	Doors exterior
4100,00	Propulsion installation	8900,00	Glass
	Construction mechanical systems		**Paint Ext**
4200,00	Manoeuvring installations	9000,00	Paint
4300,00	Cool and freeze installation	9100,00	Below waterline exterior paint system
4400,00	Hydraulic system	9200,00	Above waterline exterior paint system hull
4500,00	Additional systems	9300,00	Above waterline exterior paint system superstructure
4700,00	Cathodic protection system		**Paint Int**
4800,00	Insulation	9400,00	Tank paint system
	Electrical systems	9500,00	Interior conservation paint system
5000,00	Electrical, navcom & AV installation	9600,00	Interior technical spaces paint system
5100,00	Electrical distribution systems	9700,00	Miscellaneous paint items
5200,00	Electrical power generating system		
5300,00	Lighting systems		
5400,00	Nautical systems		
5500,00	Navigation and communication systems		
5600,00	Control and alarm systems		
5700,00	Audio, video and ICT systems		
5800,00	Household equipment		
5900,00	Miscellaneous systems		

E

Specification correlations

To obtain the correlation between top level parameters and sub level parameters first the definition of top and sub level parameters need to be established. For this thesis the top level parameters are identified as LOA and GT. For another organisation it might be different, DWT for instance. But because in the super yacht world the length of the vessels and GT are the most commonly used top level parameters it is used in this thesis. The sub level parameters of choice are presented in table E.1, these are chosen because they are the best documented of the vessels and are less prone to customer wishes than for instance a helicopter pad, which is just a choice of the customer, but every vessel needs some crew interior.

Table E.1 present the correlations between the top and sub level parameters. But before going into detail the *(O)* will be explained, the *(O)* stands for outlier. In the data there is one vessel *Symphony* that is an outlier, the volume(GT) is 1.75 times larger then the second largest vessel. To illustrate this problem two regression plots are made with and without the Symphony, shown in Figure E.1. What can be seen is that the outlier creates the effect of better fitting data, the R^2 and adjusted R^2 drop when the outlier is removed. But including the data point could give a false sense of predictably of data points. For the sub level parameters the difference for the adjusted R^2 with and without symphony is 92,4% or 83,5%. Therefore it is chosen to do the analysis with and without the symphony in order to get more realistic results.



(a) Regression analysis with outlier.

(b) Regression analysis without outlier.

Figure E.1: Evaluation outliers.

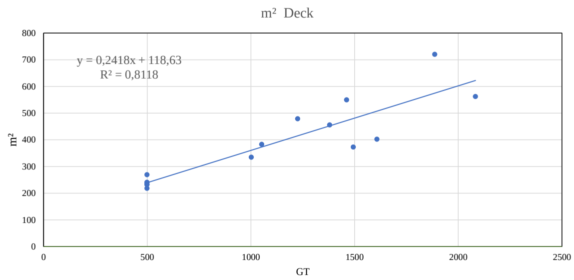
Table 5.2 present the correlations between the top, LOA and GT, and the sub level parameters. The P indicates Pearson's r correlation coefficient. It can be seen that the data points with the outlier *(O)* have on average higher correlation factors the when the outlier is removed. The R^2 values are all from linear regression other regression lines, to the power or polynomial, where found to over fit the data or did not reducing the R^2. Making the conclusion to use a linear correlation, which in term makes the model easier.

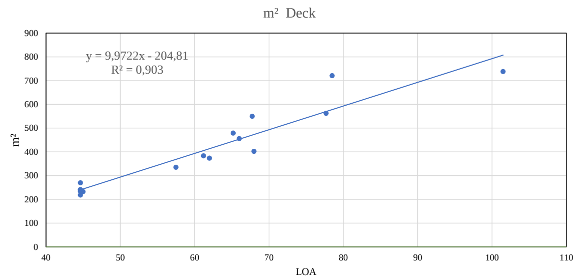
Looking at the R^2 values, it can be said that model has a lower R^2 value but for most parameters it is still above 0,7. The second conclusion is that GT is overall a better top level parameter where sub levels can be based upon. Only deck and guest m^2 have a better fit for LOA, another observation is that with removing the outlier the R^2 drops to 0.29 stating it is a bad correlation. All the plotted graphs can be found in appendix E, in the graphs also the formula is shown to give a better indication how the elements scale.

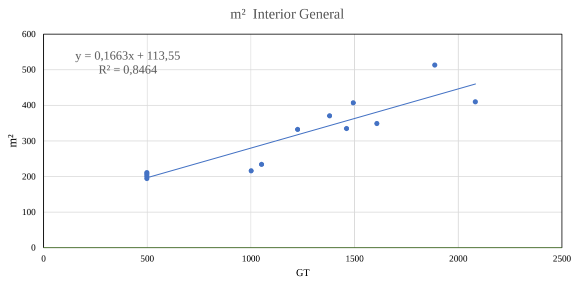
Table E.1: Table with the correlations between sub and top level parameters.

Sub level parameter	LOA P(O)	GT P(O)	LOA P	GT P	GT R^2(O)	GT R^2	LOA R^2(O)	LOA R^2
Total propulsion power KW	0,88	0,94	0,67	0,76	0,80	0,62	0,73	0,54
m² Interior General	0,94	0,96	0,90	0,92	0,93	0,85	0,88	0,81
m² Interior Owner	0,85	0,90	0,71	0,77	0,81	0,59	0,73	0,51
m² interior Guest	0,93	0,90	0,89	0,84	0,81	0,70	0,87	0,78
m² Interior Tech spaces	0,95	0,95	0,94	0,97	0,90	0,94	0,90	0,90
m² deck covering	0,95	0,90	0,95	0,90	0,82	0,81	0,90	0,90
m² Interior crew	0,99	0,98	0,98	0,99	0,97	0,97	0,98	0,97
m² outside furniture	0,77	0,83	0,54	0,59	0,69	0,35	0,60	0,29

The table shows that between the top and the sub level parameters there is a clear correlation, only a minimum correlation factor of 0,77 can be found and an average correlation of 0,91. These are good correlation knowing that 1,0 means a perfect correlation is present. Now that it is established that from top level parameters sub level parameters can be assumed, this will mean that block *(L3_M_4)* of the level 3 maturity model can be performed.







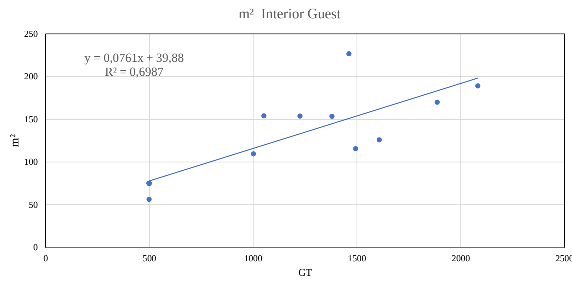


Figure E.7 presents the cost per m^2 for the range of vessel sizes. The actual cost per m^2 is left out for discrepancy. Although the correlation has a correlation of $R^2 = 0,46$ an upwards trend can be seen. The second observation is that their is a large spread for the vessels of 500GT, this is due to the finish quality demanded by the customer.

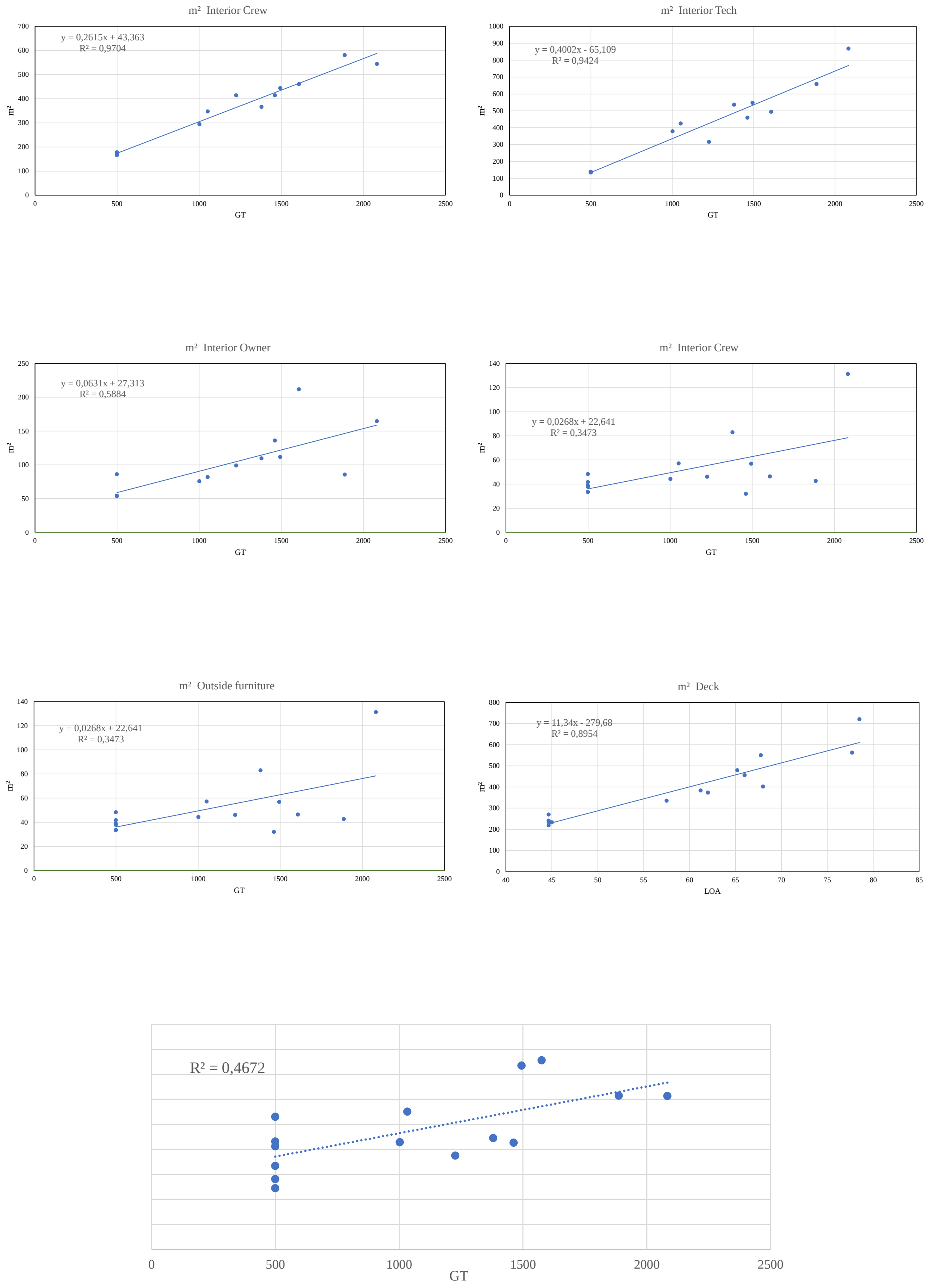


Figure E.7: Interior guest cost per m^2 for the difference vessels sizes.

F

Section lead time for base line data

Table F.1: Table with lead times in weeks for each section with $4m^2$ for vessel **A** using original data.

Block number:	1	2	3	4	5	6	7	8	9	10
Casco	2,5	2,9	1,7	1,5	5,8	2,8	2,1	0,0	0,0	0,0
Superstructure	0,0	0,0	0,0	0,0	0,0	0,0	0,0	4,1	3,4	3,3
Hotwork	5,2	5,9	3,6	3,2	11,9	5,8	4,3	15,2	12,5	11,9
Paint	8,1	3,7	5,2	2,1	2,3	2,7	2,7	14,7	2,6	1,6
Outfit	2,8	3,2	1,9	1,7	6,4	3,1	2,3	8,2	6,7	6,4
Engine	0,0	0,0	2,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Special	0,0	0,0	0,0	1,3	0,0	2,4	0,0	0,0	0,0	0,0
paint_int	0,6	0,6	0,4	0,3	1,3	0,6	0,5	0,0	0,0	0,0
Interior	4,7	5,6	7,5	11,2	0,0	1,3	6,5	13,1	24,5	0,0

Table F.2: Table with lead times in weeks for each section with $8m^2$ for vessel **A** using original data.

Block number:	1	2	3	4	5	6	7	8	9	10
Casco	5,0	5,7	3,4	3,1	11,5	5,6	4,1	0,0	0,0	0,0
Superstructure	0,0	0,0	0,0	0,0	0,0	0,0	0,0	8,3	6,8	6,5
Hotwork	10,4	11,9	7,1	6,4	23,9	11,5	8,6	30,4	24,9	23,9
Paint	16,3	7,3	10,3	4,2	4,6	5,4	5,4	29,4	5,3	3,3
Outfit	5,6	6,4	3,9	3,4	12,9	6,2	4,6	16,4	13,5	12,9
Engine	0,0	0,0	4,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Special	0,0	0,0	0,0	2,7	0,0	4,8	0,0	0,0	0,0	0,0
paint int	1,1	1,3	0,8	0,7	2,5	1,2	0,9	0,0	0,0	0,0
Interior	9,5	11,1	15,1	22,4	0,0	2,6	13,1	26,1	48,9	0,0

Table F.3: Table with lead times in weeks for each section with $12m^2$ for vessel **A** using original data.

Block number:	1	2	3	4	5	6	7	8	9	10
Casco	7,5	8,6	5,2	4,6	17,3	8,3	6,2	0,0	0,0	0,0
Superstructure	0,0	0,0	0,0	0,0	0,0	0,0	0,0	12,4	10,2	9,8
Hotwork	15,6	17,8	10,7	9,5	35,8	17,3	12,9	45,6	37,4	35,8
Paint	24,4	11,0	15,5	6,3	6,9	8,1	8,1	44,1	7,9	4,9
Outfit	8,4	9,6	5,8	5,2	19,3	9,3	7,0	24,6	20,2	19,3
Engine	0,0	0,0	6,3	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Special	0,0	0,0	0,0	4,0	0,0	7,3	0,0	0,0	0,0	0,0
paint_int	1,7	1,9	1,1	1,0	3,8	1,8	1,4	0,0	0,0	0,0
Interior	14,2	16,7	22,6	33,6	0,0	3,9	19,6	39,2	73,4	0,0

Table F.4: Table with lead times in weeks for each section with $4m^2$ for vessel **B** using original data.

Block number:	1,0	2,0	3,0	4,0	5,0	6,0	7,0	8,0	9,0	10,0
Casco	3,4	3,4	2,4	1,2	5,7	2,2	2,2	0,0	0,0	0,0
Superstructure	0,0	0,0	0,0	0,0	0,0	0,0	0,0	1,6	1,1	1,4
Hotwork	4,8	4,7	3,3	1,6	8,0	3,0	3,1	9,2	6,1	8,0
Paint	15,5	6,0	9,9	2,2	3,2	2,9	3,9	18,3	2,7	2,3
Outfit	2,2	2,2	1,5	0,7	3,6	1,4	1,4	4,2	2,8	3,6
Engine	0,0	0,0	2,7	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Special	0,0	0,0	0,0	0,7	0,0	1,3	0,0	0,0	0,0	0,0
paint_int	0,7	0,7	0,5	0,2	1,2	0,5	0,5	0,0	0,0	0,0
Interior	6,0	5,5	10,2	7,8	0,0	1,2	6,0	14,7	15,8	0,0

Table F.5: Table with lead times in weeks for each section with $8m^2$ for vessel **B** using original data.

Block number:	1	2	3	4	5	6	7	8	9	10
Casco	6,9	6,7	4,8	2,3	11,4	4,3	4,4	0,0	0,0	0,0
Superstructure	0,0	0,0	0,0	0,0	0,0	0,0	0,0	3,2	2,1	2,7
Hotwork	9,6	9,4	6,7	3,3	15,9	6,0	6,1	18,4	12,2	15,9
Paint	30,9	12,0	19,9	4,5	6,3	5,8	7,9	36,7	5,3	4,5
Outfit	4,4	4,3	3,0	1,5	7,3	2,8	2,8	8,4	5,6	7,3
Engine	0,0	0,0	5,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Special	0,0	0,0	0,0	1,5	0,0	2,7	0,0	0,0	0,0	0,0
paint_int	1,4	1,4	1,0	0,5	2,4	0,9	0,9	0,0	0,0	0,0
Interior	12,0	11,0	20,4	15,5	0,0	2,3	12,0	29,4	31,6	0,0

Table F.6: Table with lead times in weeks for each section with $12m^2$ for vessel **B** using original data.

Block number:	1	2	3	4	5	6	7	8	9	10
Casco	10,3	10,1	7,2	3,5	17,1	6,5	6,6	0,0	0,0	0,0
Superstructure	0,0	0,0	0,0	0,0	0,0	0,0	0,0	4,8	3,2	4,1
Hotwork	14,4	14,1	10,0	4,9	23,9	9,0	9,2	27,6	18,4	23,9
Paint	46,4	18,0	29,8	6,7	9,5	8,8	11,8	55,0	8,0	6,8
Outfit	6,6	6,5	4,6	2,2	10,9	4,1	4,2	12,6	8,4	10,9
Engine	0,0	0,0	8,1	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Special	0,0	0,0	0,0	2,2	0,0	4,0	0,0	0,0	0,0	0,0
paint_int	2,2	2,1	1,5	0,7	3,6	1,4	1,4	0,0	0,0	0,0
Interior	18,0	16,5	30,6	23,3	0,0	3,5	18,0	44,1	47,5	0,0

G

Lead time level alignment results

This appendix present the lead time calculation results. In section 5.6 these results are discussed. As stated the *estimation pyramid* and the *planning pyramid* need to be aligned in order to get correct result, matching a low estimation maturity with a high planning maturity will not give additional insight. In the maturity level determination it was found that RvLs has level 2 estimation maturity and level 3 planning maturity.

G.1. Level 2 Resource inclusion alignment

The alignment matrix states that level 2 *resource inclusion* can be used with level 1 *CGT*, level 2 *Analogical*, and level 3 *Data driven* maturity levels.

Table G.1: Total lead time using CGT hours as input for vessel **A**.

Time unit	m^2	CGT high	medium	low
Uren	4	654,0	662,5	684,1
	8	1.738,7	1.761,2	1.818,6
	12	1.962,0	1.987,5	2.052,2
Weken	4	18,7	18,9	19,5
	8	49,7	50,3	52,0
	12	56,1	56,8	58,6

Table G.2: Total lead time using CGT hours as input for vessel **B**.

Time unit	m^2	CGT high	medium	low
Uren	4	682,1	802,1	954,3
	8	1.364,2	1.604,2	1.908,6
	12	2.046,3	2.406,3	2.863,0
Weken	4	19,5	22,9	27,3
	8	39,0	45,8	54,5
	12	58,5	68,8	81,8

Table G.3: Lead time(weeks) for resource inclusion Level 2 with the three estimation techniques, for vessel A.

m^2	4,0	4[E1]	4[E2]	4[E3]	8,0	8[E1]	8[E2]	8[E3]	12,0	12[E1]	12[E2]	12[E3]
Phase 1	4,0	-	4,2	4,1	10,7	-	11,1	11,0	12,1	-	12,5	12,4
Phase 2	32,9	-	43,3	31,8	87,5	-	115,0	84,7	98,8	-	129,8	95,5
Phase 3	19,0	-	12,0	17,2	50,5	-	32,0	45,7	57,0	-	36,1	51,6
TLT	56,0	18,9	59,5	53,2	148,8	50,3	158,1	141,4	167,9	56,8	178,5	159,5
Est/Base (%)	-	-66,2	6,3	-5,0	-	-66,2	6,3	-5,0	-	-66,2	6,3	-5,0

Table G.4: Lead time(weeks) for resource inclusion Level 2 with the three estimation techniques, for vessel B, With Analogy Original.

m^2	4,0	4[E1]	4[E2]	4[OE2]	4[E3]	8,0	8[E1]	8[E2]	8[OE2]	8[E3]
Phase 1	4,0	-	6,6	3,3	4,9	8,0	-	13,1	6,5	9,9
Phase 2	45,3	-	49,4	38,8	35,9	90,6	-	98,7	77,5	71,9
Phase 3	17,8	-	15,6	18,2	28,1	35,6	-	31,3	36,4	56,2
TLT	67,1	22,9	71,6	60,2	69,0	134,1	45,8	143,1	120,5	138,0
Est/Base (%)	-	-65,8	6,7	-10,2	2,9	-	-65,8	6,7	-10,2	2,9
m^2	12,0	12[E1]	12[E2]	12[OE2]	12[E3]					
Phase 1	12,0	-	19,7	9,8	14,8					
Phase 2	135,8	-	148,1	116,3	107,8					
Phase 3	53,4	-	46,9	54,6	84,3					
TLT	201,2	68,8	214,7	180,7	207,0					
Est/Base (%)	-	-65,8	6,7	-10,2	2,9					

Table G.5: Parametric, resource inclusion, Table with the vessel components lead times for vessel A.

	User m^2:	4	8	12
Vessel component	$\sum$ Craftsman:	213,7	106,9	71,2
Casco	144,5	384,2	433,5	578,0
Superstructure	19,9	53,0	59,8	79,8
Piping mechanical systems	577,2	1534,5	1731,6	2308,8
Propulsion	75,9	201,9	227,8	303,7
Consturction mechanical systems	139,7	371,4	419,1	558,8
Electrical systems	22,0	58,6	66,1	88,2
Yacht equipment	143,3	380,9	429,8	573,1
Exterior	357,6	950,6	1072,8	1430,4
Paint Ext	1114,5	2962,9	3343,5	4458,0
Paint Int	156,4	415,9	469,3	625,8
Interior	602,0	1600,4	1806,0	2407,9
Interior owners	150,1	399,0	450,3	600,4
Interior guest	205,9	547,3	617,6	823,5
Interior public	455,7	1211,6	1367,2	1822,9
Interior service	74,0	196,7	222,0	296,0
Interior crew	207,6	551,9	622,8	830,4
Interior captain, hospital and staff	30,7	81,6	92,1	122,8
Interior wheelhouse and ship's office	82,4	219,1	247,3	329,7
Interior technical spaces and stores	39,5	105,1	118,6	158,1

Table G.6: Parametric, resource inclusion, Table with the vessel components lead times for vessel B.

Vessel component	User m^2: ∑ Craftsman:	4 398,8	8 150,0	12 132,9
Casco	173,2	346,5	519,7	692,9
Superstructure	32,6	65,2	97,8	130,4
Piping mechanical systems	593,7	1187,4	1781,1	2374,8
Propulsion	107,8	215,7	323,5	431,4
Consturction mechanical systems	172,9	345,8	518,6	691,5
Electrical systems	27,6	55,3	82,9	110,6
Yacht equipment	131,5	263,0	394,5	526,0
Exterior	370,7	741,5	1112,2	1483,0
Paint Ext	1258,2	2516,4	3774,6	5032,8
Paint Int	171,1	342,1	513,2	684,2
Interior	983,1	1966,3	2949,4	3932,5
Interior owners	164,4	328,8	493,2	657,6
Interior guest	171,9	343,7	515,6	687,5
Interior public	385,6	771,1	1156,7	1542,3
Interior service	92,4	184,7	277,1	369,4
Interior crew	169,3	338,6	507,9	677,2
Interior captain, hospital and staff	22,5	45,0	67,6	90,1
Interior wheelhouse and ship's office	79,0	158,1	237,1	316,1
Interior technical spaces and stores	41,8	83,6	125,4	167,2

G.2. Level 3 Network phase alignment

The alignment matrix states that level 3 *Network phase* can be used with the level 2 *Analogical* and level 3 *Data driven* maturity levels.

G.2.1. Section lead time, using level 3 *data driven* input

Table G.7: Table with lead times in weeks for each section with $4m^2$ for vessel **A** data driven estimation.

Block number:	1	2	3	4	5	6	7	8	9	10
Casco	2,6	2,9	1,8	1,6	5,9	2,8	2,1	0,0	0,0	0,0
Superstructure	0,0	0,0	0,0	0,0	0,0	0,0	0,0	2,4	2,0	1,9
Hotwork	4,5	5,1	3,1	2,7	10,3	5,0	3,7	13,1	10,8	10,3
Paint	7,9	3,5	5,0	2,0	2,2	2,6	2,6	14,2	2,6	1,6
Outfit	1,8	2,1	1,3	1,1	4,2	2,0	1,5	5,4	4,4	4,2
Engine	0,0	0,0	1,6	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Special	0,0	0,0	0,0	1,4	0,0	2,5	0,0	0,0	0,0	0,0
paint_int	0,7	0,8	0,5	0,4	1,6	0,8	0,6	0,0	0,0	0,0
Interior	5,0	5,9	7,5	10,8	0,0	1,4	5,9	14,8	23,4	0,0

Table G.8: Table with lead times in weeks for each section with $8m^2$ for vessel **A** data driven estimation.

Block number:	1	2	3	4	5	6	7	8	9	10
Casco	5,1	5,9	3,5	3,1	11,8	5,7	4,2	0,0	0,0	0,0
Superstructure	0,0	0,0	0,0	0,0	0,0	0,0	0,0	4,8	4,0	3,8
Hotwork	9,0	10,3	6,2	5,5	20,6	9,9	7,4	26,2	21,5	20,6
Paint	15,7	7,1	10,0	4,1	4,5	5,2	5,2	28,4	5,1	3,2
Outfit	3,7	4,2	2,5	2,3	8,5	4,1	3,1	10,8	8,9	8,5
Engine	0,0	0,0	3,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Special	0,0	0,0	0,0	2,7	0,0	4,9	0,0	0,0	0,0	0,0
paint_int	1,4	1,6	1,0	0,9	3,2	1,5	1,1	0,0	0,0	0,0
Interior	10,1	11,9	15,1	21,7	0,0	2,9	11,9	29,6	46,8	0,0

Table G.9: Table with lead times in weeks for each section with $12m^2$ for vessel **A** data driven estimation.

Block number:	1	2	3	4	5	6	7	8	9	10
Casco	7,7	8,8	5,3	4,7	17,7	8,5	6,4	0,0	0,0	0,0
Superstructure	0,0	0,0	0,0	0,0	0,0	0,0	0,0	7,3	5,9	5,7
Hotwork	13,5	15,4	9,2	8,2	30,9	14,9	11,1	39,4	32,3	30,9
Paint	23,6	10,6	15,0	6,1	6,7	7,8	7,8	42,6	7,7	4,8
Outfit	5,5	6,3	3,8	3,4	12,7	6,1	4,6	16,2	13,3	12,7
Engine	0,0	0,0	4,9	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Special	0,0	0,0	0,0	4,1	0,0	7,4	0,0	0,0	0,0	0,0
paint_int	2,1	2,4	1,4	1,3	4,8	2,3	1,7	0,0	0,0	0,0
Interior	15,1	17,8	22,6	32,5	0,0	4,3	17,8	44,4	70,2	0,0

Table G.10: Table with lead times in weeks for each section with $4m^2$ for vessel **B** data driven estimation.

Block number:	1	2	3	4	5	6	7	8	9	10
Casco	4,3	4,2	3,0	1,5	7,1	2,7	2,7	0,0	0,0	0,0
Superstructure	0,0	0,0	0,0	0,0	0,0	0,0	0,0	3,6	2,4	3,1
Hotwork	6,4	6,3	4,4	2,2	10,6	4,0	4,1	12,2	8,1	10,6
Paint	12,3	4,8	7,9	1,8	2,5	2,3	3,1	14,6	2,1	1,8
Outfit	2,8	2,7	1,9	1,0	4,6	1,7	1,8	5,3	3,5	4,6
Engine	0,0	0,0	3,2	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Special	0,0	0,0	0,0	1,0	0,0	1,8	0,0	0,0	0,0	0,0
paint_int	1,1	1,0	0,7	0,4	1,7	0,7	0,7	0,0	0,0	0,0
Interior	6,5	6,1	12,6	10,5	0,0	1,2	5,6	14,6	21,9	0,0

Table G.11: Table with lead times in weeks for each section with $8m^2$ for vessel **B** data driven estimation.

Block number:	1	2	3	4	5	6	7	8	9	10
Casco	8,5	8,4	5,9	2,9	14,1	5,4	5,4	0,0	0,0	0,0
Superstructure	0,0	0,0	0,0	0,0	0,0	0,0	0,0	7,2	4,8	6,2
Hotwork	12,8	12,6	8,9	4,4	21,2	8,0	8,1	24,5	16,3	21,2
Paint	24,6	9,5	15,8	3,6	5,0	4,6	6,3	29,1	4,2	3,6
Outfit	5,6	5,5	3,9	1,9	9,2	3,5	3,5	10,7	7,1	9,2
Engine	0,0	0,0	6,5	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Special	0,0	0,0	0,0	1,9	0,0	3,6	0,0	0,0	0,0	0,0
paint_int	2,1	2,1	1,5	0,7	3,5	1,3	1,3	0,0	0,0	0,0
Interior	12,9	12,1	25,1	20,9	0,0	2,3	11,1	29,2	43,7	0,0

Table G.12: Table with lead times in weeks for each section with $12m^2$ for vessel **B** data driven estimation.

Block number:	1	2	3	4	5	6	7	8	9	10
Casco	12,8	12,6	8,9	4,4	21,2	8,0	8,2	0,0	0,0	0,0
Superstructure	0,0	0,0	0,0	0,0	0,0	0,0	0,0	10,8	7,2	9,3
Hotwork	19,1	18,8	13,3	6,6	31,8	12,0	12,2	36,7	24,4	31,8
Paint	36,8	14,3	23,7	5,3	7,6	7,0	9,4	43,7	6,4	5,4
Outfit	8,3	8,2	5,8	2,9	13,8	5,2	5,3	16,0	10,6	13,8
Engine	0,0	0,0	9,7	0,0	0,0	0,0	0,0	0,0	0,0	0,0
Special	0,0	0,0	0,0	2,9	0,0	5,3	0,0	0,0	0,0	0,0
paint_int	3,2	3,1	2,2	1,1	5,2	2,0	2,0	0,0	0,0	0,0
Interior	19,4	18,2	37,7	31,4	0,0	3,5	16,7	43,8	65,6	0,0

H
Outbound estimation

Super yacht are becoming larger and larger as shown by Figure H.1[60], this means that the organisation needs to make estimations for vessel sizes that have not been build before. Making these outbound estimation could require the use of data extrapolation. However, making extrapolations could give unreliable or false results[6]. There could be effects that are not known, as discussed in the introduction discrete steps could be present. In the inbound analysis these discrete steps in man-hours where not seen, but maybe these could be present in the outbound vessels. Reducing the certainty of outbound estimation.

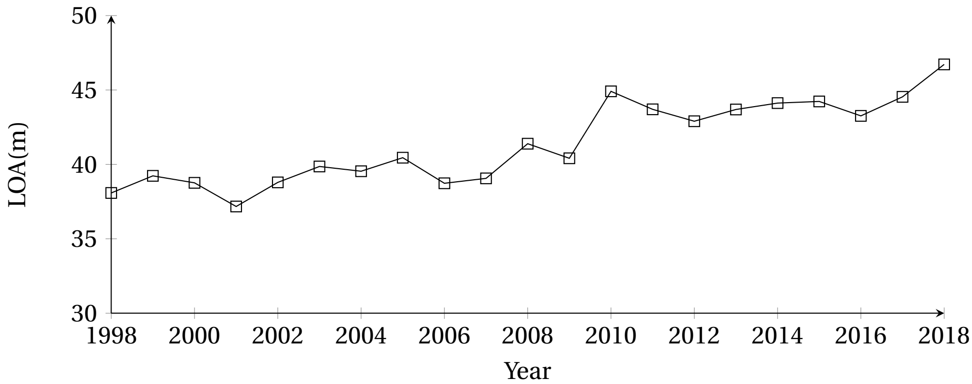


Figure H.1: Average LOA delivered in past 20 years.

In this section an outbound estimation will be performed, as stated in section 5.2.4 one vessel was removed from the data set. Table H.1 present the estimations of the outbound vessel using the first three estimation levels, *CGT*, *Analogy* and *Data driven*. The difference with the real value are presented in the second row. For the level 2*analogy* two estimation are used. The first analogy estimation is the initial estimation(INT), this estimation was made at the proposal phase of the project. The second estimation is a re-estimation(CNG) during the project. For analogy and the CGT method only the total hours are compared, in table H.2 the hours per vessel components are stated for level 2 *Data driven*.

Table H.1: Outbound vessel man-hour estimation comparison between methods.

Level	CGT[E1] High	CGT[E1] Medium	CGT[E1] Low	Analogy[2] INT	Analogy[2] CNG	Data driven[E3]
Difference(%)	-8,51	-26,97	-39,87	-19,60	-2,44	-3,24
Mean (%)	–	–	–	–	–	1,26
St. deviation σ (%)	–	–	–	–	–	26,63

Table H.1 presents the result for the three estimation maturity levels. Using the CGT for the outbound method results in an underestimation of $-26,97$ for the medium values. This is a logical trend because the

CGT method is not linear but has exponential factor of $B < 1$, meaning the slope will reduce, as shown in Figure 5.4. The initial experts opinion was to optimistic by $-19,6\%$, their re-estimation performed better with only an under estimation of $-2,44\%$. Level three *data drive*, resulted in a underestimation of only $-3,2\%$ with a σ of $26,63\%$ the value of σ is not higher then the σ found for the inbound estimation.

What can be observed is that an extrapolation of level 3 *data driven* only resulted in a error of $-3,2\%$ which is lower than the initial analogy estimation and the CGT estimations. Another observations it that when more data is known the best estimations can be made, the $-2,44\%$ after the re-estimation. Although this is only one outbound estimation hard conclusions cannot be made but using a combination of an experts judgement and data driven could result is low estimation uncertainties.

Table H.2: Table with man-hour estimations difference for the outbound estimation

Type	Percentage of total(%)	Difference(%)
Casco	14,05	-27,31
Superstructure	1,43	47,80
Piping mechanical systems	11,16	5,62
Propulsion	0,88	32,59
Consturction mechanical systems	2,23	6,77
Electrical systems	0,25	9,19
Yacht equipment	3,01	-26,60
Exterior	8,82	-17,81
Paint Ext	14,58	43,65
Paint Int	4,55	-33,36
Interior	17,65	-19,23
Interior owners	3,27	-43,45
Interior guest	2,65	62,54
Interior public	9,34	1,26
Interior service	0,98	-27,12
Interior crew	2,77	-1,22
Interior captain, hospital and staff	0,28	49,67
Interior wheelhouse and ship's office	1,48	-36,66
Interior technical spaces and stores	0,61	14,51
$\sum$ difference (%)	-	-3,24
Mean (%)	-	1,26
St deviation σ (%)	-	26,63

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