Improving the pre-outfit strategy for a shipbuilding project

Generation of a more detailed outfit schedule in the pre-contract phase

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Abstract

In ship production two basic activities can be distinguished: constructing structural components of the ship, and outfitting the ship by installing various systems and equipment that allow it to operate and perform various missions [1]. The outfitting process includes the installation of all systems and components such as piping, HVAC systems, electrical systems, painting and insulation. Those processes are carried out in different phases of the production process and are heavily interdependent.

Currently, in shipbuilding outfit planning is not sufficiently investigated [2]. The outfitting processes are characterized by low level planning and poor organization. They are distinguished by interferences, disturbances, great interdependencies and different surrounding area requirements which lead to delays, longer lead times, higher costs, more rework and a lower quality. Due to a large network of many different non-transparent parties within the outfitting processes and insufficient knowledge about the amount and type of the outfit activities it is difficult and most often not possible for a planner to create an outfit planning in an early phase that includes the strategy for a controllable process. The outfit processes start therefore in the current situation most often using a planning with a low level of controllability leading to many unexpected events.

In this research it is examined how Royal IHC can determine in the pre-contract phase, for a specific vessel type, how it should organize its resources within the outfitting process in order to improve the controllability of the outfitting processes. The controllability of a process is defined within this research as the ability to handle the process requirements and avoid negative events such as delays, rework or waiting times in order to obtain the final project results as was planned.

At first a model is developed, also known as the *Activity Loader*, that is able to make a feasible estimation in the pre-contract phase of expected outfit activities during the production of a vessel using only limited amount of vessel information. A second model, also known as the *Planning Generator*, is developed to generate a planning of the production scenario. Using this model, the user can vary specific process characteristics such as phase durations or amount of work per phase in order to find possible improvements of the controllability and performance of the outfitting processes.

The controllability decreases for example in case of an undesirable behavior of the workload, when collisions between installation activities occur, when the required crane occupancy exceeds the available crane capacity but also when more floor space is required than available. The *Planning Generator* is able to determine in an early phase the chance of occurrence of those events by measuring the workload, the unit occupancy and the crane and floor occupancy over time. Finally, the model calculates for different planning characteristics corresponding controllability values of these production scenarios from which the user can select the most preferable production scenario. This research shows that the chosen pre-outfit percentage per discipline and per section influences the controllability and performance of the outfitting processes. Also the duration of the pre-outfit phase of each section has a significant influence on specific process characteristics influencing the controllability. It is therefore important that the project planner and project manager make a substantiated choice about the pre-outfit percentage and ore-outfit duration in an early phase.

A case study is carried out, using the *Activity Loader* and *Planning Generator* for the production of Ynr 730. Results show that it is possible to increase the expected controllability by improving the workload, the section occupancy and the crane occupancy in the pre-outfit hall for a production scenario with a feasible floor occupancy using the method developed.

It is expected that the controllability and performance of the outfitting processes increase when the project planner and project manager make a substantiated choice during the pre-contract phase about the pre-outfit percentage, pre-outfit duration and other process characteristics. This will result in a production scenario with fewer delays, waiting times and rework activities leading to a reduction in costs.

Preface

Within the last phase of the Masters 'Marine Technology - Specialization Ship Production' a research had to be carried out within the maritime industry. This academic research required 9 months. Knowledge gained during the bachelors and first year of the masters is applied. After successfully completing the research the student is considered to be 'Master of Science'.

This research is carried in cooperation with Royal IHC, one of the biggest shipyards in Holland. Royal IHC is global market leader for dredging and mining vessels and a supplier of innovative ships and offshore construction. IHC has over 3000 employees based at various locations in Holland and other countries all around the world. This research is carried out at the locations 'Kinderdijk' and 'Krimpen aan den IJssel' at the department 'Central Planning'.

The first intention of this research was the improvement of the controllability of all outfitting process within a shipbuilding project. However, due to insufficient amount of time main focus is put on the controllability improvement of the outfit activities within the pre-outfit phase.

Within this report, at first a main description is given of the shipbuilding market and the outfitting processes. Afterwards, results of the literature research are discussed where more detailed knowledge is given of different phases within the shipbuilding process, planning steps and challenges and previous researches. After this part, the research methodology is described including a problem definition, the research questions, and the research structure. The research itself is divided in 2 main parts for which both the chosen methods and results are described. Finally, a case study is carried out of which the results are analyzed and discussed where after conclusions are drawn and recommendations are given.

Acknowledgments

Firstly, I would like to express my sincere gratitude to Royal IHC for giving me the opportunity to carry out this research within a real shipbuilding environment. My sincere thanks goes to Kees Meijer who supported me during my research process and Wouter Zevenbergen who gave me the opportunity to carry out the research at the Central Planning department where I have had a great time.

My sincere thanks also goes to Jenny Coenen and Christoffer Rose from the Tu Delft department "Maritime & Transport Technology Section Ship Design, Production and Operations", whose expertise, understanding, and patience, added considerably to the quality of my thesis. I also take this opportunity to express gratitude to all of the department faculty members for their help and support over the last years.

Last but not the least, I would like to thank my family: my parents and my sisters for supporting me spiritually throughout writing this thesis and my life in general.

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1 | Introduction

1.1 Shipbuilding market

In the last three decades, Asian players have risen to take over the building of most high-volume, relatively non-complex ships such as oil tankers, bulk ships and container ships, while European shipbuilders refrained in their business development from expanding capacity but focused more and more on building high complex vessels, such as ferries, mega yachts, offshore or dredging vessels [10] . It concerns most often 'custom build designs' or very small series which require extreme flexibility in the production process. Figure 1.1 shows the increasing focus of European yards on the production of complex vessels.

In ship production two basic activities can be distinguished: constructing structural components of the ship, and outfitting the ship by installing various systems and equipment that allow it to operate and perform various missions [1]. Over the last years, the amount of outfitting work increased due to an increase in complexity of the vessels and systems on board. Since the technology is easily transferable and it doesn't require a high level of education at fabrication level, European shipyards continue to lose market share in shipbuilding and cannot compensate their high labor costs and cannot combat aggressive competition from efficient Asian yards using the same techniques [8]. In order to compete within this market and stay profitable, European yards have to focus on their strength which lies within the engineering and production of high complex vessel. Attention needs to be paid to the optimization of planning, organizing and the executing of the production process in order to survive within this market.

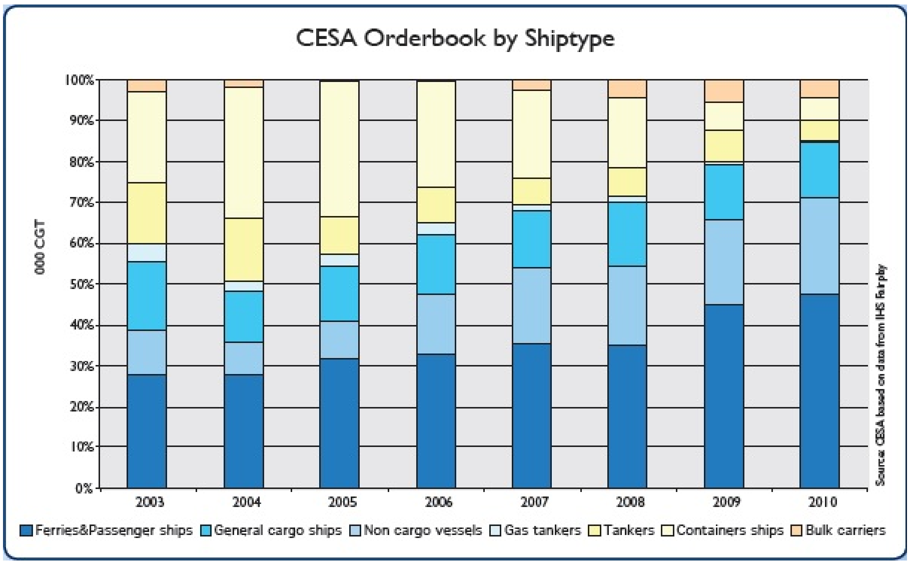


Figure 1.1: Increase of complex vessels in orderbook European shipyards (CESA, Annual report 2010-2011)

1.2 Outfitting

The outfitting process includes the installation of all systems and components such as piping, HVAC systems, electrical systems, painting and insulation. Those processes are carried out within different phases of the production process and are heavily interdependent. Figure 1.2 shows a sample section and the components to be outfitted.

Organization of outfitting work on European shipyards is characterized as a network consisting of many different parties, due to the use of suppliers and subcontractors. Currently it is assessed that 50-70% of the added value comes from external subcontractors and suppliers, whereas for even more complex vessels this can be as high as 70-80% [11]. Most important reasons for applying this strategy are the increased flexibility in production capacity, the reduced fixed labor costs but also the enhancement of the specialization of subcontractor. Due to the increasing sophisticated work more and more activities are outsourced to external parties with the required knowledge.

However, having more parties within the process requires a higher level of organization and communication. Including the fact that the outfitting processes are distinguished by interferences, disturbances, great interdependencies and different surrounding areas, the yard most often functions as a coordinator within the area of outfitting [8]. In order to prevent for delays, long waiting times or rework, integral planning and coordination of the outfitting processes is required to reduce the amount of conflict on the work site and improve the process.

This research will provide the knowledge which can be used in an early stage of the production process to organize and plan the outfitting process in such a way that it increases the flexibility and controllability. The controllability of a process is defined within this research as the ability to handle different process requirements, such as a fluctuation amount of work, in order to prevent for negative events such as delays, rework or waiting times. This research also codifies implicit knowledge about outfit processes in such a way that it is easily accessible for new employees or subcontractors.

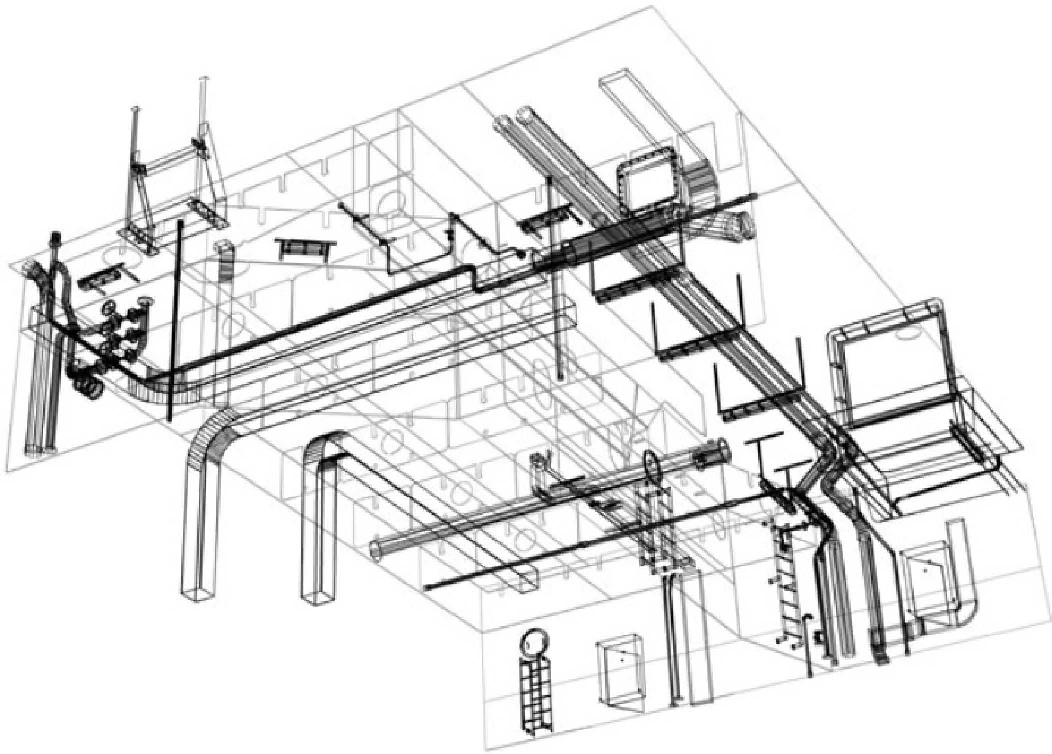


Figure 1.2: Sample ship section with outfitting components [3]

2 | Background and literature review

2.1 Ship production process

Shipbuilding has been one of the oldest industries and dates back B.C. . Especially since the 20th century it has been growing and innovation of the product and production process has been taking high standards. The production process at European shipyards where mainly small, one of a kind, high complex vessels are built, can be described as a complex process consisting of a network with many different parties involved. Owner, yard, subcontractors, investors, suppliers, classification societies, consultants etc. To stay competitive within the market, constant improvement and innovation is required in order to make the best decisions and chose the most optimal strategy to organize the production.

To get a clear overview and chronological sequence of the different phases a simplified picture of the design and production phases at European yards is shown in Figure 2.1. The production phases are outlined in this figure. Outfitting activities take place spread over the entire production process and will be discussed in chapter 2.2. Within this chapter, first an explanation about main shipbuilding phases is given.

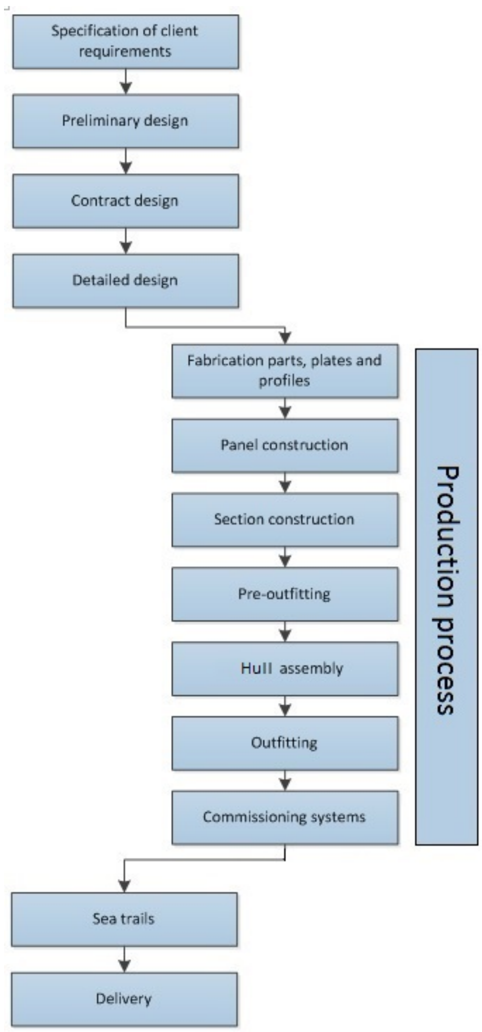


Figure 2.1: Overview ship production process with different phases

Preliminary design / contract design
At first, the desired operational profile of the vessel is translated into a preliminary design by the yard. Within this phase a first draft of the general arrangement is made, main vessel characteristics are determined and a brief description of the required systems on board is given. It depends on the client, the situation and the complexity of the vessel in what detail these documents are made. In the contract design phase, a more detailed design is made which gives the yard the possibility to make a better determination of the production process, including lead times, required resources and specifications of the materials and systems to be purchased. In this phase, the yard generates the first version of the master planning using the draft version of the section plan. With this information, the shipyard is able to estimate the production costs of the vessel and will finally present their tender price to the client.

Detailed design / Detailed planning & Preparations
As soon as it is clear that the yard will win the tender, the engineering department of the yard starts making a complete detailed design of the vessel including all systems, components and equipment. The planning department starts to generate a planning in more detail at the same time in which the engineering, the purchasing, the construction phases, outfitting phases and commissioning is planned and important milestones are set. The shipbuilding process is characterized by the fact that the production of the vessel already starts when engineering and planning are still

on going, in order to deliver the vessel on time. Therefore, in real life the different phases shown here will overlap.

Production
The construction phase can be separated into 8 different sub-phases, shown in Figure 2.1. It starts with the fabrication of all steel parts where after those are assembled to panels. This phase of the production is most often automated to a high level which actualizes high standards of accuracy, punctuality and efficiency. Finally, panels are assembled together forming complete sections.

Several outfitting components are already installed during section fabrication, such as pipes, ducts or cable trays. Most often this starts 1 week before the end of the construction of the section. For this phase, often called as 'the pre-outfit phase' a fixed end time is set, where after the section is transported to the conservation hall where it gets its first paint layers.

After painting the section, it is positioned on the slipway where it is assembled with other sections, finally forming the vessel's hull. Again, outfitting components can be installed which where still missing. After the completion of the installation of a whole system, the system can be commissioned. In the mean time, the vessel is launched and moored alongside the quay of the yard.

Sea trails and delivery
After all systems, components and equipment have been installed and commissioned in the construction phase, their performance and the behaviour of the ship itself are tested during the sea trails. After those tests, required adjustments have to be carried out where after the vessel is delivered to the owner.

2.2 Outfitting

The outfitting process of shipbuilding involves the installation of various components into a vessel's sections, such as pipes, heating, ventilation and air-conditioning (HVAC) ducts, cable trays and equipment [?]. The main focus was put on the optimization of section building and section erection on the slipway during the last decades. This was encouraged by the strategy of shipyards to keep the occupancy period of the slipway as short as possible. The shorter this period, the more ships can be produced within a certain period, which enlarges the company's revenue. However, this theory is only valid in a period with a full orderbook. When there are not enough vessels to fill up the production, the optimization of another process might have priority.

Currently, yards encounter difficulties and bottlenecks within the outfitting processes. Low level of organization leads to delays, waiting times, rework and high costs. In order to further optimize and improve the production process of vessels that have an increasing amount of outfit work, their focus shifted more towards the outfitting work. Within this chapter a more detailed description is given about these different processes. First, all outfitting phases will be discussed where after different strategies concerning 'pre-outfitting' and outsourcing of activities will be discussed.

2.2.1 Phases

As already described in chapter 2.1, outfitting takes place in several phases. Multiple moments can be defined when a certain components or system can be installed. In Figure 2.2, an overview is given of the outfit and commissioning phases over the entire shipbuilding process. It is important to notice that before a section is assembled with other sections on the slipway and its corresponding rooms are *closed*, planning of the process is based on 'section level'. After *closing* a room, planning and organizing the process is based on 'room level'. After painting the room and the installation of most components, systems can be commissioned. In this phase, planning is based on 'system-level'. In Figure 2.2 different colors show whether focus is put on section, room or system.

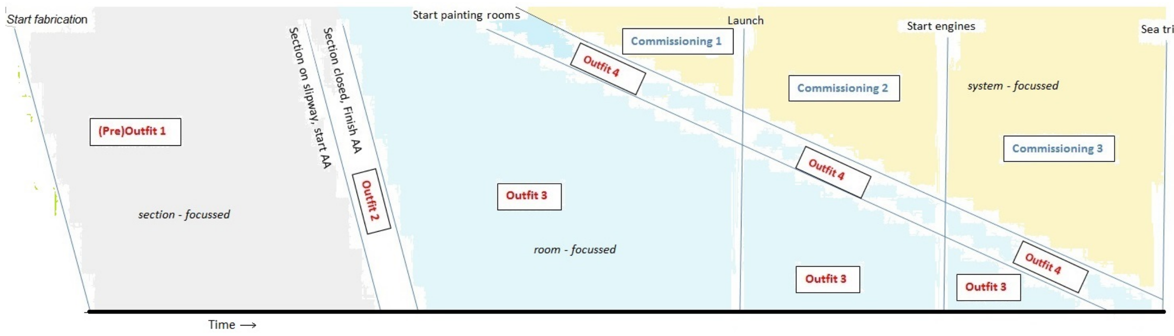


Figure 2.2: Overview phases outfitting and commissioning

(Pre) Outfit phase 1 (POF)
The pre-outfit (POF) phase is the first phase in which outfit activities can be carried out. There is no exact moment when subcontractors and yard personnel are allowed to start with the installation but using their implicit knowledge and instructions of the outfit coordinator, the starting point is indicated. In practice, the pre-outfit period starts most often 1 week before section fabrication is finished.

Sub-contractors prefer to install as much components as possible within this phase due to the high accessibility. Most often sections are built in upside down position which makes it easier for welders to build the section but also for outfitters to install piping, ducting, secondary steel and other components on the higher locations as for instance ceilings. Sometimes it requires 3 times as much man-hours to carry out the same installation activity after section assembly compared to installing the component in the POF phase [1].

At the end of the pre-outfit phase, the sections are transported to the conservation hall where they receive the first paint layer(s). Preferably, the sections are assembled on the slipway right after conservation but in reality it occurs often that the sections need to be stored for a few days until assembly can take place. This is mainly due to the fact that a shipyard optimizes the process around the occupation of a slipway and the erection schedule. Therefore buffers are scheduled in between the POF phase and the erection of the sections on the slipway.

Outfit phase 2 (SWPO)
The second phase, also known as 'slipway pre-outfit phase' (SWPO), concerns the time between placing the section on the slipway and closing a specific room by assembling another section. Within this time period, specific components and equipment are installed. This concerns most often vulnerable equipment which requires high accessibility such as main engines, generator sets and switchboards or very large components such as large pipes or ducts. Those components are most often placed in their corresponding room but mounted and aligned within the next outfit phase.

Outfit phase 3 (OF-1)
This outfit phase (OF-1) starts after a room is closed and ends when the room gets painted. No more hotwork is allowed after the start of painting the room. Within this third outfit phase most of the components and equipment that were not installed yet and require hotwork are installed. As already mentioned, the accessibility within this phase is limited which makes it more difficult and time consuming to perform outfitting work. Relatively more man-hours are required per outfit activity which lead to an increase of total costs.

Outfit phase 4 (OF-2)
This phase (OF-2) covers the time after painting a room and before commissioning of the system. The planning here shifts from 'room-level' to 'system-level'. Last outfit work includes the installation of components, parts, equipment and systems that could not be installed before the room is painted, such as cabling or insulation. Also outfit work that was not finished yet or rework to be done, is now carried out. When a complete system is installed, it's commissioning can start.

Commissioning phases 1,2 and 3
Commissioning activities concern starting up and testing of systems. Before painting of the rooms, most physical characteristics of the components are already tested using flush or pressure tests. Further tests are performed after which the system can be used. Also the commissioning activities can be divided into phases. Each phase differs according to the corresponding end milestone within the production process. Specific milestones are the launch of the vessel, the start of the main engines and the sea trials. Systems that should be commissioned before ship launch are commissioned within the first commissioning phase. Systems that should be commissioned before the start of the main engines are commissioned within the first or second commissioning phase. Other systems that should be commissioned before sea trails can be commissioned in any of the commissioning phases.

2.2.2 Pre-outfitting

Pre-outfitting strategy

Most components can be mounted within several outfit phases. However, most often each outfit activity might have its preferred stage in which it should be carried out in order to optimize costs, time and quality. Pre-outfitting involves performing those activities early in the production process. Within this chapter, the possible benefits per discipline are discussed as well as limitations. Finally recommendations are given.

Possible benefits

- Outfitting that occurs during the assembled ship stage requires workers to move to the dry dock, slipway, or land-level facility, bringing with them the materials and equipment and their construction tools [1]. When the activities are carried out within the pre-outfit phase, a reduction of transportation time can be accomplished.
- Installing outfitting materials and equipment is more difficult and time-consuming on the assembled ship because of the obstructions from structural components or the need to work in confined spaces [1]. The amount of benefits differ per shipyard and outfit discipline. It is important to determine the cost impact for each discipline in order to choose the best strategy. However, due to the non-transparency of the subcontractors little amount of data is available to perform costs and time calculations and determine their impact. [1].
- Shipyards may strive for a reduction of time spent in several shipyard facilities such as the slipway or dock during ship construction. Transferring outfitting hours to the shops or to the assembly areas alongside the dock reduces the hours spent in the dock, thus enabling higher capacity utilization and, therefore, higher productivity of the yard, even if there is no overall reduction in the number of hours to build a ship. However, this depends on the market conditions and order book of the shipyard.

Possibilities within several disciplines

For several important outfit disciplines the possibilities of pre-outfitting are discussed here. Also, for each discipline the current strategies used on different continents (UK, US and EU) are taken into account in order to estimate the maximum feasibility.

The ***electrical discipline*** consists of steelwork (supports), placing equipment, cable pulling, electric connect and commissioning. Most of the cabling work is carried out within the outfit phase (OF) due to the fact that the electrical components are most often installed after section erection. Installation of the switchboard is preferably carried out as soon as possible but due to damage and weight reasons this is carried out during the slipway pre-outfit phase (SWPO). Hangers and cable trays are most often installed within the pre-outfit phase (POF). According to Julio [12], 90% of the steelwork can be installed during the POF phase. An overview of worldwide installation strategy is shown in Appendix B.

A study in 2005 between 30 shipyards at several continents, showed that for the installation of ***HVAC and Piping systems*** it is suggested that 80% of outfitting within the pre-outfit stage is a reasonable goal; some shipyards install almost all HVAC components and equipment before section erection [1]. An overview of worldwide installation strategy is shown in Appendix B. Figure 2.4 shows the possible POF percentages assumed by Julio [4] for different HVAC component-types.

Schank et al. [1] suggest that ***painting and insulation*** can reach pre-outfitting levels of 80 percent. Several shipyards believe that further improvement is possible and that this will lead to a reduction of costs and time to build a ship [1]. Of importance is the proper advanced planning and aligning of management and production processes to accomplish more painting and insulation work prior to the section erection stage [1]. Painting and insulation work has a high interdependency with the installation of other components and equipment. Some insulation for example, can only be installed after or before the installation of a specific components. According to Pruyn and Moredo [13] at least 25% of insulation should be installed in a compartment before the installation of equipment can start [13]. An overview of worldwide installation strategy for painting and insulation is shown in Appendix B.

Joinery work describes the installation of cabins, galleys and recreation rooms. Those are primarily located within the accommodation of the vessel. Here two main differences in building strategy should be noted. When the production of the entire accommodation takes place before the accommodation is lifted on the vessel, most of the joinery outfitting is carried out within the POF phase. The second option is that the accommodation is built on the vessel itself . In this scenario, the production process consists of very little pre-outfitting due to the fact that joinery work may be damaged when installed in this early stage. An overview of worldwide installation strategy is shown in Appendix B. As can be seen in the overview, European shipyard most often use the first strategy where the separate production of the accommodation makes it possible to use high levels of pre-outfitting.

The outcome of a research by the RAND corporation [1] showed the expected influence of the installation phase on the total required time to carry out the job, based on estimations by European yards. Figure 2.3a shows the outcome and the factor for each phase. Overall it can be concluded that an average reduction in man-hours of 25% can be achieved when the job is carried out before section erection on the slipway. However, this value still differs for each specific job, discipline, ship type and shipyard.

Outfitting Factors Provided by EU Shipyards

	On Unit	On Block	On Grand Block	On Assembled Ship
Electrical Power Distribution				
Shipyard 1	1.00	1.20	1.20	1.50
Shipyard 2		1.00	2.00	4.00
Shipyard 3		1.00	1.25	1.50
Shipyard 4		1.00	1.10	1.20
HVAC				
Shipyard 1	1.00	1.20	1.20	1.50
Shipyard 2		1.00	2.00	4.00
Piping				
Shipyard 1	1.00	1.25	1.25	1.50
Shipyard 2		1.00	2.00	4.00
Shipyard 3	1.00	1.00	1.50	2.00
Shipyard 4		1.00	1.10	1.30
Joinery				
Shipyard 2		1.00	2.00	4.00
Shipyard 3			1.00	1.50
Shipyard 4			1.00	1.20
Painting and Insulation				
Shipyard 1			1.00	1.50
Shipyard 2		1.00	2.00	4.00
Shipyard 3	1.00	1.00	1.00	2.00
Shipyard 4		1.00	1.10	1.30
Structural				
Shipyard 1	1.00	1.20	1.20	1.50
Shipyard 2		1.00	2.00	4.00
Shipyard 3	1.00	1.00	1.50	2.00
Shipyard 4		1.00	1.30	1.40

(a) Relative effect pre-outfitting

Comparisons Between Types of Naval Ships That Affect Advanced Outfitting

	Naval Combatants	Naval Auxiliary
Outfit hours as a percentage of total hours	High	Low
Density	High	Low
Systems	Distributed throughout ship	Concentrated in small area

(b) Comparison effect pre-outfitting

Figure 2.3: Pre-outfitting [1]

Main activities	discipline	usually conducted at	%
Steel Work (Make penetrations in compartment - Install brackets, penetrations and foundations)	mechanical	Preoutfitting	85 - 95
Place equipment	mechanical	Preoutfitting	85 - 95
Positioning equipment	mechanical	Preoutfitting	85 - 95
Pipe fabrication and installation	piping	Preoutfitting	85 - 95
Ducts installation	piping	Preoutfitting	85 - 95
Inspection - quality control - administrative		Preoutfitting	85 - 95
Painting	painting	Preoutfitting/Outfitting	85 - 95
Insulation	insulation	Preoutfitting/Outfitting	85 - 95
Electrical connect equipment	electrical	Outfitting	100
commissioning	electrical - mechanical	Outfitting	100

Figure 2.4: Possible pre-outfit percentages according to Julio [4]

Outfitting is generalized for all vessel types in the figures shown above but in real life the ship type influences the potential savings in labor hours per discipline. A commercial cruise ship for example requires much more outfitting work compared to a container vessel and is besides that much 'denser' which makes it relatively more time consuming to carry out certain activities after section erection on the slipway. Figure 2.3b gives a similar example for a naval combatant and a naval auxiliary.

Limitations

Unfortunately, most often it is not easy to carry out the outfit activity at each preferred moment. Several limitations make it sometimes impossible to start a specific job. Below, these limitations are listed [1]:

- Lack of timely design information.
- Lack of outfitting materials or equipment.
- Concern for damage.
- Limitations imposed by the customer.
- Lack of experience in achieving higher levels of pre-outfitting.
- Facility constraints.

In order to minimize the influence of these limitation, improvement in collaboration and communication between purchasing department, engineering department and planning department is required.

Recommendations [1]

In order to minimize man-hours, rework and an increase of the product quality, relatively high percentages of pre-outfitting should be implemented within the production strategy. Data shows that for most activities, a reduction in man-hours can be achieved when this job is carried out in an early stage. The following is recommended:

1. A near complete design should always exist before the production starts, which is currently not always the case due to problems within the engineering process.
2. For each discipline the benefits of each possible installation phase should be researched in order to be able to make a good strategic decision.
3. For each discipline and activity, constraints should be researched in order to make a feasible strategic plan.

4. Finally, the highest level of possible pre-outfitting should be applied, for some discipline 80% of outfitting in the pre-outfit phase is feasible.
5. All hotwork should be completed as soon as possible. This provides an early start date for several outfit disciplines like painting and insulation.
6. As much as possible complete systems or 'packaged assemblies' should be installed instead of loose components.
7. Material and equipment purchase orders should be placed well enough in advance.

2.3 Planning

Within the shipbuilding industry the outfitting work has evolved against the background where main focus was put on the optimization of the steel structure and where the occupation of the slipway was minimized. As the amount of outfitting work grows resulting from more complex and high-value vessels, the necessity of a new shipbuilding approach which emphasizes earlier and easier outfitting work gradually emerges [8]. This makes the production planner one of the most important players.

From the definition of the outfitting process, it is not hard to see that in terms of timespan, it spreads almost across the whole ship production process, from the section assembly all the way to the delivery of a vessel [8]. A small improvement within the outfitting process might directly lead to an improvement of the total process. Being able to carry out the outfit activities in an early stage makes it possible to carry it out in better conditions. When outfitting work is carried out in better conditions, in a less cluttered environment such as in a work shop, it can be done with less men in less time with better quality and corrosion prevention; thus the work is done more efficiently. All this leads to the reduction of time and cost. [8]

In order to realize those optimizations it all comes to planning. Despite the similarities of various projects, scheduling can be very dissimilar, due different sets of outfit activities and changing boundary conditions [14]. Therefore high level planning abilities are required. Within this chapter, different kinds and levels of planning are explained as well as important dependencies between various parties.

2.3.1 Planning within shipbuilding

Corporate planning
The corporate planning is a company planning consisting off all activities on the shipyard. This means that the planning of each vessel at the yard is included. Most often, this planning doesn't contain any level of detail but only most important milestones of each project.

The corporate planning is used by the corporate planner to make decisions concerning new orders, when a potential project can start or what the minimum duration of the project might be. Interdependencies between projects can easily be located here. Although different projects have their own activities, they have to use the same facilities and resources. This requires planning with a wider range including more projects.

Master planning
The master planning is made in a very early stage, most often within the proposal phase before contract signing. It includes special milestones, most often set for the client to show lead times, the delivery date and to discuss payment moments. In order to find realistic values for these lead times, simple parameters such as 'tonnage per week' are used to make estimations.

The master planning most often include the following milestones:

- Start engineering
- Start/finish work preparation
- Start fabrication

- Start section building
- Keel laying
- Launch
- Installation main engines
- Sea trials
- Delivery

Section building planning
After generating the master planning, the roughly estimated overview is sent to the section building planner who is going to recalculate the duration and start/end of the overall phases by making a section erection planning. For each section different engineering milestones are defined as well as the start of fabrication, the pre-outfit phase, the conservation dates and the assembly on the slipway.

Outfit planning
When the section building planning is made and dates are set and confirmed for section erection, the outfit planner is able to plan outfit activities over the outfit phases. An commissioning planning is made for the commissioning of each system after all outfitting work is completed.

2.3.2 Dependencies between different parties

Within the shipyard, several departments heavily depend on each other and cooperation and communication is highly required in order to run the processes in an efficient and effective way. Figure 2.5 gives an overview of the most important (internal) dependencies. In this chapter these dependencies will be discussed.

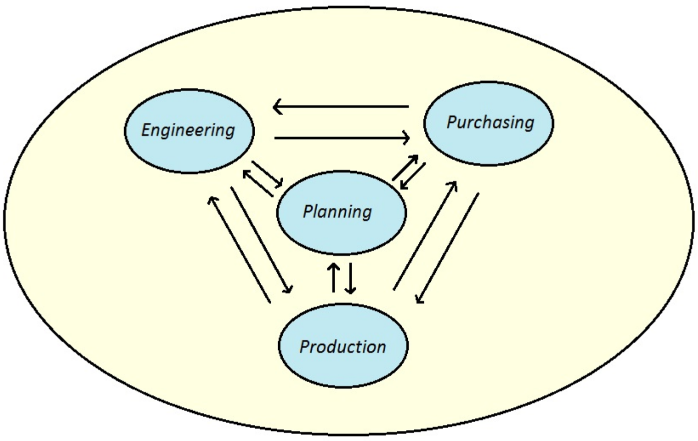


Figure 2.5: Most important internal dependencies

Engineering - Purchasing
When the engineering department knows more about specific functional characteristics of a component, it delivers this information to the purchasing department that is going to order the component at the supplier. Most often this is a critical point due to the fact that it sometimes takes very long before these functional characteristics are known. After specifying the component at the supplier, purchasing department delivers the information about the detailed characteristics of the components, such as dimensions and weight, back to the engineering department. Engineering department is then using this information to finalize the design. This shows that high standard teamwork between both department is required.

Engineering - Production
The shipbuilding industry is characterized by the fact that production starts already when engineering of the design is still on going. In order to reduce rework and waiting times, engineering department should deliver the specified drawings on time. At the start of the process, an engineering planning is made which shows exactly when a certain version of a drawing should be delivered. However, looking at historical production data of Royal IHC, it happens often that drawings are delivered too late due to delays within the engineering department, which leads to waiting time or rework when production continues and imperfections are noted afterwards.

Purchasing - Production
Purchasing department is responsible for ordering components and equipment at the suppliers but also for the negotiation and agreements of the delivery times. When it happends that a certain component is delivered too late, it might stop the production which leads to delays and higher costs. This should at all times be avoided. Specific important delivery times are always agreed with the production planners.

All departments - Planning
At all times, the central planning department knows all main details about all facets of the production process. They make sure that the communication between all other departments functions well and that possible obstacles and difficulties are solved. During the production process itself it shows all parties the current status and steers where ever it is needed. The planning department is most often part of a project management team which is responsible for the entire project.

2.3.3 Previous literature research on planning

Over the last years, extensive researches have been carried to improve planning of the shipbuilding process. In 2008, Meijer developed a decision support tool for early stage scheduling. This tool automatically generates an section erection schedule with limited amount of information. In 2012, Colthoff expanded this model by implementing a tool that automatically calculated the section building lead time using the section weight and type. Using this tool a planner was able to access different outfitting scenarios within only one day.

In 2012, Wei researched the possibilities to automatically generate a detailed outfit planning of a ship section. However, she was finally only able to generate a possible outfitting sequence and low level outfit planning without taking optimization and resource restrictions into account. Currently, Rose is conducting a research of the detailed planning of the outfitting process for an entire ship. Using various algorithms and specific input informations he is already able to generate an optimized outfit schedule for a ship section in full detail.

In 2009, Pruyn and Moredo have been investigating the development of a tool that is able to generate (pre)outfitting schedules in an early phase of the design. They found out that it is indeed possible to indicate general relations between outfitting activities. However, the general relations were not surprising. Anyone with some experience in shipbuilding will know these relations. They also found that many (external) factors play a role during the installation of equipment, pipes, cables etc. which cannot be captured in generic relations.

In 2013, a joint project between Dutch shipyards, Delft University of Technology and several subcontractors in the shipbuilding market, developed enhanced collaboration models and tools for integral planning. Main goal of the integrated planning model project was to develop a tool that will be able to generate construction planning in an early phase of design. In one of the sub-projects, Carrasquilla (2013) researched the automatic generation of a construction planning in an early phase of the design. Here all pre-outfitting and outfitting activities were main part of the construction of a vessel. At the end, only a general framework for such a model was made and tested for specific rooms in a vessel.

Steinhauer (2010) and Köning (2010) have been investigating the options for constraint-based simulations of the production process on a shipyard. They researched different methods for automatically generating a production planning including outfit activities using simulation techniques. Various authors wrote different types of literature about this research and a final simulation model is now used at Flensburger shipyard.

3 | Research description

3.1 Introduction

Within this research a method is developed to make a feasible estimation of expected outfit activities during the production of a vessel and to generate a possible production planning. Also, possibilities are researched that improve the controllability and performance of the outfitting process. A model is built that can be used by the yard to generate a similar optimal planning within the 80/80 phase [1].

In the first part of this chapter a problem description is given where main challenges and obstacles within the outfitting processes and planning processes are discussed. With the knowledge of the current problems, the main research objectives, research question and corresponding sub-questions are given in the second part of the chapter. Afterwards, a detailed description of the research structure and the corresponding scope are given.

3.2 Problem definition

Currently, in shipbuilding outfit planning is not sufficiently investigated [2]. The outfitting processes are characterized by low level planning and poor organization. They are distinguished by interferences, disturbances, great interdependencies and different surrounding area requirements which lead to delays, longer lead times, higher costs, more rework and a lower quality.

Within this chapter a description is given of the problem structure that shows most important causes which lead to such a challenging outfitting process. A difference is made between causes within the pre-contract and causes during the outfitting process itself. Figure 3.1 gives an overview of the structure. It is important to notice that the final conclusions of this research should mainly solve the problems in the pre-contract phase. In order to create a detailed planning that can be used during production, some extra steps have to be taken which is not included within this research.

[1] In this pre-contract phase, it is 80% probability that the customer will place the order and 80% probability that the supplier will be Royal IHC

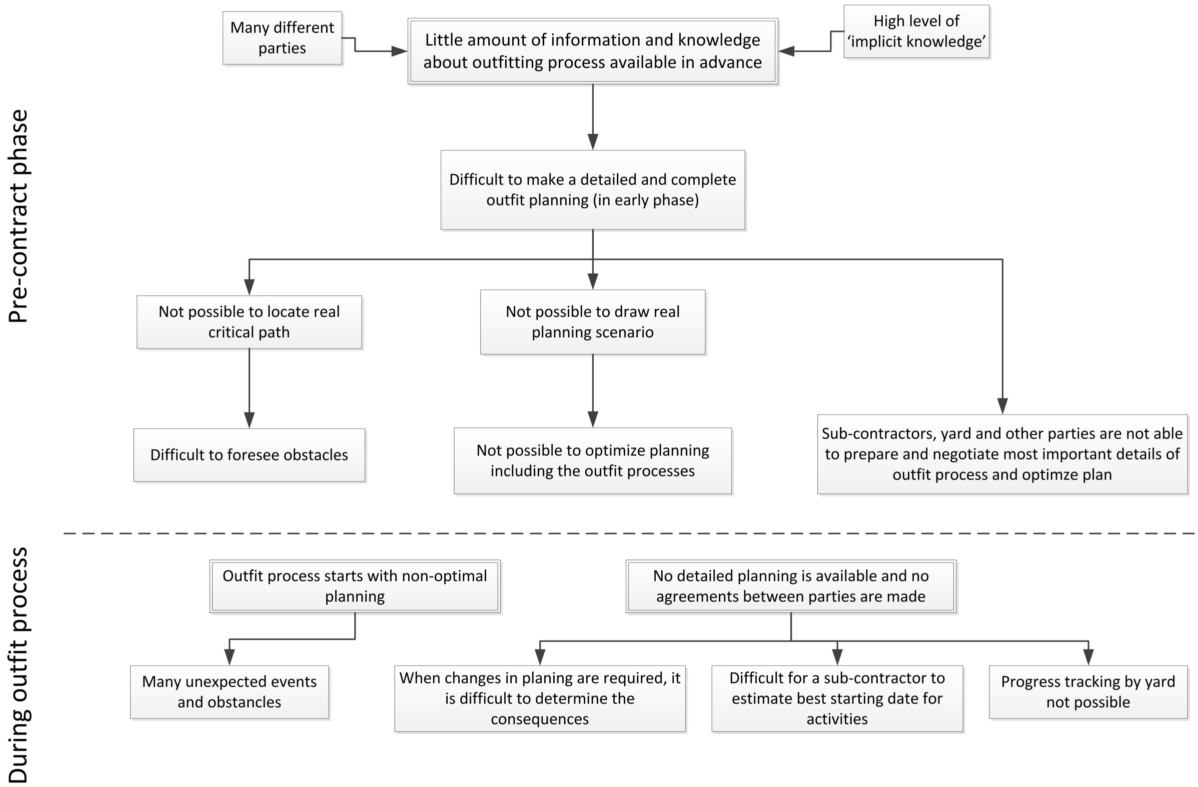


Figure 3.1: Research problem structure

3.2.1 Challenges during the pre-contract phase

During the pre-contract phase, only ***little information is available*** about the expected outfitting processes. Most often it is not known how much outfit work should be carried out, what type of work it will be or how many man-hours or other resources are required. It is also difficult to make an estimation about the possible amount of outfitting work to be carried out in a certain phase.

Two main reasons can be appointed for the lack of information. At first, due to ***the amount of different parties*** taking part in the process and their non-transparency it is difficult to obtain the required information or to make feasible estimations. Secondly, the amount of ***'implicit knowledge'*** used while determining the required information for the outfit process is high. In this high-tech industry many decisions are taken by well educated, highly skilled workers. Unfortunately, transferring this knowledge and experience from skilled employees to those less skilled or new workers is often not sufficiently systematized, and should therefore be 'codified' in a way that it is easily transferable [8]. This will prevent for inefficiencies and errors within the process when for example 'ageing' or outsourcing occurs.

A consequence of the little amount of information is the ***inability in generating a complete (detailed) outfit planning*** in an early phase. Currently only the 'outfit phases' are defined instead of the specific activities which will be carried out within each phase. Durations of those phases are estimated based on implicit knowledge as well as the corresponding start/end dates which depend on milestones or other phases.

Without having a detailed outfit planning, the project planner is ***not able to locate the real critical path.*** Currently, this is determined by using the casco planning and outfit phases that are set. However, without any content of those phases a feasible estimation cannot be made. For project management it is important to be able to locate the critical path in order to decide where they have to put their main focus on. Besides that the project team is unable to foresee and handle any obstacles.

Sub-contractors, the yard and other parties ***cannot prepare and negotiate their interdependencies*** during the production when not having an outfit planning. No detailed agreements can be made about the outfitting activities.

Also, because the outfitting process is not planned in detail, ***no optimal distribution of outfit activities is set*** over all outfit phases. Specific decisions about for example the amount of pre-outfitting, pre-outfit durations but also outsourcing of sections are difficult to take.

3.2.2 Challenges during the outfitting process

Due to an insufficient level of preparations, the production process starts most often with a non-optimal outfit planning, without detailed knowledge of the content and characteristics of outfit work and with insufficient agreements between different parties. Various consequences are described below.

During the processes itself it is difficult for the subcontractor but ***impossible for the yard to check the progress***. The amount of work which should be carried out during a certain phase is unknown and yard's outfit coordinator is not able to assess whether the subcontractor is on track or not if a certain amount of components is installed. A realistic planning and detailed analysis will help to reduce the on-site coordination effort and not to overrun the projected costs and time. Appropriate tools have to be implemented to support and improve the outfit planning [2].

The chance at delays, waiting times, rework and high costs is high due to the fact that insufficient agreements have been made between all parties. Parties have already limited communication during the production itself and many details are not discussed. These events lead to higher costs and lower product quality.

When during the production any adjustments should be made within the planning, the consequences for the outfit processes cannot be checked in detail.

3.3 Research question

The goal of this research is to explore the possibilities within planning and organizing the outfitting process in order to improve the total shipbuilding process. Within this research a tool is built that provides information to the project planners which enables them to make better decisions. In this chapter, the main research questions and sub-questions will be discussed. In order to achieve the main goal of this research, the following research objectives are set:

- Acquire knowledge about the content of the outfitting process, including activities, required resources, dependencies and constraints.
- Define formulas and relationships to estimate the required outfitting work for a specific vessel or section type.
- Use a model to generate high quality production plans using a specified input in an early stage of the process.
- Locate possible improvements to optimize the controllability and performance of the outfitting process.

3.3.1 Main research question

"How can Royal IHC, within the pre-contract phase, for different vessel types, determine in what way it should organize its resources within the outfitting process in order to improve the controllability of the total ship production process while the performance may not decrease"

Pre-contract phase: This phase is known as 'the 80/80 phase', in which it is 80% probability that the customer will place an order and 80% probability that the supplier will be IHC.
Different vessel types: The model which will be used to determine the organizational strategy, is applicable for pipe laying vessel and hopper dredgers.
Resources: The resources taken into account within this research are man-hours, crane-hours and floor space.
Controllability: The controllability of a process is defined within this research as the ability to handle the process

requirements and avoid negative events such as delays, rework or waiting times in order to obtain the final project results as was planned.
Performance: The performance of a process or sub-process is defined within this research as the required amount of total man-hours to perform all required activities.

Figure 3.2 shows how the mechanism is build up. It is assumed that the output of the research provides the project planners with information enhancing them to make better decisions. By making better decisions, resources will be better organized. Organization of the resources will have an effect on the controllability & flexibility of the process. The controllability & flexibility affect the costs and/or time of the process and/or quality of the product. When optimizing these steps, the ship production process will be improved.

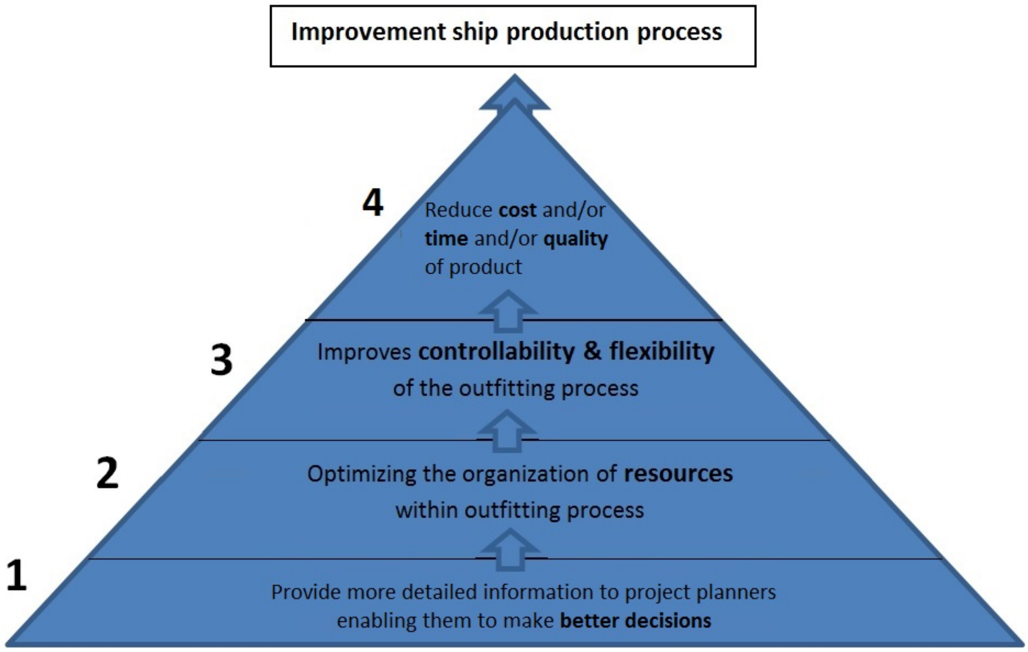


Figure 3.2: Overview structure main research question

3.3.2 Sub-questions

In order to answer the main research question, the research is split into different parts each with its own research question. It is assumed that the answers of all sub-questions together built the answer for the main research question.

- ***Sub-question #1:*** *How can the concepts of 'controllability' and 'performance' meaningfully be expressed within the outfitting process and what is their relation with required resources?*
- ***Sub-question #2:*** *What are the underlying characteristics of outfit activities, their dependencies, constraints and required resources?*
- ***Sub-question #3:*** *How can a model be built which generates high quality project plans using all collected information?*
- ***Sub-question #4:*** *What standard rules can be used by the project planners in order to realize the desired improvements within the outfitting process?*

3.4 Research structure

This research is split in two different parts. Within the first part conceptual models are defined for the estimation of outfit activities for different disciplines. In the second part of the research, these outfit activities are used to generate a planning of the production scenario. Using different production scenarios, thorough analysis will be performed in order to find improvements of the controllability within the outfit process of a complex vessel.

This chapter gives insight in what kind of approach will be taken, in other words what strategy to follow during this research.

Figure 3.3, gives a clear overview of the research structure. Using this approach, final conclusions could be drawn and recommendations could be given in an efficient and effective way. Below, each step will be discussed.

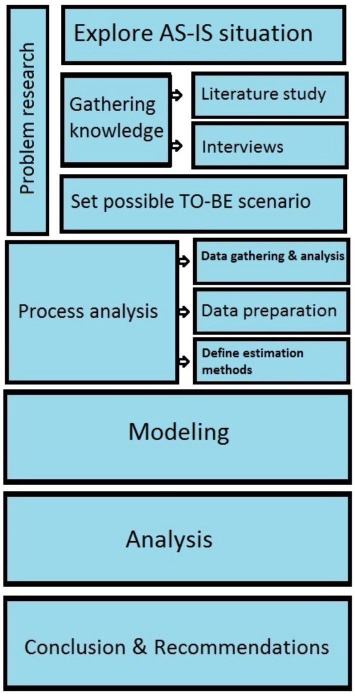


Figure 3.3: Overview research structure

3.4.1 Problem research

In order to locate main problems and set direction for possible changes within the outfitting process, the 'AS-IS' situation was drawn. Different types of sub-processes and phases are explored and distinguished. Finally a possible TO-BE situation is drawn where specific improvements are implemented. Here the process is running in an optimal condition where costs and lead times are minimized and delays, waiting times and rework do not exist.

Two different kinds of knowledge sources within this phase are considered: *Internal knowledge source* and *external (or general) knowledge source*. *Internal knowledge sources* include all the knowledge gained from processes or organizations within IHC. All information obtained about the yard is considered to be *internal knowledge*. To acquire this knowledge interviews are held with specific employees. Finally, the 'AS-IS situation' is drawn using this information. *External knowledge sources* are sources outside the yard and are used to draw the 'TO-BE situation' and to provide knowledge about possible methods to reach this desired scenario. An important way to acquire this knowledge is the literature research where scientific articles, reports and books are read to obtain information (chapter 2)

Main purpose within problem research is to draw the difference between the AS-IS situation and the TO-BE situation. It is assumed that answering the main research question, will provide the yard the knowledge to make the step to the TO-BE situation. To be able to find a feasible answer, the question is split into multiple sub-questions (chapter 3). After defining the problem and the research questions, a strategic approach for this research will be set. This presents the research structure used to answer the sub-questions.

3.4.2 Process analysis

After obtaining the required knowledge and information about the process, data is gathered to be able to create a model which generates specific solutions to reach the 'TO-BE situation'. This analysis is split in 3 different parts:

1. Data gathering & analysis
2. Data preparation
3. Definition of estimation methods

At first, data is gathered. Acquiring data is done by using company's historical databases or implicit knowledge supplied by employees and subcontractors. Before just simply accepting the data found, it is analyzed in order to determine whether the data can be used or not, using statistical tests. Finally, the data need to be prepared in a way that it can be used to define estimation methods required as input for the models.

In this part of the research all required knowledge to built the final models that create the activities and generate a planning should be gathered. To be able to generate a planning, to set up phases, durations and start/end times, all required outfit work should be known. For each activity, the required man-hours, the constraints and the required facilities should be known.

3.4.3 Modeling

Two models are build after obtaining all knowledge and required estimation methods. The first model ("The Activity Loader") is able to create all required outfit activities with their corresponding characteristics using only limited amount of input information. The second model the("Planning Generator") uses the output of the first model and generates a planning. Within this model, parameters can be changed in order to improve the outfit processes. *The Activity Loader* will be discussed in detail in chapter 5.11 and the *Planning Generator* will be discussed in chapter 6.4 [15].

3.4.4 Validation and verification

At different phases within the research, validation or verification is required to determine the feasibility of the methods used. Figure 3.4 gives an overview of the different validation and verification steps in the modeling process. The chosen techniques heavily depend on the type and amount of data available. Below, several techniques are discussed.

Degeneration test: After obtaining a possible conceptual model, degeneration tests can be used to check the behavior of the model with a specific input and specific model parameters. When the behavior is similar to the problem entity, the model is considered positive.

Extreme condition test: Extreme condition tests can be performed to see the behavior of the output of the model for any extreme or unlikely input value. The model is considered valid, whenever the output in this situation shows a feasible value.

Face validity: When no data is available to use for the validation, face validation can be used. Individuals, knowledgeable about the system are asked whether the model and/or its behavior are reasonable.

Historical data validation: If historical data is available that is not used for the creation of the model, historical data validation techniques can be used. This technique determines whether the output of the model is similar to the data. The smaller the offset, the more feasible the model.

Operational graphics: When the behavior and/or output of the model are visually displayed, it can be determined whether the model behaves correctly or not.

Although validation and verification techniques are applied, there may still be an offset between the estimations made by the models and the real scenarios. Within chapter 7.10, this offset is given and discussed within a case study and further recommendations are given in order to decrease the offset.

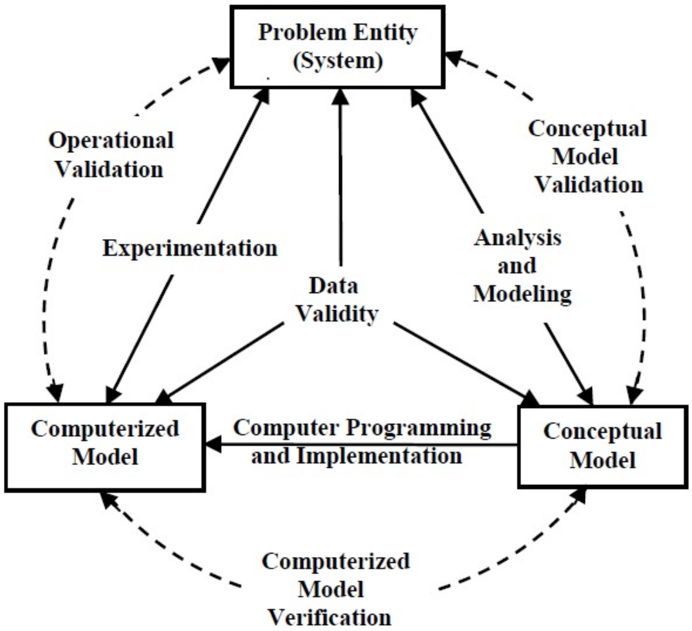


Figure 3.4: Validation and verification at different steps in the modelling process [5]

Conceptual model validation
Within the first part of the research where activities are generated, methods are developed to give an estimation about the expected outfit activities including their most important characteristics. For example methods to estimate the amount of pipe spools, HVAC ducts or cable trays in a section. Statistical methods are applied to obtain parameter values for the conceptual models. With those models, the user is able to make an estimation about the problem entity which is here covered by the outfitting processes.

Conceptual model validity determines that the theories and assumptions underlying the conceptual model are correct and that the model its representation of the problem entity its structure are logic, and mathematical and causal relationships are 'reasonable' for the intended purpose of the model [5]. The validation steps are explained in detail within each corresponding chapter where also the chosen validation method is discussed.

Computerized model verification
After obtaining all conceptual models describing the problem entity, computerized models are made. All conceptual models found in the first part of the research are programmed in the software of the *Activity Loader* that generates all outfit activities. Thorough verifications are made in order to check the correctness of the software code. The same is done for the *Planning Generator*. Results are discussed in chapter 5.11 and 6.4.

Operational model validation
Finally, it is checked if the output behavior of both models has sufficient accuracy for their intended purpose over the domain of the intended models applicability. This validation is discussed in chapter 7.10 applying a certainty analysis on the case study of a pipe laying vessel.

Data validation
For many different steps in the modeling and validation process data was required. Before this information could be used, data validation techniques had to be applied in order to make sure that the data was correct and feasible. Most often, data bases have been used which contained production data. This data needed to be validated and when necessary modified or rejected.

3.4.5 Conclusions & recommendations

Using the output of multiple runs of the *Planning Generator*, conclusions can be drawn. During this process, main focus is put on the pre-outfit process where phase durations and POF percentages are varied and optimized for all activities. Specific tendencies are found and lessons are learned about the sensitivity of parameters which finally effect the controllability and performance of the outfitting process and the total production process.

With the conclusions drawn, recommendations are given that can be used at Royal IHC. Also specific recommendations and possibilities for further research are given.

3.5 Scope

At the start of the research, limitations are set to draw the scope and range which is taken into account during the research. Below, most important limits are discussed.

Process range
The process range taken into account within this research covers the period from the start of pre-outfit phase until the delivery of the vessel. However, specific milestones within the production process, such as section erection, start engines, sea trials and delivery, are used as input.

Commissioning activities are simplified and generalized per type of room.

Although there are strong interdependencies between the outfitting processes, engineering and purchasing, the activities of those departments are not taken into account.

The outfit process is simplified within this research to 3 outfit-phases instead of 4. The two outfitting phases after 'closing' room are combined and defined as 'outfit phase'.

Vessel types
Due to the fact that Royal IHC built over the last years mainly pipe laying vessels and hopper dredgers, main focus in this research is put on those two vessel types. When using these two types, most data was available and the final conclusions can be easily implemented in the process. The applied method in this research can be used for other vessel types in order to find similar improvements in their outfitting processes.

Recent projects at Royal IHC will be used as data source for gathering the information required for this research. A differentiation is made between the following 2 types of data:

- **Quantity data**
  In case of 'quantity data', data is gathered about the amount of components which are expected in a certain vessel design for a specific discipline. It is assumed that the specific yard where the vessel is built does not influence the design, the amount of components, and so the amount of work which has to be carried out.
- **Priority / Constraint data**
  Data is gathered to see what within the AS-IS situation is prioritized and which constraints have to be taken into account for different outfitting activities. Priorities and constraints might differ for each yard which requires consistency in vessels from 1 yard when data is gathered for this research.

Outfit disciplines

It is assumed that all required outfit work during the production process of pipe laying vessels and hopper dredgers can be divided over the disciplines listed below. Due to limited amount of time, only the first 6 disciplines are taken into account. In chapter 7.10 the effect of this limitation is discussed.

1. **Pipe installation**
2. **HVAC duct installation**
3. **Cable tray and strip installation**
4. **Secondary steel works**
5. **Painting**
6. **Scaffolding works**
7. Electrical cable installation
8. General ship component installation
9. Mission equipment installation
10. Joinery
11. Floor installation
12. Insulation

4 | Model requirements

4.1 Introduction

Two models, the *Activity Loader* and the *Planning Generator* are built within this research. Both models are built in Microsoft Excel using Visual Basics. Their functional requirements and non-functional requirements are discussed within this chapter. A detailed description of the model design of the *Activity Loader* is given in chapter 5.11 and a detailed description of the model design of the *Planning Generator* is given in chapter 6.4.

The flowchart shown in Figure 4.1 presents the overall structure of this research. Both models are an important part. The internal structure of the models are further discussed in chapter 5.11 and 6.4.

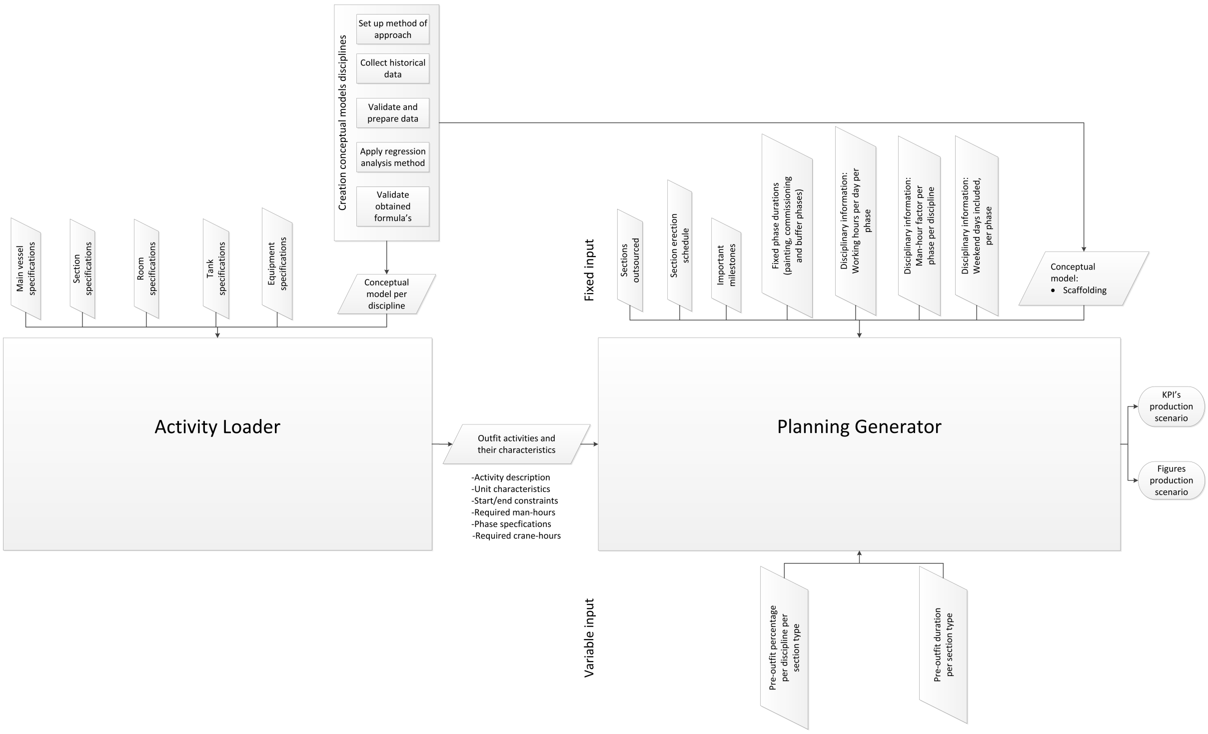


Figure 4.1: Flowchart structure research models

4.2 The Activity Loader

4.2.1 Functional requirements

The main goal of the *Activity Loader* is the generation of all outfit activities and their most important characteristics. In order to obtain lists with outfit activities two different types of input are required. First, main information about the vessel is required such as main vessel information but also section and room characteristics. The second input consists of conceptual models that estimate the expected amount of work and outfit activities using the basic vessel information. Knowledge about all outfit disciplines is gained in the first part of this thesis research and is used to create the conceptual models. An overview of the input is shown in Table 4.1 below.

Input 1: Basic vessel information	**Input 2:** Conceptual models
Main vessel characteristics	Piping model
Section information	HVAC model
Room information	Cable tray model
Tank information	Secondary steel model
Equipment information	Painting model

Table 4.1: Input *Activity Loader*

Functional requirements of the *Activity Loader* are:

- The *Activity Loader* automatically generates input sheets using only limited vessel information.
- The *Activity Loader* estimates the required amount of outfit work for all units (sections, rooms, tanks and ship parts).
- The *Activity Loader* translates the amount of work per activity into the required amount of man-hours.
- The *Activity Loader* estimates the required amount of crane-hours for each activity.
- The *Activity Loader* creates section, room, tank and ship part outfit activity lists including specific activity characteristics such as start and end constraints.
- The *Activity Loader* is able to export the final output to the *Planning Generator*.

The output of the model consists of lists with section, room, tank and ship part outfit activities. The installation activities of the equipment are implemented in the room outfit activity list. Parts of the hull and accommodation of the vessel need to be painted during the production process. These conservation activities are listed in the ship part outfit activity list.

The outfit activities consist of a description of the activity, a description of the corresponding unit, the required work to be carried out, the start and end constraints, the initial required man-hours when the activity would be carried out in the pre-outfit phase and the required crane-hours in the POF-hall. A more detailed description of the output is given in chapter 5.11.

4.2.2 Non-functional requirements

Non-functional requirements of the model are:

Reliability:
The reliability of the *Activity Loader* does have a sufficient level. This means that the possible offset of the estimations compared to the real values is known. Results of the reliability analysis are shown in chapter 7.10.

Documentation and maintainability:
The software code of the model is programmed in such a way that it is easy for a user to implement adjustments or to extend the model.

Usability:
The Activity Loader is created in a way that it is usable for everybody. The layout makes it easy to understand how the model should be used and what information is required.

Robustness:
The Activity Loader is created in a way that it is not likely that a user accidentally damages the model.

4.3 The Planning Generator

4.3.1 Functional requirements

The main goal of the second model, the *Planning Generator*, is to create an outfit planning of a specific production scenario and present multiple important process characteristics that indicate the performance and controllability. The model has 3 different types of input. At first, the output of the *Activity Loader*, consisting all required outfit activities for each unit which forms the basic of the input of the *Planning Generator*. Secondly, specific (planning) information that will not change while running multiple scenarios, such as standard durations or milestones. Part of the fixed input is also the conceptual model of the scaffolding discipline which is used to determine the amount of scaffolding work during the outfit process. Several variables are required that can be varied within the *Planning Generator* in order to improve a production scenario. The third input consist of the values of those variables that will change while running multiple scenarios. The 3 types of input are listed in Table 4.2 shown below.

Input 1: Export *Activity Loader*	**Input 2:** Fixed input information	**Input 3:** Variable input information
Outfit activities per unit	Sections outsourced Section erection schedule Important milestones Fixed phase durations Man-hours factor per disciplines per phase	POF percentages per section type, per discipline, per phase POF-duration per section type

Table 4.2: Types of input for the *Planning Generator*

Functional requirements of the *Planning Generator* are:

- The *Planning Generator* divides the amount of work that should be carried out over all phases using the outfit percentages per phase and the specific rooms that belong to a section.
- The *Planning Generator* inserts scaffolding activities where required.
- The *Planning Generator* inserts commissioning activities where required.
- The *Planning Generator* inserts start dates, end dates and durations for all activities using the given constraints and other input information.
- The *Planning Generator* creates a complete outfit planning including all outfit activities in all units (sections, rooms, tanks and ship parts).
- The *Planning Generator* calculates most important outfit process characteristics and KPI's.
- The *Planning Generator* draws figures that present the behavior of the workload over time per discipline, the unit occupancy over time, the crane occupancy over time and the floor occupancy over time.
- The *Planning Generator* consists of a mechanism that is able to run multiple different scenarios and saves all different outputs in order to locate possible improvements in the outfit process.

The output of the *Planning Generator* consists of 3 parts. The first part contains the outfit planning including all activities. The second part contains most important characteristics of all outfit processes. In the third part of the output figures are drawn that present the behavior of important outfit characteristics over time.

4.3.2 Non-functional requirements

Non-functional requirements of the model are:

Usability:
The *Planning Generator* is created in a way that it is easy to use. The layout makes it easy to understand how the model should be used and what information is required. Also the output of the model is presented in a way that it is easy to make a quick judgment about a specific production scenario.

Documentation and maintainability:
The software code of the *Planning Generator* is programmed in such a way that it is easy for a user to implement adjustments or to extend the model.

5 | Research Part 1: *Activity generation*

5.1 Introduction

Within this first part of the research, characteristics for activities which will be taken into account are defined. In order to generate a production planning within the next phase, the following information need to be obtained for each activity:

- Type of activity
- Duration of activity (in time and man-hours)
- Specific production phase in which the activity is carried out
- Dependencies and constraints
- Required facilities for each activity

One of the methods to make a feasible estimation for future scenarios is to examine the past and try the find specific relationships. This quantitative research method required statistical knowledge. Therefore in the first part of this chapter, findings of extra literature research concerning statistical methods is discussed. Afterwards for each discipline a detailed description of their research is given in which the required information is obtained. A standard chapter structure is used starting with an introduction and description of the research method used. Afterwards, the research results are shown as well as the validation results. Finally, conclusions are drawn.

5.2 Statistical methods used

Within this research, various statistical methods will be used to make a feasible estimation of future scenarios. In order to generate a planning, estimations should be made to obtain the amount of work, activity durations, start and end times. The statistical methods used are discussed in Appendix C.

5.3 Top down approach v.s. bottom up approach

Two ways are used for the estimation of certain characteristics. The top-down approach first estimates a characteristic of the overall systems such as the amount of components in the entire vessel. Afterwards, this system is split into subsystems and now the characteristics for each subsystem are estimated. When using the bottom-up approach, first certain characteristics of subsystems are estimated where after the characteristic of the overall system is estimated.

When using the bottom-up approach, small changes in the chosen variables might have large fluctuations in the final outcome for the overall system. When this approach is used, final checks and validation need to be performed to check the feasibility of the outcome.

5.4 Definition of standard section types and room types

5.4.1 Introduction

Within the production planning, activities are linked to specific sections, blocks, rooms, systems and sometimes to the entire ship. The activities and their characteristics for a specific section or room depend on the type of section or room. For instance, for a wheelhouse section different activities needs to be carried out compared to an engine room section. Besides the type of activities, also the characteristics such as duration, start or end times will differ. In order to determine the activities and make a feasible estimation about their characteristics, section types and room types for a pipe laying vessel and a hopper dredger are defined and shown in Appendix D.

5.4.2 Section types

Section types are defined based on:

- The location of the section
  - Depends on the height of the location
  - Depends on the longitudinal position of the section
  - Depends on the transversal position of the section
  - Sections containing specific parts of the vessel, such as the forecastle, the bulbous bow or the wheelhouse.
- The content of the section
  - Including auxilary machinery
  - Not including auxilary machinery

5.4.3 Room types

A list of room types is defined in order to determine the specific activities and their characteristics. The types are defined based on their function and difference compared to other rooms. Most of the rooms defined can be found in a pipelaying vessel and in a hopper dredger but some are specifically for one of both vessel types. An overview is shown in Figure D.3 in Appendix D.

5.5 Parameters and constraints within the outfitting process - Piping

5.5.1 Introduction

Each pipe laying vessel and hopper dredger contains most often thousands of pipe spools, distributed throughout the vessel. Those pipe spools belong to different systems and all have their own characteristics such as length, weight and installation phase. Within this chapter, a method will be developed to make a feasible estimation about:

- The amount of pipe spools per section
- The characteristics of the pipe spools in a specific section
- The required amount of man-hours for the installation of the pipe spools in a specific section
- The required amount of crane hours per section for the installation of the pipe spools in a specific section

5.5.2 Research method

In this research the top-down approach is applied and the method is split into 4 different steps. In the first step, the total amount of pipe spools in a specific vessel is estimated. In the second step, the total amount of pipe spools per group of sections is estimated where after in the third step the amount is estimated for each section. When the amount of pipe spools per section is known, the characteristics per spool including the length, weight, installation time and required facility usage are estimated in the last step. Figure 5.1 below gives an overview of the structure.

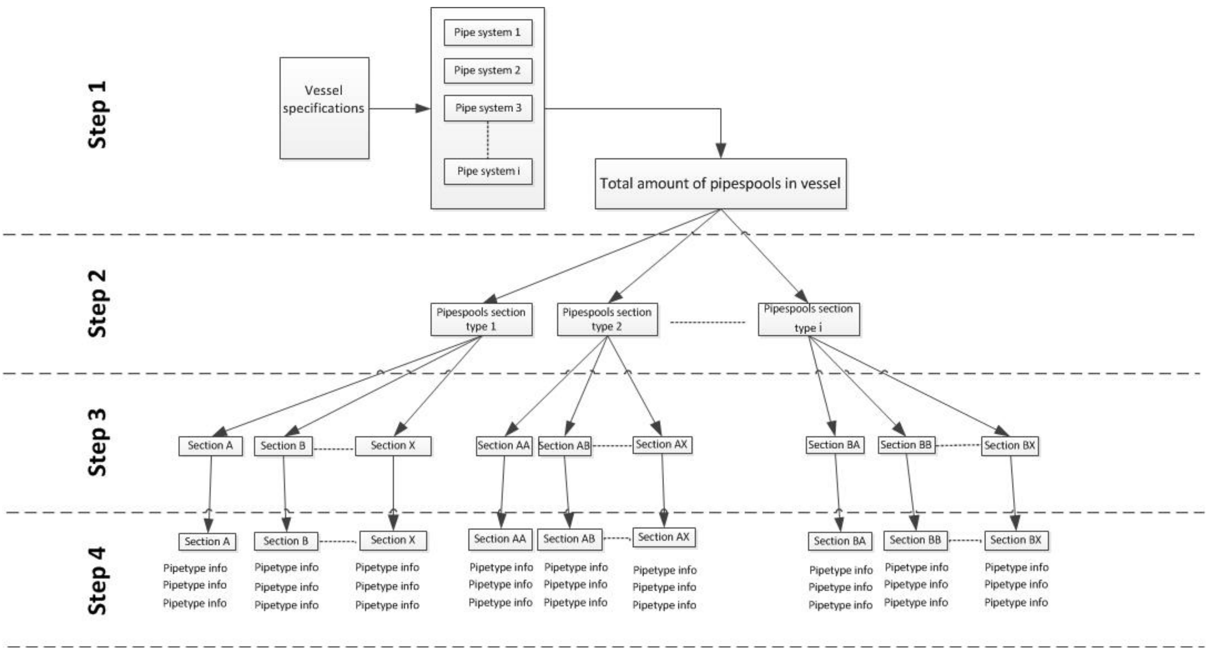


Figure 5.1: Sub-research structure piping

Step 1

In this first step a method is developed which determines using only little information the total amount of pipe spools in a specific vessel. The following sub-steps are applied:

Sub-step 1: Define different types of piping systems and select for each system a dependent vessel characteristic as variable when possible.

Sub-step 2: Use linear regression analyses in order to find a relationship between the dependent variable and the amount of piping of a specific system in a vessel.

Sub-step 3: Validate the obtained linear formulas and constants.

Step 2

In the second step, the total amount of pipe spools is distributed over all possible section types. In this step, groups of sections and friendships between specific section types are taken into account. It is assumed that when a section type is present, it contains a constant percentage of the total amount of pipe spools. Section types interact together in their groups and friendships which causes fluctuations in their total amount of piping. The groups and friendship are defined in such a way that this leads to realistic values.

- Groups of sections

For calculating the amount of components at a specific part of the vessel, it has been researched which sections can form a group in a way that groups are similar for most vessels of the same vessel type. Below the groups for a pipe laying vessel and a hopper dredger are listed:

Pipelaying vessel:

- Aftship sections
- Midship - sections containing bottom parts [1]
- Midship - sections not containing bottom parts
- Foreship - sections containing double bottom

[1]Here the word 'bottom part' is used instead of 'double bottom' due to the fact that some sections might not contain a part of the double bottom but do have bottom plating and are located at the lowest level

- Foreship - sections not containing double bottom
- Accomodation sections

Hopper dredger:

- Aftship sections
- Midship - side sections containing bottom parts
- Midship - mide sections containing bottom parts
- Midship - sections not containing bottom parts
- Foreship -sections containing double bottom
- Foreship - sections not containing double bottom
- Accomodation sections

- Friendships between sections

A vessel doesn't necessarily contain all section types. A smaller vessel might for example contain only 'side sections' within the double bottom instead of also sections located midship. Initially all pipe spools are distributed over all types of sections. When a specific section type is not present within the vessel, the spools which are 'reserved' for this type should then be assigned to a section type that is present. Some types are therefore 'coupled' within the model and are considered to be each others 'friend'. Within a friendship between two or more sections, one section could be 'the leader'. This means that this specific sections obtain all spools of each missing section in that friendship. Below, different situations are explained.

Scenario 1: All section types within a group are present, type A, C and D are friends:

$$Grouppercentage = \alpha(type_A) + \beta(type_B) + \gamma(type_C) + \theta(type_D) \tag{5.1}$$

where

$\alpha =$ A constant percentage of specific sectiontype A

$\beta =$ A constant percentage of specific sectiontype B

$\gamma =$ A constant percentage of specific sectiontype C

$\theta =$ A constant percentage of specific sectiontype D

Scenario 2: Only 3 of 4 section types within group are present, type A, C and D are friends and section type A is defined as leader of 'friendship':

$$Grouppercentage = (\alpha + \gamma)(type_A) + \beta(type_B) + \theta(type_D) \tag{5.2}$$

where

$\alpha =$ A constant percentage of specific sectiontype A

$\beta =$ A constant percentage of specific sectiontype B

$\gamma =$ A constant percentage of specific sectiontype C

$\theta =$ A constant percentage of specific sectiontype D

Scenario 3: Only 3 of 4 section types are present within group, type A, C and D are friends and no section type is defined as leader:

$$Grouppercentage = (\alpha + 0,5 * \gamma)(type_A) + \beta(type_B) + (\theta + 0,5 * \gamma)(type_D) \tag{5.3}$$

where

$\alpha =$ A constant percentage of specific sectiontype A

$\beta =$ A constant percentage of specific sectiontype B

$\gamma =$ A constant percentage of specific sectiontype C

$\theta =$ A constant percentage of specific sectiontype D

Step 3
When the total amount of pipe spools for a section type is known, in this step the amount of pipe spools per section is estimated. It is assumed that the amount of piping in a section does have a linear relationship with the percentage of volume of that section type. Therefore the following simple formula is used:

$$N_s = N_t * \frac{V_s}{V_t} \tag{5.4}$$

where

N_s = Amount of pipe spools in specific section

N_t = Total amount of pipe spools for specific sectiontype

V_s = Volume of specific section m^3

V_t = Total volume of group sections within sectiontype m^3

Step 4
In this step the characteristics for pipe spools in a section are estimated with which the total required man-hours for the installation of the pipe spools can be determined. The formula shown below is used for the estimation of man-hours [8]. For more details see Figure E.1 in Appendix E.

$$H = 30 + (45 * \alpha) + (30 * N_s) \tag{5.5}$$

where

H = Required amount of man-hours for installation of spool

α = Usage of crane when weight > 50 kg (1 or 0)

N_s = Number of supports for spool

The formula shows that the amount of man-hours for the installation of a pipespool depends on the amount of supports and the weight of the spool. The weight of a spool determines whether a crane should be used or not. Research at Royal IHC showed that the number of supports for a specific pipespool depends on the length and the diameter of the spool. Figure **??** in Appendix E shows this relationship between diameter and minimum distance between supports.

The production phase in which the spool will be installed also influences the installation time. Due to lack of accessibility and increasing time for preparation and transportation, it cost for most of the pipe spools more time to install the spool 'on-board'.

Pipe types are defined based on important characteristics. The amount of supports, weight and installation period of the spool are considered to be important. With these characteristics, 6 pipe types within the 3 different outfit phases are defined and shown in Figure E.2 in Appendix E.

5.5.3 Research results and validations

Results and verification step 1
In this step of the research, data is used of the pipe laying vessels with Yardnumber (Ynr) 727 and 7719 and hopper dredgers with Ynr 7720, 718 and 1269. Due to the fact that it is not feasible to draw a line using two data points for pipe laying vessels, this research step is first carried out for hopper dredgers and afterwards applied on the pipe laying vessels and verified.

At first pipe system types are defined. For pipe laying vessels 16 types and for hopper dredgers 18 types could be defined using data from Royal IHC pipespool databases. For each of these types it is determined which of the following vessel characteristics could be best used as a dependent variable:

- Length

- Breadth
- Depth
- Deadweight
- Power
- Accommodation capacity (crew capacity)
- Hopper capacity
- Length x breadth
- Length x breadth x depth

Because the top-down method is used, and differences in outcome might have high consequences in further steps, here only 'very strong correlations' between variables, corresponding with a correlation coefficient higher than 0.8 are used [16]. For piping systems with a correlation coefficient lower than 0.8, a constant amount of piping is set. In a later phase of the research, calculations also showed that setting this constant instead of defining a linear relationship leaded to a more feasible solution.

For each piping system the best line is drawn and its formula is determined. Also the maximum and minimum possible lines are determined to get an idea of the expected data range. Figure 5.2 shows a summary of the magnitude of the error for pipe systems per vessel type. A detailed overview of these values is shown in Appendix E in figures E.8 and E.3.

Verification showed that the obtained method and values are also applicable for a pipe laying vessel. As Figure 5.2 shows, most of the maximum differences in pipe spools for each pipe system are very little. For both vessels it turns out that the total amount of hydraulic pipe spools shows large fluctuations. This might be caused by the high dependency on the amount and type of equipment on-board which differs per vessel.

Maximum difference	Pipelayers	Hopper dredgers
0% - 1%	10	7
1% - 2%	4	3
2% - 3%	-	2
3% - 4%	1	3
4% - 5%	-	-
5% - 6%	-	-
6% - 7%	-	2
7% - 8%	-	-
8% - 9%	1	-
9% - 10%	-	-
10% - 11%	-	-
11% - 12%	-	-
12% - 13%	-	-
13% - 14%	-	-
14% - 15%	-	-
15% - 16%	-	-
16% - 17%	-	-
17% - 18%	-	-
18% - 19%	-	-
19% - 20%	-	1

Figure 5.2: Results of verfication first step (Difference total pipe spools per system estimated and real)

Results and verification Step 2

This Step of the research is separately carried out for pipe laying vessels and hopper dredgers. Data is used for the Yardnumbers 727, 7719, 7720, 718 and 1269.

-Hopper dredgers-

Distribution over part of ship

First, a general check is performed where the distribution of all pipe spools over the accommodation, the aft-, mid-and fore-ship is calculated. The results are shown in Figure E.4 in Appendix E. The differences in percentages between the data used are rated using the standard deviation. The highest standard deviation is 3,98%. This is measured compared to the total amount of pipe spools in that vessel which would be 100%.

Distribution over groups
A further 'split-up' is made from ship parts to groups that include several section types. The groups are also shown in Figure E.4 in Appendix E with their description and values. Group number 3, which includes midship section above the double bottom, does have a high standard deviation of the used data due to a relative long midship of yardnumber 718. This is measured compared to the total amount of pipe spools which would be 100%.

Per section type
All averages of the groups defined are set as constants. The sum of the pipe spools of all section types included in that group should be equal to this group-percentage set. Finally, percentages are set per section type. An important aspect here which should be taken into account are the 'friendships' between section types. Results are shown in Figure E.5 in Appendix E. The highest maximum difference between the data used and the value set is 6,49% (measured compared to the total amount of pipe spools which would be 100%) and the standard deviation between the estimated and real data is 3,18%.

Verification of step 2
Now all percentages are known, overviews are obtained of the yard numbers used and the calculated percentages in order to check the feasibility of the parameters and values found. This overview is shown in Figure E.6 in Appendix E. For each Ynr the average difference is below 1% and the standard deviations are below 2%. However, when for each section type the difference in pipe spools per section type is calculated, some outliers are noted. Especially section type 27 within the aft-ship of Ynr 718 shows an unacceptable difference. For these section types, further research is recommended.

-Pipelaying Vessels-

Distribution over part of ship
The results of the distribution of the total amount of pipe spools is shown in Figure E.9 in Appendix E. The differences in percentages between the data used are rated using the standard deviation. The highest standard deviation is 2%. This is measured compared to the total amount of pipe spools which would be 100%.

Distribution over groups
Also the results of the distribution of the pipe spools over the section groups are shown in Figure E.9 in Appendix E and have a highest standard deviation of 2,62%. This is measured compared to the total amount of pipe spools which would be 100%

Per sectiontype
When the total group percentages are set, now the constant percentages per section type are calculated. Results are shown in Figure E.10 in Appendix E. With a highest maximum difference between the data used and the value set of 2,62% (measured compared to the total amount of pip spools which would be 100%) and a standard deviation between the estimated and real data of 1,60% the results are considered positive.

Verification and validation of step 2
After obtaining the percentages per section type, these values are verified and validated with the real values of Ynr 727, 7719 and 730. Results are shown in Figure E.11 in Appendix E. Again the amount of pipe spools per section type are measured compared to the total amount of pipe spools (100%). The maximum difference for the vessels is around 3% and the standard deviation of estimated percentages and the real percentages of all section types is around 1% for both vessels. Verification with the yardnumbers used for the obtainment of the parameters values shows better results compared to the validation with Ynr 730. For this validation significant outliers are noted. However, the calculated offset is the total offset of all sections grouped within their corresponding section type. For several section types further research and an expansion of the dataset is recommended. Further results per section are discussed in the next step.

Results and validation step 3

The amount of pipe spools in each section is estimated within this step, using the section volume relative to the total volume in the section type. This method is applied for Ynr 730 and the results are shown in Figure **??** in Appendix E.

During the validation the estimated amount of pipe spools for a section type is accepted when:

- The difference with the real amount is less than 30 spools
- The difference with the real amount of spools is less than 30% of the maximum amount (estimated or real).

Of the total 107 sections used, the estimated amount of spools of 57 sections was accepted. The estimations in the first and second step were considered feasible but when a group of sections with similar section types is split into separate sections, fluctuations are noted. Sections with similar characteristics, type and location can contain complete different amounts of pipe spools. In order to take this into account, another method should be used for the estimation of pipe spools in a section. A method should be used which is based on the location of systems and equipment for which piping is required and which takes the routing into account. In this research a global estimation had to be made using a low level of detail. When a more precise answer is preferred, another approach should be developed.

Results and validation step 4

Within this step, a method is developed for the estimation of the characteristics of the pipe spools in a certain section and to calculate the amount of man-hours for mounting the spools using this information.

Using data from Ynrs 727, 7719, 7720, 718 and 1269 the expected percentage of pipe types in a certain section is calculated. A model is build that analyses all sections in a certain section type and determines the percentage of spools per type. Results for both vessel types are shown in Figure E.7 and E.12 in Appendix E.

This method and final outcome is validated using 3 different sections of Ynr. 730 of different section types and the results are shown in Figure E.13 in Appendix E. The real estimated values for the percentages of pipe spools for a certain type is in similar range compared to the real values. In this part of the research, no distinction is made between the outfit phase in which a spool is mounted, due to the fact that this characteristic is not yet used within this phase of the research.

5.5.4 Certainty & conclusions

In order to determine the uncertainty of the developed method, the expected offset is calculated using the standard deviation. For the 3 pipe laying vessels with yardnumbers 730, 727 and 7719 the estimated amount of pipe spools is compared with the real amount of pipe spools. The standard deviation of the offset is calculated for each section type and shown in Figure 5.3. For some section types such as the moonpool sections, high uncertainties are noticed. Only little amount of data was available of those section for the creation of the model and the data available showed large fluctuations. This results in larger uncertainties.

Section type	Amount of sections	st.dev [ps]
1	8	17
2	2	70
3	20	21
4	1	73
5	2	183
6	16	46
7	2	134
8	17	70
9	4	137
10	6	104
11	2	48
12	2	2
13	12	84
14	18	101
15	6	45
16	2	51
17	6	135
18	2	67
19	16	99
20	6	137
21	6	53
22	8	35
23	8	35
24	39	53
25	6	24
26	2	36

Figure 5.3: Standard deviation uncertainty offset estimated data and real data 730, 727 and 7719

The results of the verifications and validations show that it is difficult to give a feasible estimation about the amount and type of pipe spools at a specific location in a vessel when only basic vessel information is used as input. The location and type of equipment, the choices of the engineer and many other factor have significant influence. However, knowing the offset and the uncertainty, using the results of this research the yard does have a tool that could be used to give a rough estimation in an early phase while currently they do not have this ability.

The results show that offset and therefore the uncertainty within this method get larger in the 3rd step. The results for the estimation of the amount of pipe spools per part of the vessel, group of section types and for each section type shows most often relatively lower expected offsets. However, when a section type is further divided into sections, larger differences between the real and estimated values are noticed. In order to simplify the method, it is assumed that the amount of pipe spools in a specific section is proportional to the part of the volume compared to the total volume of its corresponding section type. Validation has shown that this assumption is not valid in most of the cases. Expanding the dataset with more vessels will improve the estimations. However, when a more feasible outcome is preferred another approach is recommended. Using another approach, locations and type of equipment and other systems with need piping should be taken into account. In this research, the input information is limited which made a more detailed approach impossible.

For all pipe spools a standard average factor is used to calculate the required man-hours for installing the spools in a specific phase. However, this factor might be dependent on the type of pipespool. Although these factors are based on real production data, it is recommended to implement a more detailed method instead of 3 general values applicable for each spool.

5.6 Parameters and constraints within the outfitting process - HVAC

5.6.1 Introduction

HVAC system
The discipline 'HVAC' covers heating, ventilation and air-conditioning systems installed on-board. These systems

have the function to regulate the temperature and humidity within specific rooms and spaces in the vessel. Large amounts of ducting and piping are installed to supply equipment with air, water or other liquids.

The amount of components at a specific location heavily depends on the type of room or space of which the air should be handled and the chosen location where the equipment is installed. The location of ducting and piping also depends on the choices of the engineer while routing the duct- and pipelines during the design phase.

During the design process of a pipe laying vessel and hopper dredger, the engineer can choose between two main configurations: A central or local HVAC system. With a central system, the main air handling equipment (AC units) are installed in the 'The AC-room'. From there, ducting and piping is routed to the specific locations where the air needs to be handled. When choosing for a local configuration, each space contains its own air handling unit(s) which regulates the air condition for that specific area. Ducting and piping supply these units with cold and warm air. While analyzing the different vessels, it was noticed that all hopper dredgers do have a HVAC systems with a 'central configuration' while pipe laying vessels have a 'local configuration'. Therefore the following assumption is made within this research: hopper dredgers have a central HVAC configuration while pipe laying vessels have a local HVAC configuration.

It is clear that it is a big challenge to give a good estimation in an early phase about the amount of ducting, piping and equipment for HVAC at each location due to the fact that the configuration and space- or room requirements are not known yet and that the amount and location depends on many different factors.

The research is divided in the subsystems listed below. It is assumed that all systems contain piping and equipment components but only the air-conditioning system and ventilation system contain ducting.

- Air-conditioning system
- Ventilation system
- Heating system
- Cooling system

Different sub-systems

- Air-conditioning system
The air-conditioning system maintains the condition of the air in a specific room by adjusting the humidity and temperature in the room. It is assumed that this system contains:

- Ducting: *Spiro and square ducting at the following locations:*
  - Side sections of aft- and fore-ship
  - Side sections of midship containing auxiliary machinery
  - Mid sections in aft- and fore-ship
  - Deck sections midship
  - All accommodation sections
- Piping
- Equipment: *Air handling units incl. foundations*

- Ventilation system
The ventialtion system takes care of the circulation of air within a room by supplying a room with air and subtracting old air from the room. It is assumed that this system contains:

- Ducting: *Spiro ducting at the following locations:*
  - Side sections in the mid-, fore- and aft-ship.
  - Mid-sections in the fore- and aft-ship.

  - All accommodation sections

- Piping
- Equipment:*Supply and exhaust fans*

- Heating system
The heating system supplies the AC-units or heaters with warm air in order to maintain a certain temperature in a room. It is assumed that this system contains:

- Piping
- Equipment: Hot water boilers, circulation pump

- Cooling system
The cooling system supplies AC-units with cold air or liquids in order to maintain a certain temperature in a room. It is assumed that this system contains:

- Piping
- Equipment: Chiller unit, circulation pump

5.6.2 Research method

Within this chapter an estimation method for the amount of components in the HVAC system is created. Because the HVAC system contains 3 different component groups (piping, ducting and equipment), this investigation is also split in 3 parts. Below, for each part the research method is discussed. In order to give a clear overview of these methods, their structure is presented in different flowcharts.

Research method - Ducting
Unfortunately, the amount of data sources containing information about the amount and location of ducting was limited. Only for pipe laying vessel with Ynr 727, detailed data for each section was obtained while for the hopper dredgers with Ynr 7720 and 1269 only the total amount of ducting was known. Due to the low level of detail in the available data, the bottom-up approach is used. The little amount of data and the used bottom-up approach require good validation of the method used. Further improvement with the use of extra data sources is recommended. After analysis of several yard numbers and literature, the following assumptions are made:

- According to subcontractor Heinen Hopman and Royal IHC its HVAC experts, the required amount of man-hours for mounting a duct does have a linear relationship with the inner surface of that duct. During the research, the total amount of ducting is therefore calculated in total square meter.
- No ducting is installed in spaces below the first deck. The first ducts are located in the ceiling of deck 1.
- Ducting is most often mounted on the ceiling of each room. The amount of ducting which could be expected in a room or section depends therefore on the surface of that specific area and the amount of decks. It is chosen to find the correlation between section volume and amount of ducting.
- No ducting is installed in the double bottom. Therefore, the volume of the double bottom in a section is subtracted from the total section volume obtaining 'the net volume'. For further calculations this 'net volume' is used.
- Side sections most often contain tanks or void spaces. Within these areas, no ducting is installed. Therefore, during research a clear distinction is made between side sections and mid sections where only specific side sections contain ducting.
- The type of section determines the amount of ducting. Here no distinction is made between vessel types. For instance, an accommodation section of a hopper dredger with volume X, contains the same amount of ducting compared to a similar section with the same volume of a pipe laying vessel.

In order to develop a feasible estimation model, the following method is applied:

Step 1: Create list of section types containing ducting of specific HVAC system for pipe laying vessels and hopper dredgers, using 3D view of vessels.

Step 2: Using data of Ynr 727, find the linear relationship between net volume and amount of ducting for each section type using regression analysis.

Step 3: Validate the obtained formula's in order to determine the applicability for hopper dredgers.

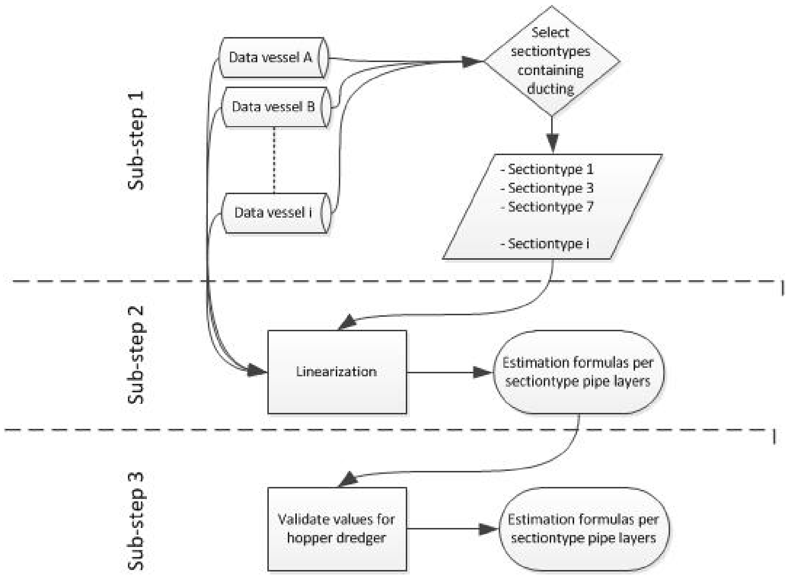


Figure 5.4: Flowchart structure research method HVAC ducting

Research method - Piping
For this part of the research data is used of the pipe laying vessels with Ynr 727 and 7719 and the hopper dredgers with Ynr 7720, 718 a 1269. The method applied in the discipline 'Piping' is also used here. More information can be found in chapter 5.5.

Research method - Equipment
Within this part of the research a method is developed to give a feasible estimation for the required amount of man-hours for the installation of the HVAC equipment in a specific room. The type and quantity of equipment components in a room depends on the function, location and dimensions of a room. Here it is important to notice that the equipment is linked to the room instead of a section. Two sections of a similar section type can contain different types of rooms and therefore can contain different types and amounts of equipment.

Within this part again the bottom-up approach is used due to the little amount of data and the fact that the amount and type of components depends heavily on the room type instead of the vessel characteristics. Data is used of the pipe laying vessels with Ynr 727 and 7719 and hopper dredgers with Ynr 7720 and 718. The Steps of the applied method is described below.

Step 1: Using data of previous projects: select for each room its corresponding room type and create a list of installed HVAC equipment including their characteristics.

Step 2: Determine for each room type the average amount and type of equipment.

Step 3: Translate the average amount and type of equipment per room type to man-hours using literature sources [17].

Step 4: Define 6 categories of total man-hours and link a specific category to each specific room type.

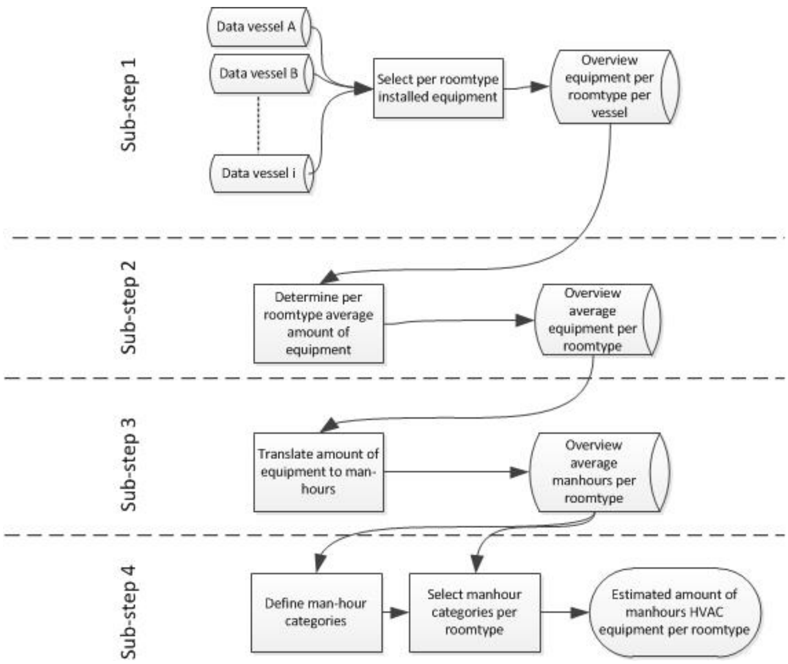


Figure 5.5: Flowchart structure research method HVAC equipment

5.6.3 Research results, verification and validation

Results, verification and validation ducting

Regression analysis is used to find a linear relationship between the amount of ducting in a specific section and it's corresponding net volume. In Appendix F an overview is shown of the graphs used during the calculations. For each the air-conditioning and ventilation system 3 different formulas are found to calculate the total inner surface of the installed ducting in the side-sections, mid-sections and accommodation sections. Sections with a correlation coefficient less than 0.5 are considered to have a constant amount of ducting due to the weak correlation [18]. An overview with the corresponding parameters is shown below in Figure 5.6 and 5.7:

$$I = \alpha X + \beta \tag{5.6}$$

where

$I =$ Total inner surface ducting installed in specific section in m^2

$\alpha =$ The effect of the net section volume on the amount of ducting

$X =$ The section (net)volume

$\beta =$ A constant amount of ducting

System	Alpha (α)	Beta (β)	Description sectiontype	St.dev diff	Min diff	Max diff	Average diff	Correlation C_r
Airconditioning - Side sections	0,02	0,00	*Aftship, Foreship, Midship (only sections incl aux)*	18,06	0,29	59,47	11,26	0,59
Airconditioning - Mid sections	0,01	0,00	*Aftship, Foreship, Midship (only deck sections)*	6,81	0,63	21,48	4,75	0,76
Airconditioning - Accomodation sections	0,00	38,53	*Accomodation*	27,35	1,81	78,34	22,27	0,13
Ventilation - Side sections	0,00	5,71	*Aftship, Foreship, Midship*	9,03	1,48	20,59	7,63	0,07
Ventilation - Mid sections	0,01	0,49	*Aftship, Foreship*	2,38	0,00	21,73	5,08	0,67
Ventilation - Accomodation sections	0,00	17,06	*Accomodation sections*	15,46	0,66	47,25	10,77	0,16

Figure 5.6: Result - Parameters found for total inner surface ducting in sections and statistical values for each group of section types

While trying to find the correlation for a specific group of section types between their net volume and the amount of ducting, data is used of only 1 vessel. The graphs in Appendix F show that it is difficult to find a relationship that covers all data points. For each group of section types the standard deviation, the minimal and maximum difference and the average difference is calculated for the different amounts of ducting in the sections and shown in Figure 5.6.

Looking at the graphs and correlation coefficients, it seems that for several groups of sections a linear relationship exists. However, for some sections large differences are noted. Some sections of similar type and volume do have very different amounts of ducting due to choice of the engineer of routing the ducts. For sections with a high standard deviation in the outcome, further research is recommended.

The parameters shown above are determined using data of a pipe laying vessel. One of the assumptions was that these parameters were applicable for both a pipe laying vessel and a hopper dredger. In order to be allowed to use the same parameters for a hopper dredger, the results are validated. In Figure 5.8 results of this validation are shown. With a relative small difference between the estimated value and the real value (less than 5%), the parameters for the estimation of air-conditioning ducting in a hopper dredger are considered acceptable. The estimations of the amount of ducting of the ventilation system however do have a larger relative difference with their real values.

Pipelayer			**Hopper Dredger**		
Sectiontype	***Airconditioning***	***Ventilation***	***Sectiontype***	***Airconditioning***	***Ventilation***
1			1		
2			2		
3			3		
4			4		
5			5		
6	2		6		
7			7		
8		1	8		
9	1	1	9		
10			10		1
11			11	1	1
12			12	1	1
13			13		
14	2	2	14		
15	2	2	15		
16	2	2	16		
17	2	2	17		
18	2	2	18	2	2
19	1	1	19	2	2
20			20	2	2
21			21	2	2
22	2	2	22		
23	1	1	23		
24	3	3	24		
25	3	3	25	2	2
26	3	3	26	2	2
			27	2	2
			28	2	2
			29	3	3
			30	3	3
			31	3	3
			32	3	3
			33	2	2

Figure 5.7: Overview used parameter type per section type

	Square meter inner surface total ducting of vessel - REAL		*Square meter inner surface total ducting of vessel - Estimated*		Difference (m²)		Difference (%)	
Yardnumber	Airconditioning	Ventilation	Airconditioning	Ventilation	Airconditioning	Ventilation	Airconditioning	Ventilation
727					-26,13	-4,82	98,72%	99,36%
7720					-37,36	199,36	95,08%	158,40%
1269					-2,01	44,64	99,26%	130,20%

Figure 5.8: Overview outcome validation parameters

Results and validation piping
Results of piping within the HVAC system are shown in Appendix F. These results are obtained using the method described in Chapter 5.5. Validation and discussion of the results of this method can be found in chapter 5.5.3

Results and verification equipment

In the first and second step of this part of the research, a list is created with all equipment per room type including their average capacities. Here data is used of 2 pipe laying vessels with Ynr 727 and 7719 and 2 hopper dredgers with Ynr 7720 and 718. During analysis of the data it appeared that the installed equipment per room type differs significantly between rooms of similar room type and volume. Therefore, it is chosen to set up an estimation method using a constant value for the amount of equipment instead of a linear relationship.

In the third step the required amount of man-hours is estimated using literature sources which presented data for the translation of equipment type and capacity to man-hours [17]. The results for the first steps are shown in Appendix F. One of the consequences of using the bottom-up approach is a fluctuation in the outcome. In order to damp these fluctuations and to simplify the outcome, in the last step 5 different 'categories' are defined with each a specific constant amount of man-hours. An extra category is added for the AC-room of a hopper dredger which contains the air-conditioning equipment when a central configuration is used.

In Figure 5.10 and 5.9 below, the categories are listed and including the data presented in a graph. Finally, Figure 5.11 shows the statistical analysis of the method used and graph in Figure 5.9. With an average difference of 1 man-hour and a maximum difference of less than 5 man-hours, the man-hour categorizing method used is considered feasible. However, the obtained average amount of man-hours in a room requires detailed validation and possible improvement with extra data.

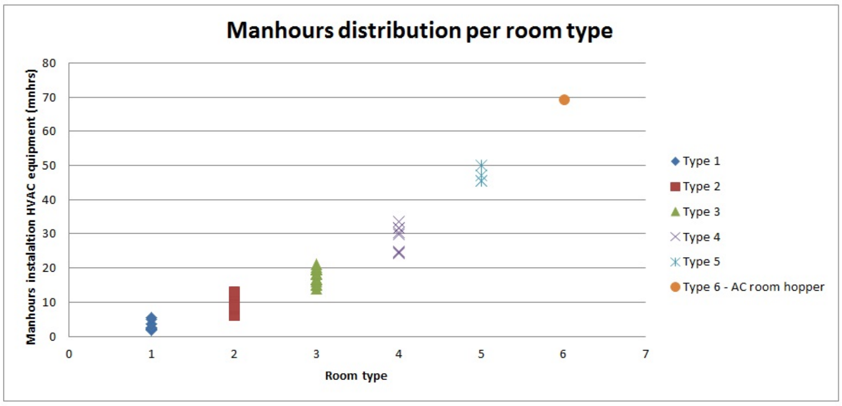


Figure 5.9: Required amount of man-hours for installing equipment in rooms

Categorynumber:	*Manhours:*
1	
2	
3	
4	
5	
6 (AC-room)	

Figure 5.10: Average required amount of man-hours for installing equipment in room

		Manhours:
Pipelayer	St dev	1,75
	Min difference	0,00
	Max difference	4,57
	Avg difference	1,16
Dredger	St dev	1,11
	Min difference	0,00
	Max difference	4,59
	Avg difference	1,10

Figure 5.11: Statistical analysis - results using man-hour categories for installation of HVAC equipment in rooms

5.6.4 Certainty & conclusions

Conceptual models are obtained within this chapter to estimate the amount of components within the HVAC system. For all systems the location and amount of components heavily depend on the choices of the engineer. Unfortunately, for most systems limited amount of data was available and therefore the formulas found might show large offsets for specific ships where other types of choices are made by the engineer. Therefore larger datasets and maybe more input variables such as the use of a central or local HVAC system configuration are recommended to make better estimations.

In order to determine the uncertainty within the developed method, the standard deviation for each section type in a pipe laying vessel is calculated. The overview is shown in Figure 5.12 below. The standard deviation shows the possible offset of man-hours in a certainty range of 68%. Several section types show significant high uncertainties due to insufficient data used to built the model and large fluctuations between the available data values.

	Manhours HVAC			
	St. Dev piping	St.Dev ducting - airco	St.Dev ducting - vent	St.dev total
1	0,0	1,4	0,0	1,4
2	0,0	2,8	0,0	2,8
3	18,7	4,1	25,8	48,6
4	0,0	5,5	0,0	5,5
5	10,7	6,9	14,8	32,4
6	9,1	8,3	12,5	29,9
7	2,3	9,7	3,2	15,1
8	7,8	11,0	10,8	29,6
9	19,9	12,4	27,4	59,7
10	37,4	13,8	51,6	102,9
11	0,0	15,2	0,0	15,2
12	0,0	16,6	0,0	16,6
13	50,7	17,9	70,0	138,6
14	34,0	19,3	46,9	100,2
15	0,0	20,7	0,0	20,7
16	15,6	22,1	21,5	59,2
17	3,2	23,5	4,4	31,0
18	0,0	24,8	0,0	24,8
19	49,2	26,2	67,9	143,4
20	0,0	27,6	0,0	27,6
21	7,0	29,0	9,7	45,7
22	8,3	30,4	11,5	50,2
23	2,2	31,7	3,0	36,9
24	26,6	33,1	36,8	96,5
25	7,7	34,5	10,6	52,8
26	35,1	35,9	48,4	119,4

Figure 5.12: Standard deviation uncertainty offset HVAC man-hours estimated man-hours and real man-hours

Ducting
The 'inner surface' of the ducts is used for the translation of the amount of ducting to the required amount of man-hours for the installation of the ducts. According to subcontractor 'Heinen Hopman' X man-hour is required for a duct with an inner surface of 1 m^2. This value is used within this research but it is recommended to validated this with real production data.

Within the method applied, specific section types of pipe laying vessels are coupled to similar section types of hopper dredgers. Insufficient detailed data was available during this research to determine the uncertainty within detail for the estimation of the amount of ducting within a specific section of a hopper dredger. In order to be able to use the obtained formulas for hopper dredgers, further research should be carried out including validation and determination of the uncertainty.

Due to the fact that only data is used of 1 vessel for the determination of the parameters, further research is recommended. With a similar method but an extended dataset the parameters will have a higher quality and the final error is expected to decrease. Especially the results obtained for hopper dredgers should be further researched. The error for the amount of ducting within the ventilation system is unacceptable with the current parameters.

Piping
See chapter 5.5.4 for the certainty and conclusions about the method applied to estimate the amount of pipe spools in a specific section.

Equipment
With the applied method values are found which seem to be in a feasible range. However, only a verification of the parameters is carried out but no real validation of the method and values. For both vessel types only 2 yard numbers were available to use as input and therefore it is highly recommended to expand this dataset in order to obtain more certainty in the fluctuating amount of man-hours required for the installation of equipment in a specific room.

The amount of man-hours required for the installation of a specific type of equipment is determined using different literature sources. It is recommended to validate these numbers using real process data in order to determine the uncertainty and reduce the final offset of the estimation compared to the real amount of man-hours required.

5.7 Parameters and constraints within the outfitting process - Cable trays

5.7.1 Introduction

At many different locations in the vessel different types of equipment and components are installed that need to be supplied with electrical energy or electrical signals. In order to transport this energy and signals, wires are routed throughout the vessel. Special steel structures also knows as cable trays, support the cables over their entire length. Therefore, the required amount of supports depends on the total cable length in a vessel which is confirmed by Royal IHC its 'design and calculation' experts.

Cable trays are most often installed in the POF phase before the section is painted. During the section conservation the trays get all their required paint layers in order to be able to install cabling already in an early outfit phase. At Royal IHC, subcontractors strive for 90% pre-outfitting of cable trays.

Within this chapter a method is researched that makes an estimation of the required amount of cable trays in a specific section including the corresponding man-hours for installation. At first the method used will be explained where after the results and validations are discussed. Finally conclusions and recommendation are given.

5.7.2 Research method

Within this research, data is used of vessels built at Royal IHC in the past. Pipe layers with Ynr 727 and 7719 and hopper dredgers with Ynr 718 and 1269 are used. Of these vessels a 3D-model is obtained in which the cable trays where drawn. This data required preparation before it could be used. In this part of the research, the bottom-up method is applied. Below, the different steps are listed and a corresponding flowchart is shown in Figure 5.13.

Step 1: Subtract data from the 3D models in order to obtain lists of cable tray information per section of each vessel.

Step 2: Find correlation between the total length of cable trays in a section and specific section characteristics.

Step 3: Use regression analysis techniques to find feasible formulas to estimate the total length of cable trays using the value of the depend section characteristic.

Step 4: Translate the total length of cable trays in a section to required amount of man-hours for installation of the trays.

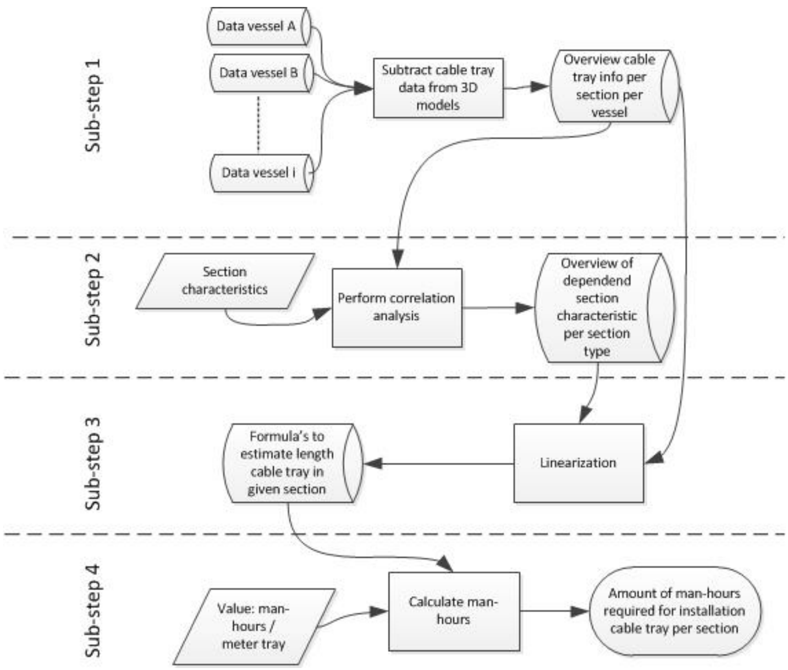


Figure 5.13: Flowchart structure

Step 1
In the first step information is subtracted from the 3D-models in order to make lists of cable trays including their characteristics such as length and width for each section per vessel. In order to remove errors in the data, the tray characteristics in the lists are compared with the corresponding section plan to find overlap between sections.

Step 2
Within this step a method should estimate the amount of required man-hours for the installation of cable trays in a specific section. According to Wei (2012), John S. Page [6] and Royal IHC experts, the amount of man-hours required for installation of the cable trays depends on the total length of the trays. This assumption is also used within this research. In order to estimate the total length of cable trays in a section, first the dependent section characteristic needs to be determined. Therefore, the correlation factor is determined between the total length of trays in a section and the section characteristics shown in Figure 5.14. For several section types the length, width, height or surface area effects the total length of cable trays, depending on the direction the trays are installed. For other section types, the amount of equipment effects the total length of cable trays, where section weight or volume might have the best correlation.

Section characteristics:
Section length
Section width
Section height
Section surface area
Section volume
Section weight

Figure 5.14: Possible dependent section characteristics

Step 3
After finding the dependent section characteristic in the previous step, a regression analysis can be performed in order to obtain the parameter values for the linear formula shown below:

$$I = \alpha X + \beta \tag{5.7}$$

where

$I =$ Total length of cable trays in specific section in m

$\alpha =$ The effect of the section characteristic on the length of cable trays

$\beta =$ A constant length of cable tray in m

Step 4

Using production data of Royal IHC and expert opinion it is found that on average 1,38 man-hours are required for the installation of 1 meter cable tray. According to Page [6], it cost around 1 man-hour to install 1 meter cable tray with a width of 30 cm. His results are shown in Figure G.1 in Appendix G. In this research it is chosen to work with the man-hour parameter found at Royal IHC while the outcome of the research is applicable within that specific production process. The formula below is used:

$$H = \alpha * X \tag{5.8}$$

where

$H =$ Required man-hours for installation cable trays

$\alpha = -$

$X =$ Amount of cable tray length in section in m

5.7.3 Research results and validation

Step 1

For all 4 vessels used, a list is obtained including all required information.

Step 2

For each section type and its corresponding sections in the dataset, the correlation is checked between all section characteristics and total length of cable trays. The method explained in chapter 5.2 is used. It is assumed that a correlation factor of at least 0,5 is acceptable. When for all section characteristics a correlation factor lower than 0,5 is found, it is assumed that there is no correlation. In order to be able to make an estimation about the cable tray length in those sections, the average length is taken and used as constant value. The figures below give an overview of the results.

Hopper dredger				
Section type	alpha	constant	Correlation 'r'	Dep. Var
1		3,78	< 0,5	Constant
2		14,20	< 0,5	Constant
3	0,60	-34,12	0,81	Weight
4		0,29	< 0,5	Constant
5		16,84	< 0,5	Constant
6		12,16	< 0,5	Constant
7		0,00	< 0,5	Constant
8		35,35	< 0,5	Constant
9		0,00	< 0,5	Constant
10		1,01	< 0,5	Constant
11		0,00	< 0,5	Constant
12		20,09	< 0,5	Constant
13		0,00	< 0,5	Constant
14		7,47	< 0,5	Constant
15		0,00	< 0,5	Constant
16	0,14	-19,86	0,72	Weight
17		2,79	< 0,5	Constant
18		33,59	< 0,5	Constant
19		17,95	< 0,5	Constant
20		7,07	< 0,5	Constant
21		34,10	< 0,5	Constant
22		0,00	< 0,5	Constant
23		0,00	< 0,5	Constant
24		7,29	< 0,5	Constant
25		0,00	< 0,5	Constant
26		0,00	< 0,5	Constant
27		0,00	< 0,5	Constant
28		0,00	< 0,5	Constant
29		9,60	< 0,5	Constant
30		146,54	< 0,5	Constant
31		79,79	< 0,5	Constant
32		0,00	< 0,5	Constant
33		49,00	< 0,5	Constant

Pipe laying vessel				
Section type	alpha	constant	Correlation 'r'	Dep. Var
1		0,00	< 0,5	Constant
2		0,00	< 0,5	Constant
3		0,34	< 0,5	Constant
4		0,00	< 0,5	Constant
5		46,51	< 0,5	Constant
6		43,33	< 0,5	Constant
7		0,00	< 0,5	Constant
8		64,59	< 0,5	Constant
9		239,12	< 0,5	Constant
10		0,00	< 0,5	Constant
11		0,00	< 0,5	Constant
12		0,00	< 0,5	Constant
13		0,00	< 0,5	Constant
14		105,95	< 0,5	Constant
15	46,31	-594,47	0,64	Breadth
16		91,59	< 0,5	Constant
17	0,19	-39,59	0,61	Volume
18		69,43	< 0,5	Constant
19		111,79	< 0,5	Constant
20	0,03	-7,07	0,84	Volume
21	0,09	2,88	1	Weight
22	0,30	4,00	0,69	Weight
23	3,17	-118,59	0,99	Weight
24		18,89	< 0,5	Constant
25	6,80	-39,98	0,99	Weight
26		139,40	< 0,5	Constant

Figure 5.15: Results research length of cable tray for specific section type

Step 3

The parameter values found are shown in Figure 5.15. In order to determine the validity of this method and the values found, data of pipe laying vessel with Ynr 730 is used for validation. A detailed overview of the validation and offset is shown in Figure **??** in Appendix G. Figure 5.16 below shows most important values.

St. dev	45,21	m
Max diff	191,57	m
Min diff	0	m

Figure 5.16: Validation results

In order to determine the expected uncertainty the estimated values of the length of cable trays in the sections of Ynr 727 and 730 are compared with the real values. The results are shown in Figure 5.17. The standard deviation shows the offset in a certainty range of 68%.

Section type	No. of sections	stdev [m]
1	8	0,00
2	2	0,00
3	20	0,83
4	0	0,00
5	2	38,80
6	16	20,93
7	0	0,00
8	18	26,07
9	4	104,95
10	6	0,00
11	2	0,00
12	2	0,00
13	12	0,00
14	18	30,87
15	12	23,29
16	2	58,42
17	3	14,78
18	2	46,92
19	16	54,70
20	6	18,42
21	6	4,92
22	8	8,38
23	8	51,47
24	33	37,67
25	6	106,72
26	2	5,25

Figure 5.17: Determination uncertainty offset cable tray length in sections using data Ynr 727 and 730

Step 4
As explained, the amount of man-hours for the installation of the cable trays can be found by multiplying the total length by a factor found.

5.7.4 Certainty & conclusions

Within this research a method is developed for the estimation of the required man-hours for the installation of cable trays in a specific section. Possible correlations between the amount of cable trays and section characteristics are researched in the second step. For most of the section types it was found that the correlation factor was not acceptable and that a constant value of tray length had to be set. This leads to a higher uncertainty and offset between the real values and estimated values.It can be concluded that the amount of cable trays in a specific section differs significantly for each vessel where other design choices might be made by the engineer and specific systems and equipment is positioned at other locations. Further research and the development of a method taking other (maybe more detailed) variables into account is recommended. However, the yard is already able to say something about the expected amount of cable trays using the method developed in this research using only limited amount of vessel information.

The method is applied for both pipe laying vessels and hopper dredgers. Data of only 1 vessel could be used for pipe laying vessels while data of 3 vessels is used for hopper dredgers. Ynr 730, with which the validation is carried out, has many similarities with the vessel used for obtaining the data (Ynr 727). In order to improve the model, it is recommended to expand the dataset with data of more vessels. Besides that another validation should be done with a different pipe layer as well as an extra validation for the parameter values found for hopper dredgers.

The uncertainty analysis shows that for some sections the 68% certainty range has an offset of more than 100 m cable tray. For other sections this range is significantly smaller and acceptable. Especially for the sections with a large possible offset, further research is recommended before using these values.

5.8 Parameters and constraints within the outfitting process - Secondary steel works

5.8.1 Introduction

At specific locations in a vessel steel components such as ladders, manholes or foundations are mounted, each which a specific function. These components are most often relatively small and can be installed in an early phase of the production process. Such components which are most often installed in the section during the pre-outfit phase form the group 'secondary steel works'.

Secondary steel components are either produced by a third party or by the yard itself. After production the components are transported to a storage where they wait until they can be mounted in their specific section. According to specialists at Royal IHC, around 90% of all components is installed in the POF phase.

5.8.2 Research method

Within this chapter a method is developed to make a feasible estimation for the required amount of man-hours for the installation of all secondary steel components in a section and room. Due to the fact that components are located at a specific location, the bottom-up approach is used. Below an overview is given of the research steps taken. The flowchart in Figure 5.18 draws the structure of this research method.

Step 1: Definition types small iron works using data available and expert opinion.

Step 2: Determination number of components per secondary steel type per section.

Step 3: Determination average required man-hours for the installation of a specific secondary steel component type.

Step 4: Determination required man-hours per section using data of yard number built at Royal IHC.

Step 5: Find correlation between section characteristics and amount of required man-hours for the installation of secondary steel components.

Step 6: Use regression analysis in order to find the parameter values for the estimation formulas.

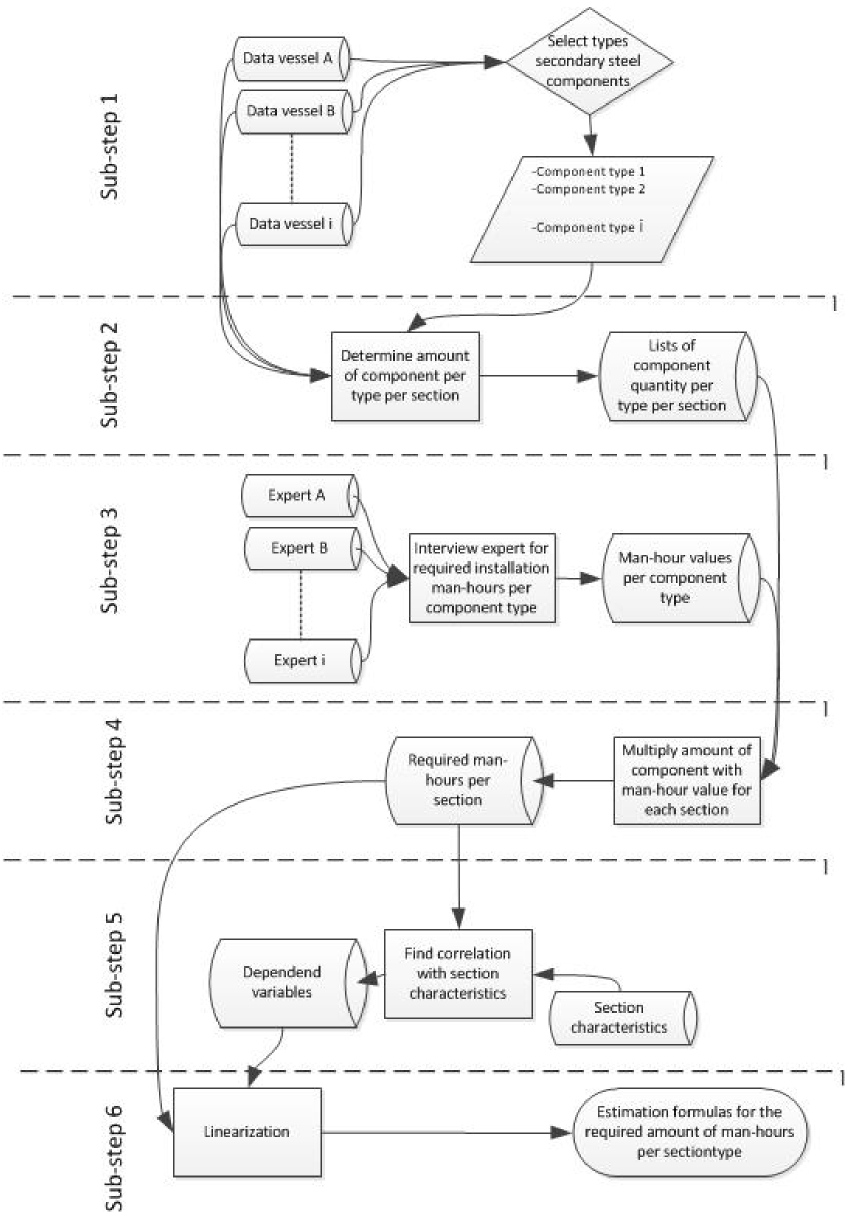


Figure 5.18: Flowchart with research structure

5.8.3 Research results and validation

Step 1

Using data of pipe laying vessels with Ynr 727 and 7719 and hopper dredgers with yard number 7720 and 718 and expert opinion, the general types of secondary steel components are determined. Figure 5.19 gives an overview of these components.

Foundations
Platforms
Ladders
Stairs
Hoisting beams
Manholes
Hand Grips
Padeyes / hoisting eyes
Drainplugs
Steps
Railings
Doors (Splash- and Weathertight)
WT Sliding door
Anodes
Fixed windows
Markings (manhole + tanks)
Bollards
Double bollards
Fairleads
Double fairleads
(Deck) guide rollers
Chocks

Figure 5.19: General secondary steel components

Step 2

For each section of the 4 vessels used in this research the amount of components per type is determined using specific drawings of each vessel.

Step 3 and 4

In order to determine the required amount of man-hours for the installation of a specific component type, interviews are done under IHC personnel. Five persons are asked how many man-hours it would costs to install a specific component with average dimensions. After obtaining 5 answers, the average amount of hours is used for further research. Results of the interview are shown in Figure H.1 in Appendix H. The total required man-hours are obtained when the amount of components per type are multiplied with their corresponding man-hours.

Using overviews of the amount of components per type per section, found in the second step, the total amount of man-hours for the installation of secondary steel components per section is calculated.

Step 5

Now all data is obtained, regression analysis can be performed to find parameter values with which the estimation can be made. In order to be able to estimate the total required man-hours for a specific section, a dependent section characteristic should be determined. Possible variables are listed below:

- Section length
- Section breadth
- Section height
- Section surface area (LxB)
- Section volume (LxBxH)
- Section weight

For each variable the corresponding correlation coefficient is calculated. A correlation greater than 0.8 is generally described as *strong*, whereas a correlation less than 0.5 is generally described as *weak* [16]. In this part of the research the variable with the highest correlation is chosen. Most often the weight or length of the section had a strong correlation with the amount of secondary steel. In case of similar correlation, section weight or volume are preferred. When all variables have a weak correlation, a constant value is used.

Figures H.2 and H.3 in Appendix H shows for each section type the dependent variable when a strong correlation was found. Due to insufficient data, not all section types could be researched. For those types, the symbol 'X' is shown in the Figures.

Step 6
After determination of the dependent variable, regression analysis is used to find the parameters for the linear estimation formula $\alpha x + \beta$. Results for both pipe laying vessels and hopper dredgers are shown in Figure H.2 en H.3 in Appendix H.

5.8.4 Certainty & conclusions

In this chapter, formulas are developed to give an estimation about the expected amount of man-hours required for the installation of secondary steel works in a specific section. These estimations can be made in an early phase of the design process (80/80 phase) when only little amount of information is available.

	Man-hours	
Section type	**Amount of section**	**St.Dev. Man-hours**
1	4	8,4
2	2	0
3	12	10,3
4	3	8,2
5	2	0
6	8	3,4
7	0	0
8	15	31
9	4	55,3
10	3	1,2
11	3	4,1
12	1	0
13	8	25,7
14	9	22,1
15	6	69,9
16	2	0
17	3	23
18	2	0
19	15	44,7
20	4	44,6
21	6	38,7
22	4	9,8
23	6	65,3
24	37	73,6
25	5	19,4
26	2	0

Figure 5.20: Standard deviation uncertainty offset estimated man-hours and real man-hours

For some section types, the results have relatively high standard deviations and a high uncertainty. This means that the estimated amount of man-hours might have a significant difference with the real values for that section type. Within the development of this method, average dimensions of components are taken into account. Amount and location of components are based on limited amount of data. For a higher quality outcome, further research using an expanded dataset is recommended.

5.9 Parameters and constraints within the outfitting process - Painting

5.9.1 Introduction

During the production of a vessel various amounts of paint layers need to be applied. These painting activities are spread over the production period. Planning of the activities is required in order to optimize the process. Within this chapter, all characteristics of all different painting activities are researched and a model is developed to make feasible estimations in an early phase of the design process.

Activity characteristics which should be taken into account are the duration, the possible start and end times and other dependencies and constraints. The required amount of man-hours depend on the type and amount of work that should be carried out. The amount of work depends on the surface area which should be treated. The method with which the surface is calculated differs and depends on the unit such as a section, room or hull which should be taken into account. In order to translate the amount of work to man-hours, productivity parameters will be used. In the past, several researches have been carried out to determine the magnitude of such parameters. Figure I.1 in Appendix I gives an overview of parameters which are used in this research. [6] [9].

A separate research is carried out for each type of activity. In the following chapters each corresponding estimation method is discussed.

5.9.2 Conservation of sections

At the end of the pre-outfit phase, each section is transported to the conservation hall where the sections are cleaned, painted and dried. The number of paint layers depends on the type of section. In between applying the paint layers, each layer needs to dry. After the last layer is dried, the section is transported to the slipway or a storage area. Within this chapter, a method is developed to estimate the total duration required for cleaning, painting and drying each section including the corresponding required amount of man-hours.

Surface area
The surface area of a specific section can be estimated using the weight of the section, the average plate thickness and the steel density. The formula below is used:

$$S_s = \frac{W_s}{\rho} * \frac{1}{t_{avg}} \tag{5.9}$$

where

S_s = Section surface (m^2)
W_s = Section weight (kg)
ρ = Steel density (kg/m^3)
t_{avg} = Average plate tickness (m)

Cleaning
When a section arrives in the conservation hall, its entire surface needs to be cleaned before it can be painted. With the estimated surface of the section, the required amount of man-hours for cleaning can be estimated using a productivity parameter. The following formula is used:

$$T_{mcs} = S_s * \alpha_c \tag{5.10}$$

where

T_{mcs} = Time required for cleaning section ($man - hours$)

S_s = Section surface (m^2)

α_c = Parameter cleaning, 0,0010 ($Mnhrs/m^2$) [9]

Painting & drying
The painter can start with (spray-) painting the section when the cleaning activity is finished. For most sections only 1 layer of paint is added in the conservation hall. However, for sections containing bottom plating already 5 layers of paint are added to the bottom plating due to the fact that the accessibility is reduced when the section is placed on the slipway. Painting a double bottom section cost therefore significantly more time. Formulas to calculate the required amount of man-hours and the total duration are shown below.

$$T_{mps} = S_s * \alpha_p \tag{5.11}$$

where

T_{mps} = Time painting a 'normal' section ($man - hours$)

S_s = Section surface (m^2)

α_p = Parameter painting first coat, 0,0024 ($Mnhrs/m^2$) [6]

$$T_{mps_{db}} = S_s * \alpha_p + (L_s * W_s * 4 * \beta_p) \tag{5.12}$$

where

$T_{mps_{db}}$ = Time painting a double bottom section ($man - hours$)

S_s = Section surface (m^2)

α_p = Parameter painting first coat ($Mnhrs/m^2$)

α_p = 0,0024 ($Mnhrs/m^2$) [6]

L_s = Section length (m)

W_s = Section Width (m)

β_p = Parameter painting second coat, 0,0016 ($Mnhrs/m^2$) [6]

After applying each layer, the paint needs to dry on average 6 hours according to painting specialist at Royal IHC. The drying period normally depends on the type of paint and on clients requirements. The formula below can be used to determine the total duration of the treatment of a section in the conservation hall.

$$T_s = \frac{T_{mcs} + T_{mps}}{N_p} + T_d \tag{5.13}$$

where

T_s = Duration for 'normal' section ($hours$)
T_{mcs} = Time cleaning a section ($man - hours$)
T_{mps} = Time painting a 'normal' section ($man - hours$)
N_p = Number of persons working in hall
T_d = Duration for drying after painting ($hours$)

$$T_{s_{db}} = \frac{T_{mcs} + T_{mps_{db}}}{N_p} + (5 * T_d) \tag{5.14}$$

where

$T_{s_{db}}$ = Duration for 'double bottom' section ($hours$)
T_{mcs} = Time cleaning a section ($man - hours$)
$T_{mps_{db}}$ = Time painting a 'double bottom' section ($man - hours$)
N_p = Number of persons working in hall
T_d = Duration for drying after painting ($hours$)

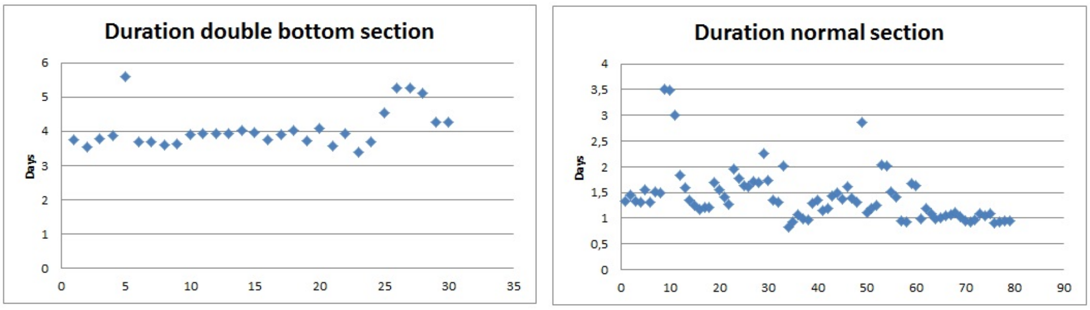
Validation
The formulas are validated using the information from the conservation hall at Royal IHC - location Krimpen. Normally 2 persons are working in each hall, 8 hours per day. Planning department plans 6 days for a double bottom section and 4 days for every other section. This includes 1 day for changing sections and transportation.

Figure 5.21 shows the results for the calculations of the sections of the pipe laying vessel with Ynr 727. The averages of the treatment of double bottom sections and a normal section are 4,05 and 1,42. When 1 day is added for changing sections and transport there is a safety buffer left of 1 and 1,5 day for unpredictable events. The graphs show that the variation between the estimations is small.

The following assumptions are made during the development of the estimation method:

- Surface area of components installed in the sections are not taken into account.
- A section is considered to be 'a flat plate' when calculating the total surface area. Here surfaces covered by a weld are taken into account as 'surface to be painted'.
- Specific rooms which require extra painting layers (such as switchboard rooms, generator room and anchor chain room) are not taken into account.
- It is assumed that the section is already dry when it arrives in the conservation hall.
- Transportation is always available.
- No other possible events that might delay the process occur.

Due to the fact that simplifications are made and the effect of possible delaying events is not taken into account, the difference between the estimated durations and the durations used by the planners is considered acceptable.



(a) Results: Duration of treatment db section

(b) Results: Duration of treatment normal section

Figure 5.21: Validation with Ynr 730

5.9.3 Conservation of rooms

Painting of a room starts when rooms are closed and when all components are installed in that room except components that should not be painted. The moment painting of a room starts is an important deadline in the planning. All disciplines and subcontractors should have installed most of their equipment and components before this specific moment in time. All rooms already contain a first layer of primer which was added during the section conservation. Now, 2 more final layers should be added. Before the painter can start, the surfaces need to be cleaned. After cleaning the painter can start and adds the layers using 'spray painting'. In between both layers and after the final layer, a drying period of 6 hours should be taken into account.

Surface

Within this research a room is simplified to a rectangular block. For all rooms, the walls have to be painted and for all rooms, except accommodation areas, also the ceiling should be painted. Floors are painted and treated in a later phase. The following two formulas shown below are used to calculate the surface. It should be noticed that possible stiffeners on the walls in the room are not taken into account when calculating the surface area.

$$S_r = 2H_r(L_r + B_r) \tag{5.15}$$

where

S_r = Total surface of room (m^2)

L_r = Total length of room (m)

B_r = Total Breadth of room (m)

H_r = Total height of room (m)

$$S_{ra} = 2H_r(L_r + B_r) + (L_r * B_r) \tag{5.16}$$

where

S_{ra} = Total surface of room in accomodation space (m^2)

L_r = Total length of room (m)

B_r = Total breadth of room (m)

H_r = Total height of room (m)

Cleaning

The time and man-hours required for cleaning a room can be estimated using the formula shown below:

$$T_{mcr} = S_r * \alpha_c \tag{5.17}$$

where

T_{mcr} = Time required for cleaning room ($man - hours$)

S_r = Room surface (m^2)

α_c = Parameter cleaning, 0,0010 ($Mnhrs/m^2$) [9]

Painting & Drying

The time and man-hours required for painting a room can be estimated using the formula shown below. In between applying a paint layer, an average drying period of 6 hours is taken into account.

$$T_{mpr} = (S_r * \alpha_p) + (S_r * \beta_p) \tag{5.18}$$

where

T_{mpr} = Time required for painting room ($man - hours$)

S_r = Room surface (m^2)

α_p = Parameter painting first coat ($Mnhrs/m^2$)

α_p = 0,024 ($Mnhrs/m^2$) [6]

β_p = Parameter painting second coat, 0,027 ($Mnhrs/m^2$) [6]

$$T_r = \frac{T_{mpr}}{N_p} + 2 * T_d \tag{5.19}$$

where

T_r = Time required for treatment room ($hours$)

T_{mpr} = Time required for painting room ($man - hours$)

N_p = Number of persons working

T_d = Time required for drying ($hours$)

Validation

For different surface areas the amount of painting work is calculated using the formulas shown above. The results are shown in Figure 5.22. This figure shows the amount of time required for painting an accommodation or normal room when 1 or 2 persons is working 8 hours a day.

The following simplifications are made when using this method:

- It is assumed that each room is a rectangular block.
- No time for building scaffolding is taken into account.
- It is assumed that 1 room is painted at the time.
- It is assumed that a room is painted with a maximum of 2 persons.

The estimations are validated using production data from Ynr 727. Figure 5.23 shows the difference between estimated duration and real duration in days. It is difficult to draw conclusions from the actual durations due to the fact that these values are integer. Besides that, these values contain 'noise' because a painter can sometimes paint

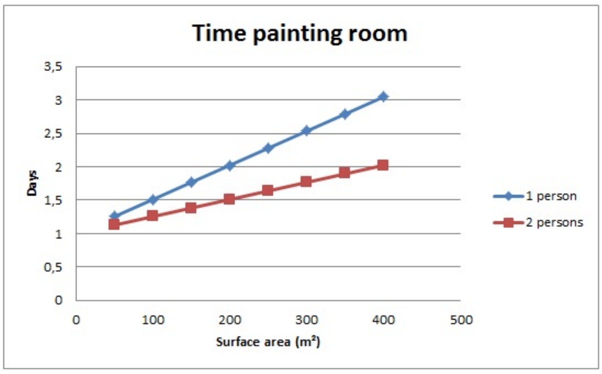


Figure 5.22: Results: Duration of painting room

another room while the other is drying. When the estimated values and the real values are compared, a difference between 0 and 2 days is noted. This difference can be linked to multiple causes. In order to stay within the safety zone a noise factor of 2 days is added when estimating the total duration. It is assumed that the painter is needed during this 'extra time' which might be a consequence of building scaffolding or waiting times.

Nr.	Type	Normal / acco	m2	Days 2 pers	Days 1 pers	Real
Rm 2301	Switchboardroom	Normal	206,78	1,52	2,05	2
Rm 2312	Seperatorroom	Normal	129,97	1,33	1,66	2
Rm 3306	E-workshop	Normal	72,373	1,18	1,37	2
Rm 3209	Crane HPU Room	Normal	162,47	1,41	1,83	4
Rm 3210	Winch room	Normal	162,47	1,41	1,83	4
Rm 5633	Laundry room	Acco	195,49	1,49	1,99	2
Rm 10605	Heli room	Acco	121,76	1,31	1,62	2

Figure 5.23: Validation method duration painting room

$$T_r = \frac{T_{mpr}}{N_p} + 2 * T_d + T_{safety} \quad (5.20)$$

where

T_r = Time required for treatment room (*hours*)

T_{mpr} = Time required for painting room (*man* − *hours*)

N_p = Number of persons working

T_d = Time required for drying (*hours*)

T_{safety} = Time required for unknown events (2*days* = 24*man* − *hours*)

5.9.4 Conservation of tanks

It is assumed that all tanks need to be treated before the launch of the vessel in order to be operational and obtain a good stability condition. Several different tanks can be distinguished and each type does have its own required type of treatments which is shown in Figure 5.24.

At Royal IHC, research has been carried out and minimal, expected and maximum values are obtained for the duration of activities. Figure 5.25 gives an overview. In this research it is assumed that durations for blasting, cleaning and painting (task 1 until 7) depend on the size of the tank. Therefore, using the results from this research at Royal IHC, corresponding productivity parameters are calculated. Durations for closing, repairing and curing is assumed to be constant for each tank. In this research it is assumed that 1 day contains 8 working hours and that the activities are carried out by 1 person.

Type tank: \ Required activity:	Cleaning	Sand blasting	Pressure testing	Painting	Add oil
Waterballast tank	x	x	x	x	
Freshwater tank	x	x	x	x	
(Fuel)oil tank	x		x		x
Sludge tank	x		x		x
Void space	x		x	x	

Figure 5.24: Required treatments activities per type of tank

ID	Task Name	Times (in Days) — Time Distribution: Triangular O (min)	M (most likely)	P (max)
10	Start			
20	Blast			
30	Cleaning			
40	1st Coat			
50	Vent			
60	Stripe Coat			
70	2nd Coat			
80	Vent 2			
90	Measuring			
100	Insp. Scaff.			
110	Scaff. + Pipe			
120	Closing + UT, Visual			
130	Repair			
140	Insp + Vent			
150	Curing			
160	Finish			

Figure 5.25: Results research Royal IHC durations painting tank

Surface

Research has been carried out at Royal IHC to find the relationship between the volume of a tank and the surface of a tank. Within this relationship the possible area of stiffeners within each tank is taken into account. In this research, 4 types of tanks are distinguished. Results are shown in Figure I.2 in Appendix I. The formula below and final parameters shown in Figure 5.26 can be used.

$$S_t = \gamma * x^{\sigma} \tag{5.21}$$

where

S_t = Total surface of tank (m^2)

x = Tank volume (m^3)

γ = Constant value

σ = Constant value

Sand blasting

Several tanks need to be sand blasted before the layers of paint can be applied. The required amount of man-hours for this activity depends on the surface of the tank and the corresponding productivity parameter. At Royal IHC research showed that on average the minimal time for blasting is 2 days, the expected time is 3 days and the

Type:	γ	σ
DB wingtank	13,313	0,8466
DB centertank	10,564	0,8577
Wing side tank	3,665	0,9429
For/aft peak	19,928	0,7251

Figure 5.26: Values for gamma and sigma to calculate tank surface

maximum time is 4 days. Using this information and a minimum tank volume of 50 m^3 and a maximum tank volume of 750 m^3 the productivity parameter is calculated using a linear formula.

$$T_{mst} = S_t * \alpha_s \tag{5.22}$$

where

T_{mst} = Time required for sandblasting a tank (man-hours)

S_t = Tank surface (m^2)

α_s = Parameter sandblasting ($Mnhrs/m^2$)

$$\alpha_s = \omega * V_t + c \tag{5.23}$$

where

α_s = productivity parameter blasting for specific tank type ($Mnhrs/m^2$)

ω_s = Dependency factor of tank volume on productivity

V_t = Tank volume (m^3)

c = constant value ($man - hours$)

	50 m³	750 m³	ω	c
DB wingtank	365	3617	0,00738	21,3063
DB centertank	302	3089	0,00861	21,3993
Wing side tank	147	1884	0,01382	21,9689
For/aft peak tank	339	2422	0,01152	20,0941

Figure 5.27: Values for calculating productivity parameter blasting per tank type

Cleaning

The time and man-hours required for cleaning a tank could be estimated using the formula shown below. Again the productivity parameter for cleaning is calculated using given maximum, minimum and expected durations determined by Royal IHC:

$$T_{mct} = S_t * \alpha_c \tag{5.24}$$

where

T_{mct} = Time required for cleaning tank ($man - hours$)

S_t = Tank surface (m^2)

α_c = Parameter cleaning ($Mnhrs/m^2$)

$$\alpha_s = \omega * V_t + c \tag{5.25}$$

where

α_s = productivity parameter cleaning for specific tank type ($Mnhrs/m^2$)

ω_s = Dependency factor of tank volume on productivity

V_t = Tank volume (m^3)

c = constant value ($man - hours$)

	50 m³	750 m³	ω	c
DB wingtank	365	3617	0,00738	33,31
DB centertank	302	3089	0,00861	33,40
Wing side tank	147	1884	0,01382	33,97
For/aft peak tank	339	2422	0,01152	32,09

Figure 5.28: Values for calculating productivity parameter cleaning per tank type

Pressure testing

To prevent for leakages in all tanks, pressure tests are carried out after sandblasting and cleaning. At Royal IHC, a group of 2 persons is constantly assigned for this activity. Normally a pressure test takes around 3 days independent of the type and size of a tank. Due to the fact that an error might be discovered, IHC planners take 2 days extra time into account while making the planning.

This job can start after sandblasting and cleaning the section and when all hotwork is finished. The man-hours of this activity are not taken into account within the painting discipline due to the fact that this activity is carried out by a special 'pressure testing team'.

Painting or applying oil & drying

Most tanks need to be painted and some need a layer of oil in order to prevent for corrosion. Again the productivity parameter for painting is calculated using given maximum, minimum and expected durations determined by Royal IHC:

$$T_{mpt} = 2 * (S_t * \alpha_p) \tag{5.26}$$

where

T_{mpt} = Time required for painting tank ($man - hours$)

S_r = Tank surface (m^2)

α_p = Parameter painting ($Mnhrs/m^2$)

$$\alpha_s = \omega * V_t + c \tag{5.27}$$

where

α_s = productivity parameter cleaning for specific tank type ($Mnhrs/m^2$)

ω_s = Dependency factor of tank volume on productivity

V_t = Tank volume (m^3)

c = constant value ($man - hours$)

	50 m³	750 m³	ω	c
DB wingtank	365	3617	0,00738	9,31
DB centertank	302	3089	0,00861	9,40
Wing side tank	147	1884	0,01382	9,97
For/aft peak tank	339	2422	0,01152	8,09

Figure 5.29: Values for calculating productivity parameter painting per tank type

$$T_{maot} = (S_t * \alpha_p) \tag{5.28}$$

where

T_{maot} = Time required for oil layer tank (man-hours)

S_r = Tank surface (m^2)

α_p = Parameter applying oil layer using brush, 0,026 ($Mnhrs/m^2$) [6]

Closing, repairing and curing
After painting, tanks need to be closed, repaired when needed and cured. Within this research, the average duration, determined by Royal IHC, is taken into account. Values are shown in Figure 5.25. In total, these final activities take 20 days. The required man-hours for this activity are not taken into account within the painting discipline due to the fact that most of the time no personnel is required.

Validation
Within this part of the research the formula's and values are based on real data obtained after research by Royal IHC. The values obtained within this research are determined in a way that they stay within the boundaries set by Royal IHC. Therefore it is assumed that the outcome is considered acceptable.

5.9.5 Conservation of the hull and accommodation

The hull and accommodation need to be painted before launch. When this activity starts, all hotwork close to the hull and accommodation plating needs to be finished. Due to the fact that 'spray painting method' is used, no other jobs can be carried at the time that the painter is working. Therefore, at Royal IHC the hull is painted during the weekend in 24-hours shifts. This activity is most often scheduled in the last weekends before the launch.

Surface
In order to estimate the duration and required man-hours, again the surface should be calculated. The formulas shown below can be used [19]:

$$S_{hb} = (2T + B) * L_{bp} * P \tag{5.29}$$

where

S_{hb} = Surface of bottom hull including boottop (m^2)

T = Maximum draft (m)

B = Maximum breadth (m)

L_{bp} = Length between perpendiculars (m)

P = 0,70 - 0,75 as would be similar as for 'dry cargo ships'

$$S_{ht} = (3,4 * \nabla^{\frac{1}{3}} + 0,5 * L_{wl}) * \nabla^{\frac{1}{3}} \tag{5.30}$$

where

S_{ht} = Surface of hull topsides (m^2)

∇ = Displacement vessel (m^3)

L_{wl} = Length waterline (m)

$$S_{ac} = H_{ac} * B_{ac} * L_{ac} \tag{5.31}$$

where

S_{ac} = Surface of the accomodation (m^2)

H_{ac} = Maximum height of the accomodation (m)

B_{ac} = Maximum Breadth of the accomodation (m)

L_{ac} = Maximum Length of the accomodation (m)

Cleaning

For cleaning the surface the formula shown below is used:

$$T_{mch} = (S_{hb} + S_{ht}) * \alpha_c \tag{5.32}$$

where

T_{mch} = Time required for cleaning hull (man-hours)

S_{hb} = Surface of bottom hull including boottop (m^2)

S_{ht} = Surface of hull topsides (m^2)

Painting & drying

At the bottom of the vessel under the waterline, 5 layers of paint should be applied and above the waterline 3 layers should be applied. At the end of the pre-outfit phase, the sections containing bottom plating already got all their required layers of paint. Therefore, the sum of the surface area of the double bottom plating of all double bottom sections should be subtracted. In order to calculate the required amount of man-hours per part of the hull the following formula can be used.

$$T_{mphp} = (S_{hp_{net}} * \alpha_p) + (N * S_{hp_{new}} * \beta_p) \tag{5.33}$$

where

T_{mphp} = Time painting specific part of the hull (man-hours)

$S_{hp_{new}}$ = Surface part of hull (m^2)

α_p = Parameter painting first coat (Mnhrs/m^2)

α_p = 0,0024 ($Mnhrs/m^2$) [6]

N = Number of extra coats

β_p = Parameter painting extra coat, 0,0016 ($Mnhrs/m^2$) [6]

5.9.6 Conservation of deck

Preferably, the painter paints the deck before the launch of the vessel due to possible bad weather after launch which might delay the activity. At the deck, 2 layers of paint are applied using a 'roller'. It is preferred to install as much as possible equipment and components on the deck before painting but most often after painting the deck, still some need to be installed. After the installation specific areas are painted again.

Surface
In order to estimate the duration and required man-hours, again the surface should be calculated. The formulas shown below can be used :

$$S_d = L_{oa} * B * N \text{ [19]} \tag{5.34}$$

where

S_d = Surface of weatherdecks including upper top of deck houses (m^2)
L_{oa} = Length over all (m^2)
B = Maximum Breadth (m^2)
N = 0,88 as would be similar as used for 'cargo vessels'

Cleaning
For cleaning the surface the formula shown below is used:

$$T_{mcd} = S_d * \alpha_c \tag{5.35}$$

where

T_{mcd} = Time required for cleaning deck (man-hours)
S_d = Surface of bottom hull including boottop (m^2)
α_c = Parameter cleaning, 0,0010 ($Mnhrs/m^2$) [9]

Painting & drying
After cleaning, 2 layers op paint have to be applied. A drying time of 6 hours will be taken into account. For cleaning the surface the formula shown below is used:

$$T_{mpd} = (S_d * \alpha_p * 2) \tag{5.36}$$

where

T_{mpd} = Time painting deck (man-hours)
S_d = Surface deck (m^2)
α_{p1} = Parameter painting first coat, 0,0036 (Mnhrs/m^2)

5.10 Parameters and constraints within the outfitting process - Scaffolding

5.10.1 Introduction

During the production process of a vessel, scaffolding is used to reach certain locations in a safe way. Various activities are carried out at a certain height that exceeds the maximum reachable height of a worker. In these situations scaffolding sections are built on which a worker can stand while carrying out the task. In this chapter, the development of a method for the estimation of the required amount of scaffolding and the corresponding man-hours will be discussed.

5.10.2 Research method

According to safety rules, a worker is not allowed to work at a height greater than 2 meters without protection. At locations with a height exceeding this limit, scaffolding might be used. Especially when the duration of the activity is relatively long, scaffolding is preferred.

In order to estimate the required amount of man-hours for the erection and dismantling of the scaffolding, the following steps are taken:

Step 1: The required amount of scaffolding is determined.

Step 2: Using the amount of scaffolding and specific parameters found in literature, the total required man-hours are estimated.

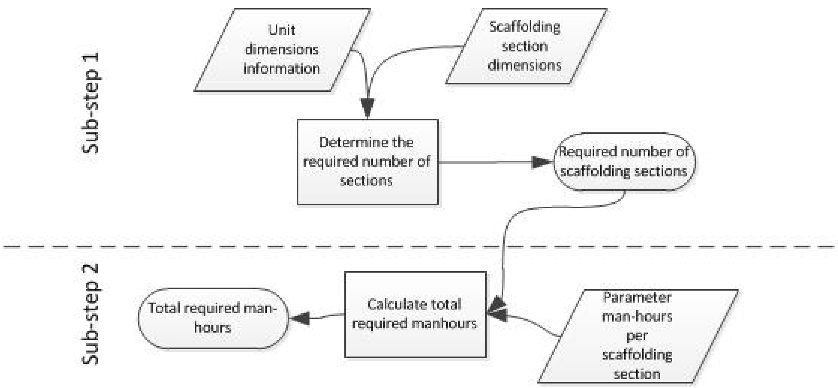


Figure 5.30: Flowchart research structure

5.10.3 Research results

Step 1

Scaffolding is built in standard sections with a length of 2,13 meters, a width of 1,52 meter and a height of 1,52 meter [6]. The amount of scaffolding sections depends on the type of work, the location and the environment. It is assumed that these characteristics for each activity are known. Depending on the dimensions of the section, room, tank or other unit, the amount of required scaffolding sections can be calculated. In chapter **??** it is shown per activity whether scaffolding might be used or not.

Step 2

When the amount of scaffolding sections is known, the required amount of man-hours for erecting and dismantling the sections is estimated. The total amount of man-hours are calculated separately for erection and dismantling using productivity parameters. These parameters depend on the length and height of the scaffolding needed. When more scaffolding is built relatively less time is required for transportation. However, when scaffolding is built at a height exceeding 2 meters, relatively more time is required. The values are shown in Figure 5.31 below.

Length	Manhours required per section					
	1 or 2 section high			More than 2 section high		
	Erect	Dismantle	Total	Erect	Dismantle	Total
1 to 2 sections long	1,4	1	2,4	1,7	1,2	2,9
3 to 5 sections long	0,9	0,6	1,5	1	0,7	1,7
6 sections & more long	0,7	0,4	1,1	0,9	0,5	1,4

Figure 5.31: Manhours required for erecting and dismanteling scaffolding [6]

5.10.4 Conclusions

Within this chapter the required man-hours for the erection and dismantling of scaffolding activities is determined. The methods found are applied in the *Planning Generator*. In the next part of the research the application of scaffolding is further discussed.

5.11 Model design: The Activity Loader

Introduction

After obtaining all required information for the estimation of outfit activities, a model was built in Microsoft Excel using Visual Basics. The main function of the *Activity Loader* is the translation from basic vessel, section, room, tank and equipment information using the conceptual estimation models found within this chapter, into lists of outfit activities. These activities will contain most important information such as required man-hours and start- and end-constraints.

It is assumed that the *Activity Loader* will be used in an early phase of the design process. Therefore only limited design information is available for the user. The following materials are required when using this model:

- Main vessel specifications
- Section plan
- First draft of general arrangement

The time to fill in the input sheets depends on the complexity and size of the vessel. It takes not more than 1 day to fill in this model for a 150 m pipe laying vessel. Running the model itself takes roughly 1 minute. The final output, containing activity lists is finally transported to the *Planning Generator*. This model uses the activity lists and other input information to generate a planning of the production scenario.

Within this chapter the design of the model is discussed in more detail. The flowchart in Figure 5.32 gives an overview of the required input of the model, the output and the steps that should be taken to get to the output. In Appendix K an overview is given of the programmed code.

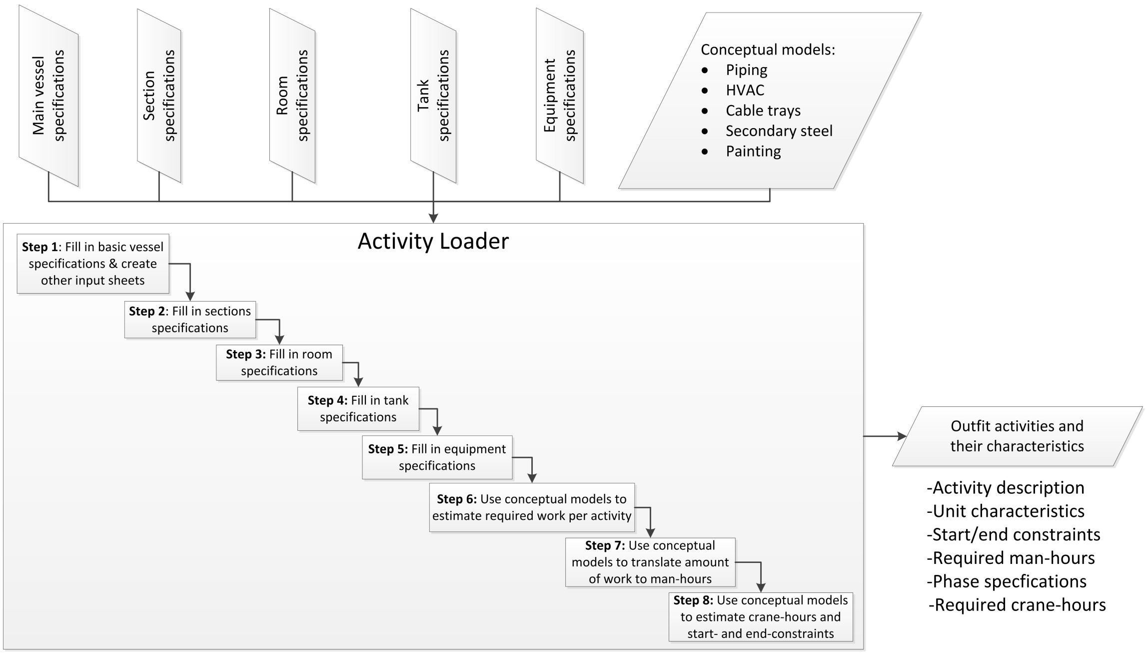


Figure 5.32: Flowchart structure *Activity Loader*

Input

Two different types of input are required in the *Activity Loader*: vessel characteristics and conceptual estimation models of the disciplines taken into account within this research.

Vessel characteristics
Vessel, section, room, tank and equipment specifications are required. Table 5.1 below presents the required types of information.

Conceptual models
All conceptual estimation models found in the first part of this research have been implemented in the model. The models are able to estimate the amount of work and man-hours in a specific unit using the specifications of that unit defined in the first input.

Working mechanism

Step 1: Define vessel specifications
At first, the user should define the main vessel specifications. These values are used by the model as input for the conceptual estimation models but also to generate input lists for sections, rooms, tanks and equipment. An example of this input sheet is shown in Figure K.1 in Appendix K.

Step 2: Define section specifications
The user defines in the second step all sections of the vessel. In this input sheet fields are present where most important section characteristics can be defined. The model automatically determines the section type when the user selects various location options of a section. An example of this input sheets is shown in Figure K.2 in Appendix K

Input type	Required information
Vessel specifications	Vessel type Vessel dimensions Installed power Crew capacity Number of sections, rooms and tanks Amount of equipment per type
Section specifications	Section number Section type Section coordinates Section weight
Room specifications	Room number Room type Room coordinates
Tank specifications	Tank description / number Tank location Tank volume Rooms touching tank
Equipment specifications	Type / description equipment component Required man-hours for installation Required crane-hours during installation Phase-constraints Corresponding rooms

Table 5.1: Required input information vessel characteristics

Step 3: Define room specifications
In the third step, the user defines all rooms present in the vessel. This input sheet is similar to the section input sheets and contains input fields for most important room characteristics. The type of room is automatically determined by the model using selected location information. An example of this input sheets is shown in Figure K.3 in Appendix K.

Step 4: Define tank specifications
The user needs to define each tank within the fourth step. This input sheets is automatically prepared for the amount of tanks defined in the first vessel specification sheet where the number of tanks per type was defined. In this step most important characteristics of each tank are required as well as the rooms touching a specific tank. Finally this 'tank-room link' is used within the *Planning Generator* to determine the date that the conservation of the tank can start. A picture of this input sheet is shown in Figure K.4 in Appendix K.

Step 5: Define equipment specifications
The information defined in the vessel characteristic input sheet (step 1) about the equipment and general components present is used for the automatic creation of an equipment input sheet. Main equipment such as the main engines, switchboards, gearboxes or (bow) thrusters can be defined. Also a list for 'other equipment' is present to define other components. This information is used to generate installation activities of the equipment. No conceptual estimation model is created to generate man-hour and constraint information of this discipline. Therefore extended input information is required. In Figure K.5 in Appendix K a picture is shown of this input sheet.

Step 6: Use conceptual models to estimate the amount of work in the sections and tanks
The *Activity Loader* automatically determines the required amount of outfit work for the sections, tanks and ship parts, using the knowledge of the conceptual estimation models, after the user inserted all required information. The required amount of work in a room depends on the amount of work that is already carried out in the pre-outfit phase in the corresponding section(s). The *Planning Generator* estimates the amount of work in a room using the

pre-outfit and slipway pre-outfit percentage and the sections belonging to a room. In this sixth step, activity lists are obtained for sections, rooms, tanks and ship parts.

Step 7: Use conceptual models to translate the amount of work to man-hours for sections, tanks and ship parts
The conceptual models are again used to translate the required amount of work per activity, obtained in the previous step, to the required amount of man-hours.

Step 8: Use conceptual models to estimate the required amount of crane-hours and start- and end-constraints for each activity
Using the conceptual models the expected required crane-hours for each activity are estimated. In this step also specific start- and end-constraints for each activity are determined.

Step 9: Export output to *Planning Generator*
The activity lists are finally exported to the *Planning Generator* that uses the lists to generate an outfit planning.

Output

After inserting all required information in each input sheet, the activity model generates the outfit activities. This information is finally exported to the *Planning Generator*.

Those activities contain the following information:

- Activity ID
- Activity description
- Unit (section, room, tank or ship parts)
- Unit number
- Unit type
- Unit coordinates
- Outfit discipline
- Total work to be carried out in man-hours for 100% POF
- Start constraint of activity
- End constraint of activity
- (For some activities: Duration)
- Corresponding outfit phase
- Total required crane hours for 100% POF
- (For tanks: Rooms 'touching' tank)

Model verification

For 10 random sections the final output is checked in order to verify the correctness of the programmed software. It is considered that the software gives a feasible picture of the output of the conceptual estimation models.

6 | Research Part 2: *Generation of planning*

6.1 Introduction

This research tried to find possible ways to improve the controllability of the outfit process by organizing the process in a specific way while the main performance may not decrease. Conceptual models are obtained in the first part of this research that predict outfit activities and their characteristics. In the second part, this information is used to research how the production process should be planned and how the resources should be organized in order to obtain controllability improvements.

The activities are used including three other types of input to create a production planning. Finally Key Performance Indicators (KPI's) measure for each production scenario the level of different types of controllability and the performance of the outfit processes.

Within this chapter, different types of controllability are discussed as well as the performance of the process. Finally, also the model is discussed in more detail including the KPI's and figures.

6.2 Controllability

The outfitting processes are characterized by low level planning and poor organization [1]. Many interferences, disturbances and other unexpected events occur which leads to delays, waiting times, rework and eventually higher costs. A process that is more controllable will have less unexpected events and a higher ability to handle these events and is therefore less vulnerable for delays, waiting times and rework.

One of the possible unexpected events that occur within the outfitting processes is an unexpected increase in the amount of work at a specific moment. The team of workers that is responsible for the corresponding outfit activities has no capacity left to carry out the required jobs and delays or waiting times are inevitable. In order to avoid this situation, the amount of outfit work at each time is estimated for each discipline. It is assumed that the amount of unexpected events will decrease when the required amount of man-hours over time is leveled.

Another event that affects the controllability of the outfit process is a collision between two activities within the same area and which are scheduled to be carried out at the same time. When such an event occurs, delays, waiting times and possibly rework might be the consequence. It is assumed that the chance at a collisions between two activities decreases when the activity density at a specific moment in time decreases as well.

Last event taken into account within this research that affects the controllability of the outfitting process is the occurrence of too little facility capacity at a specific moment in time. Multiple facilities are used within the production process such as cranes or production areas but all have a limited capacity. In order to avoid delays and waiting times, the chance at an exceeding capacity demand should be reduced. It is assumed that the controllability will increase when the outfit processes are organized in such a way that the expected amount of exceeding required capacity decreases.

In the second part of the research the following subjects are measured for each production scenario in order to determine the expected controllability of the outfit processes.

- Personnel levelling
- Unit occupancy
- Crane occupancy
- Floor occupancy

6.3 Performance

The performance of the outfit processes is determined by the amount of man-hours required to carry out all outfit activities in a specific production scenario compared to the required amount of man-hours in the current production scenario at Royal IHC. The less man-hours required, the higher the performance. The performance can be measured for one specific discipline but also for all disciplines together.

As discussed in chapter 2.2.2 about pre-outfitting , it costs on average less time to carry out a job in the pre-outfit or slipway pre-outfit phase mostly due to a higher accessibility. Therefore, a higher POF percentage results generally in less required man-hours and a higher performance.

It might happen that a small decrease in the performance of an outfit process results in a significant increase of the controllability. An increase in controllability means less unexpected events and less (extra) costs. The performance is affected by the controllability and should therefore always be judged in combination with the corresponding controllability.

In this part of the research, the performance of each specific outfit discipline is taken into account but also the overall performance of all disciplines together.

6.4 Model design: The Planning Generator

6.4.1 Introduction

The *Planning Generator* uses the output of the *Activity Generator*, consisting of all outfit activities, and additional process information to generate a planning of a specific production scenario. After a 30 minute run on a simple laptop, the model presents the output of the model, where after the production scenario can be judged and possible improvements can be noticed.

A more detailed description of the model design of the *Planning Generator* is given in this chapter after a main description was given of the model requirements in chapter 4. A flowchart in Figure 6.1 below gives an overview of the input and the output of the model and the required steps that should be taken to get to the output. In Appendix L an overview is shown of the programmed code.

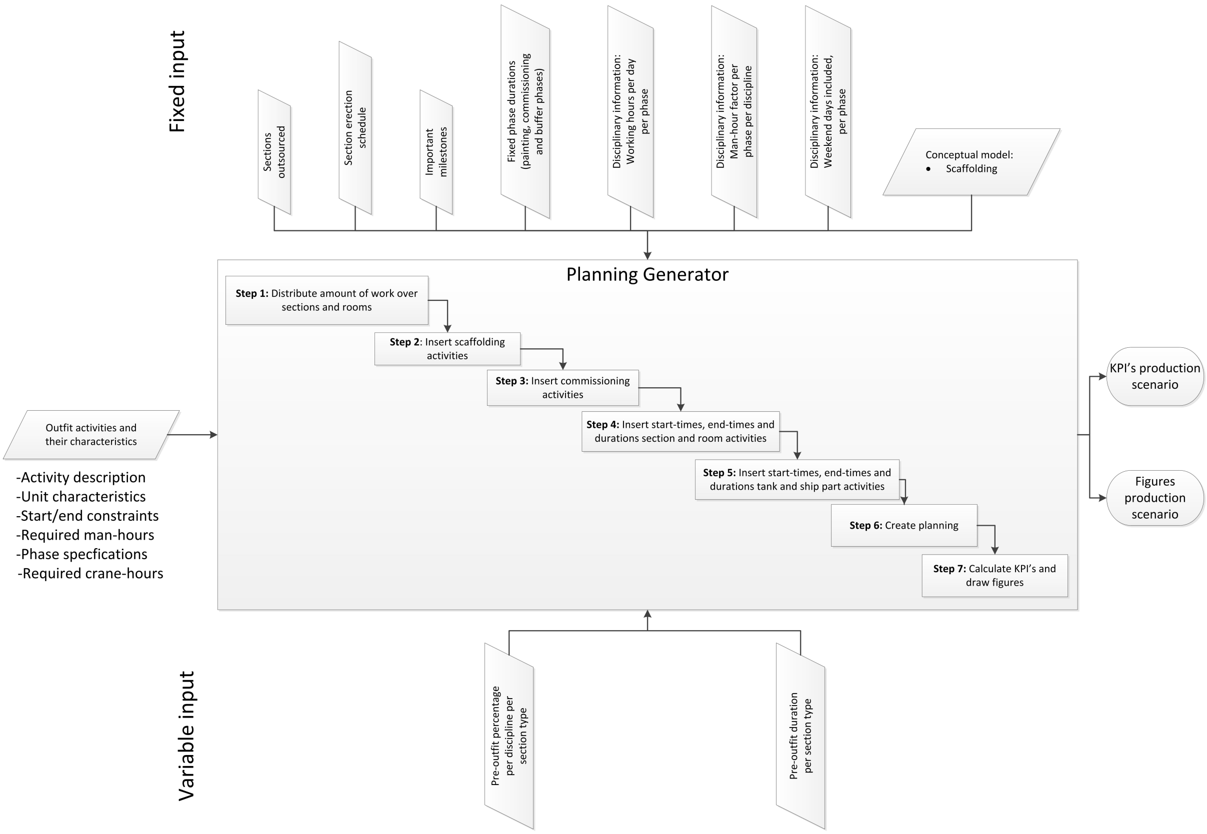


Figure 6.1: Flowchart structure *Planning Generator*

6.4.2 Input

Two different types of input are distinguished: Fixed and variable input. The fixed input considers input information that will not change while improving the outfit process within this research. Variable input considers input information that can be adjusted before the start of each run of the model in order to find any improvements in the production scenario of a vessel concerning its outfit process.

Fixed input: Outfit activity list
Activity lists of outfit activities in sections, rooms, tanks and specific ship-parts are exported from the *Activity Loader* into the *Planning Generator*.

Fixed input: Sections outsourced
Not all sections are built and pre-outfitting at the shipyard. On average around 60% of the sections are outsourced to other locations according to production data of Royal IHC. This influences the production process significantly and is therefore taken into account within the *Planning Generator*. The outsourced sections are included for several process characteristics, such as the workload of a subcontractor, while for other characteristics, such as floor occupancy or crane occupancy, the sections are excluded. This will be discussed in chapter 6.4.4.

Fixed input: Section erection schedule
The section erection schedule is considered 'leading' in the ship production process in order to optimize the occupancy of the slipway [20]. This schedule determines the day that a section is positioned on the slipway and when it is welded to the other sections. This forms the basis of the production planning and therefore effects the start and end date of other outfit phases.

Fixed input: Important milestones
In the contract phase, the yard discusses most important milestones with the client, such as keel laying, the launch of the vessel, the sea trails and the delivery [20]. The occupancy of the yard and the requirements of the client influence the chosen dates for these milestones and are therefore not automatically generated by the *Planning Generator*. The end or start date of many (outfit) activities depend on those milestones. Therefore a specific input page is made for the definition of the dates of those events in the *Planning Generator*.

Fixed input: Specific phase durations
The final production planning consist of several phases. Figure 2.2 in Chapter 2.2 gave a general overview of all possible phases. The *Planning Generator* uses the phases shown in Figure 6.2 and Table 6.1 for the distribution of all activities.

Figure 6.2: Overview outfit phases used by the *Planning Generator*

Phase:	Start constraint	End constraint	Initial duration
Pre-outfit	Free	Start painting section	10 days
Painting section	Free	Start buffer	4-6 days
Buffer	Free	Start section erection	15 days
Slipway pre-outfit	Milestone start section erection	Milestone finish section erection	n.a.
Outfit phase	Finish section erection	Start first commissioning phase	n.a.
Commissioning phase 1	Milestone commissioning	None, depends on duration	5 days
Painting room	End commissioning 1	Depends on duration	5 days
Commissioning phase 2	End painting room	Dependent milestone	To be calculated
Sea trails	Milestone date	Milestone date	n.a.

Table 6.1: Specifications outfit phases used by the *Planning Generator*

Most phase durations are automatically calculated by the *Planning Generator* in step 4 but for several phases the duration is assumed to be constant and their duration is used as input. It concerns the following phases:

- Buffer phase
- First commissioning phase
- Room conservation phase
- Second commissioning phase

Fixed input: Disciplinary information
Three types of disciplinary information are required in order to generate a production scenario:

- Working hours per day, per outfit phase for each discipline
- Weekend days included or not, per phase for each discipline
- Man-hour factors, per phase for each discipline

For each discipline the number of work hours per day per outfit phase are defined in order to translate the number of man-hours to required amount of workers per day within a discipline. This amount differs at Royal IHC per project and depends on the workload at that time. Table 6.2 below presents expected average values estimated by experts opinion.

Sometimes several disciplines, such as 'painting' also work during the weekend in specific phases. Therefore it is defined in the *Planning Generator* whether a subcontractor is working during the weekend in a specific outfit phase or not.

Discipline:	Hours/day - POF	Hours/day - SWPO	Hours/day - OF	Work weekend?
Piping	-	-	-	No
HVAC	-	-	-	No
Cable trays	-	-	-	No
Secondary steel	-	-	-	No
Section conservation	-	n.a.	n.a.	No
Room conservation	n.a.	n.a.	-	No
Tank and ship part conservation	n.a.	n.a.	-	Yes
Scaffolding	-	n.a.	8	No

Table 6.2: Working hours per day, per phase for each discipline used by the *Planning Generator*

For most components, the required installation time differs per outfit phase due to a difference in accessibility and other circumstances [1]. The factor that multiplies the required amount of man-hours for the installation of that component in a specific phase depends on the component characteristics and on the phase. Due to the fact that no detailed information is available within the *Planning Generator* on 'component-level', average factors are used for each discipline with which the initial amount of man-hours for the installation of all components of that unit in the pre-outfit phase are multiplied. These are chosen according to production information and expert opinion at Royal IHC. Table 6.3 below shows the initial values used.

Discipline	POF phase	SWPO phase	OF phase
Mount piping - Piping	-	-	-
Mount ducting	-	-	-
Mount piping - HVAC	-	-	-
Mount equipment	-	-	-
Mount cable trays	-	-	-
Install secondary steel	-	-	-
Paint sections	-	-	-
Paint rooms	-	-	-
Paint tanks	-	-	-
Paint hull	-	-	-
Paint accommodation	-	-	-
Paint deck	-	-	-

Table 6.3: Man-hour factor per phase for each discipline used by the *Planning Generator*

Fixed input: Conceptual model - Scaffolding
A conceptual model is built in order to determine the amount of man-hours required for the erection and dismantling of scaffolding sections in a specific unit (chapter 5.10). The information and knowledge of this conceptual model is used as input information in order to calculate the amount of work and corresponding man-hours.

At Royal IHC, scaffolding is required when a work-location can not be reached. This height-limit is set at 2 meters. For each section and room type it can be selected within the *Planning Generator* whether scaffolding is either never required or required when the section or room is higher than 2 meters. During this research it is assumed that sections exceeding a height of 2 meters need scaffolding during the POF process and rooms exceeding a height of 2 meters require scaffolding sections during the outfit phase.

Variable input: Percentage of work per outfit phase
The relative amount of work carried out in each outfit phase can differ per phase and per discipline. A specific discipline might for example carry out 80% of all required work in the pre-outfit phase while another discipline carries out only 30% of all the outfit work. This percentage can vary for each section type as well.

For each run, new percentages can be selected per discipline, per phase and per section type in order to improve the outfit process. Varying the amount of work per section type and discipline affects the workload over time but also other process characteristics such as the amount of persons in a section or the required crane usage at a specific moment. It is assumed that the initial amount of work carried out in the SWPO-phase does not change due to the fact that very specific components are most often installed within this phase and can not be installed in another phase, due to vulnerability and accessibility problems.

The *Planning Generator* consists of a specific input sheet for the relative amount of work per phase. An example of this sheet is shown in Figure L.1 in Appendix L. At Royal IHC, these percentages differ per project and per discipline. However, production data and expert opinion provided averages according to the current situation which are shown in Table 6.4 below.

Discipline	POF phase	SWPO phase	OF phase
Piping	-%	-%	-%
HVAC (ducting)	-%	-%	-%
HVAC (piping)	-%	-%	-%
HVAC (equipment)	-%	-%	-%
Cable trays	-%	-%	-%
Secondary steel	-%	-%	-%
Painting	-%	-%	-%
Scaffolding	-%	-%	-%

Table 6.4: Estimated average percentages of work carried out in each phase in current situation

Variable input: Duration pre-outfit phase
The initial duration of the pre-outfit phase of each section is 2 weeks or 10 working days. However, this value can be adjusted before each run of the *Planning Generator* in order to find improvements of the controllability within the outfit processes. Sections with only a little amount of outfit work might not need the entire 3 weeks on their POF-location while other sections with many outfit components might need even more time in order to install the components without changing the POF percentage.

In the *Planning Generator* this duration can vary and can be selected for each section type.

6.4.3 Working mechanism

Step 1: Distribution amount of work over sections and rooms
The export of the Activity Loader consists of lists of section outfit activities, room outfit activities, tank outfit activities and ship part outfit activities. The section outfit activities include the total amount of work that should be carried out in that section while the room activities do not include this information. When a specific components is not installed during the POF- or SWPO-phase, it should be installed during the outfit phase in a specific room. That means that the amount of outfit work that should be carried out in a certain room, depends on the amount that is already carried out in the corresponding sections during the previous phases. A method is required to determine which rooms belong to which sections.

In order to assign work to a specific room, a section-room link is used. This method uses the x,y and z coordinates of the sections and rooms to determine whether a room or section belong together. Both sections and rooms are modelled as rectangular blocks. The percentage of volume of the cubic of the section which is covered by the cubic of the room is calculated. When there is an overlap of their corresponding volume, it is considered that there is a link between that section and room. The amount of work that should be transported from the section to that room is calculated using the relative amount of overlap of that room compared to other rooms that have overlap with that section. The formula below is used to give an example of the calculation of the percentage of components that should be assigned to a specific room when 2 rooms are included within that section:

	Erection (section)	Dismantling (Section)	Erection (room)	Dismantling (room)
Start constraint	Start POF	n.a.	Room closed	n.a.
End constraints	n.a.	End POF	n.a.	End painting room
Duration	1 day	1 day	1 day	1 day

Table 6.5: Specifications scaffolding activities

$$N_{r1} = \frac{V_{r1}}{\sum_{i=1}^{n} V_{rn}} \tag{6.1}$$

where

N_{r1} = percentage of components in section belonging to specific room 1

V_{r1} = Volume of room 1 covered by section

V_{rn} = Sum of volumes of all rooms covered by section

The *Planning Generator* automatically calculates the amount of work that needs to be carried out in the outfit phase in each room for all activities using the outfit percentages per phase and section-room link described above.

Step 2: Insert scaffolding activities

In the second step, scaffolding activities are generated for all sections and rooms that require scaffolding. Within this research, the constraint is fixed and all sections and room with a height exceeding 2 meters are considered to require scaffolding. The assumed characteristics of the erection and scaffolding activities are shown in Table 6.5 below.

The *Planning Generator* automatically generates the scaffolding activities including their characteristics. The start date, end date and durations of these activities are inserted in step 4 using the constraints set in this step.

Step 3: Insert commissioning activities

Normally commissioning is carried out on 'system-level'. Because it is not known where all specific components of a system are located in a vessel it is difficult to estimate in which rooms specific system components can be found. Therefore, the commissioning phase is simplified in the *Planning Generator* and is based on 'room-level'. It is assumed that each room does have 2 commissioning phases. In the first phase the last mechanical work is carried out such as the connection of systems or pipes that are flushed and pressure tested. In the second commissioning phase, the systems are started and tested.

It is assumed that the duration of the first commissioning phase of systems in a room is constant. This duration is on average 5 days according to expert opinion. The first commissioning phase should be finished when the conservation phase of the room starts.

After the conservation of a room, systems in that room can be started and tested. Although commissioning activities are normally carried out on 'system-level' the *Planning Generator* simplifies the approach and bases those activities again on 'room-level'. The finish date of the second commissioning phase depends on a milestone that is set for each specific room type. An overview of these milestones for each room type is shown in Figure L.2 in Appendix L. In order to determine the duration of this phase, a special mechanism is implemented which takes the levelling of the painting schedule into account. The end date of the commissioning of multiple rooms might depend on the same milestone, such as 'ship launch', 'start main engines', or 'start sea trails'. Because the end date of the room conservation phase depends on the start date of the second commissioning phase, many room conservation activities might be scheduled at the same time when a constant duration would be used for the second commissioning phase. Therefore, for each type of milestone, the duration of the second commissioning phases is varied in order to level the workload of the conservation department. The *Planning Generator* automatically gives rooms that were closed earlier a longer duration for starting up and testing their systems in order to equal the outfit phase durations. It is assumed that a difference of 1 day between the end date of the painting phases of different rooms would be sufficient to level the workload of the conservation department.

In this step, the two commissioning activities including the two commissioning phases are generated for each room using the characteristics shown in Table 6.1. In the next step, the constraints are translated to start and end dates.

Step 4: Insert start dates, end dates and durations of section, room and ship part activities

In the fourth step, the start dates, the end dates and durations are defined for all section, room and ship part activities. Figure 6.3 below explains the method applied by the *Planning Generator* in this step to find the start dates, end dates and durations of all activities using their characteristics and constraints shown in Table 6.1 .

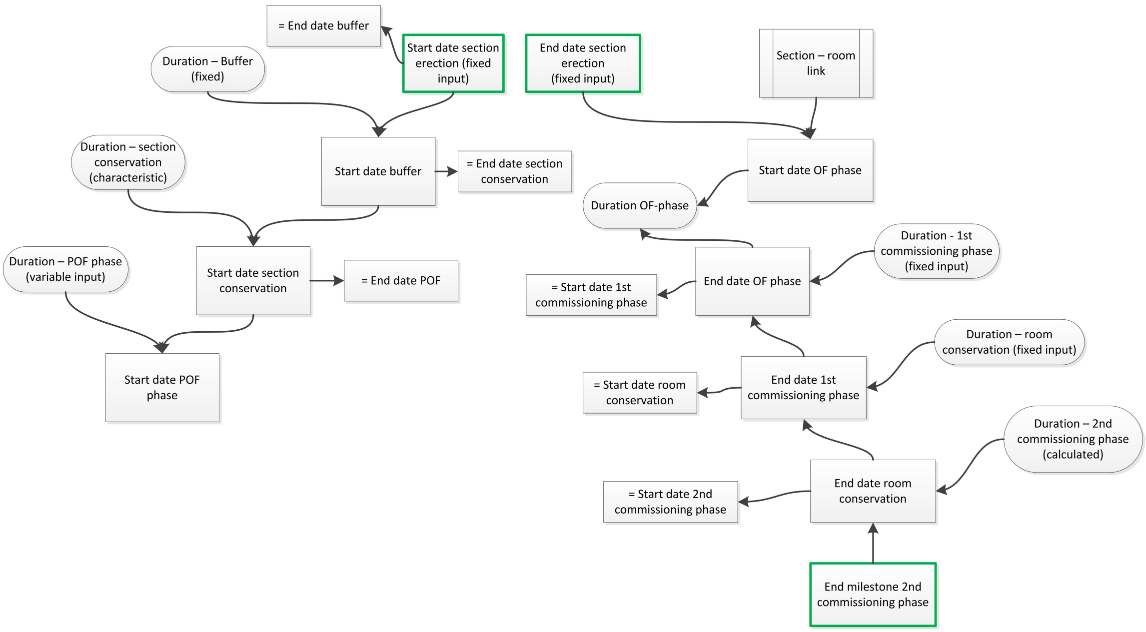


Figure 6.3: Method applied by the *Planning Generator* to find start dates, end dates and durations

The start date of the section erection, the end date of the section erection and the final 'end milestone' of the second commissioning phase are used by the *Planning Generator* as starting point to find the required start and end dates and durations of all other phases.

The duration of the conservation of a section depends on the required amount of painting work and is therefore a characteristic of the activity. The total duration was calculated by the *Activity Loader*.

The section-room link is used for the calculation of the closing date of a room. A room is considered 'closed' when the erection of all its corresponding sections is finished. The section-room link determines which sections belong to a specific room by checking the overlapping volumes using the section and room coordinates. The end date of the section erection shows the date at which a section is welded to the other sections on the slipway. The maximum end date of the erection of the sections belonging to a room, is the date that that room is considered closed. This is the start date of the outfit phase of a room.

Step 5: Insert start dates, end dates and durations of tank and ship part activities

In the fifth step, the *Planning Generator* determines at first the start date of the conservation of each tank. Painting of a tank can only start when all hot work activities within the rooms 'touching' this tank are finished. The output of the *Activity Loader* showed for each tank which rooms where touching that tank. Using the maximum end date of the outfit period of those rooms, the start date of painting the tank is determined. Finally, the *Planning Generator* determines the end date of the tank conservation using the start date and the duration which was calculated by the *Activity Loader* and was given as an activity characteristic.

The ship part activities include the conservation of the hull, the accommodation and the deck of the vessel. According to production data of Royal IHC, the conservation department starts with painting the hull, accommodation and deck on average 8 weeks before the launch of the vessel. The *Planning Generator* uses this as an assumption and determines the start date of those activities. The end date is determined by the launch of the vessel.

Step 6: The creation of a planning
After applying the first 5 steps, all activities are generated and prepared to be implemented in a planning. The *Planning Generator* lists the section, room, tank and ship parts activities and calculates for each day within the production process the required amount of persons per day for each activity. The formula shown below is used:

$$N = \frac{H_m}{W * D} \tag{6.2}$$

where

$N =$ Expected amount of persons working on the activity per day

$H_m =$ Total amount of required man-hours for the activity

$W =$ Working hours of discipline per day

$D =$ Duration of activity

Step 7: Calculation of KPI's and draw figures
The *Planning Generator* creates different output sheets in which several different process characteristics are calculated. The activities are listed in each sheet and different characteristics are measured per sheet. KPI's are calculated and figures are drawn using this output. Finally, all interesting outfit process characteristic values are presented in an overview. Another output overview contains charts presenting the behavior of most important outfit process characteristics over time.

6.4.4 Output

In order to make a judgment about the controllability and performance of the total outfitting processes different process characteristics should be checked and judged. For each discipline the controllability and performance is checked and due to the high level of interdependency between the different parties also the interdisciplinary controllability and performance is taken into account. Disciplines meet each other in section and rooms, but also when they have to use cranes. Information is subtracted from the output about the following subjects:

- Performance per discipline
- Resource leveling per discipline
- Unit occupancy (sections, rooms and tanks)
- Crane occupancy (POF-hall)
- Floor occupancy (POF-hall and conservation hall)

In order to judge the controllability in the subjects shown above, specific KPI's were required. Several planners of Royal IHC have been interviewed to find KPI's that are meaningful are useful when measuring and judging a production scenario. During the interviews, different scenarios have been presented where after the planners had to explain how their method of judging works. For each subject indicators are chosen and discussed below.

Performance
The *Planning Generator* calculates for each discipline the total required amount of man-hours, also known as the performance. Within this research the performance depends only on the chosen POF percentage due to the fact that the total amount of work in a project does not change and the required amount of man-hours depends on the phases in which the work is carried out.

Each subcontractor would like to choose the scenario with the lowest required amount of man-hours which results most often in the lowest expected costs. However, the controllability should always be taken into account while a low controllability can lead to disturbances and unexpected events during the production process that lead again to higher costs. For a planner, it might be a trade off whether to choose for a good performance or for a good controllability. The conclusions of this research will give the planner extra knowledge to make this decision while judging a production scenario.

The calculation of the performance KPI is shown below. The higher the value of this KPI, the better.

$$KPI_P = \frac{M_c}{M_n} \tag{6.3}$$

where

KPI_P = The expected performance of a discipline
M_c = Total amount of expected man-hours in current production scenario
M_n = Total amount of expected man-hours in new scenario

Resource leveling
The controllability of the outfit process decreases when not enough workforce is available for the required amount of work. In this situation, a subcontractor should reschedule jobs what results in delays and waiting times. The *Planning Generator* calculates for each day during the production process, the required amount of man-hours per discipline where after most important characteristics could be research. Outsourced sections are included due to the fact that a subcontractor also supplies workforce at the corresponding external locations.

Subcontractors most often change the capacity of their workforce during a project at some specific moments. During busy periods, such as the POF period more people are required compared to more quiet periods such as the end of the outfit phase. Within this research it is assumed that a subcontractor changes the size of his team during the launch of the vessel. When a vessel leaves the slipway and is moored on the quayside, the production of another vessel can start on the slipway where a new team is required. Therefore, most often a subcontractor reduced the size of the team working on the project in order to be able to supply the new vessel with enough workforce.

For each discipline the behavior of the required workload is checked using figures. An example is shown in Figure 6.4 below. The blue-colored bars in the chart present the total amount of man-hours required that day in the POF phase. The red-colored bars present the total amount of man-hours required that day in the SWPO-phase and the red-color bars present the man-hours in the outfit phase.

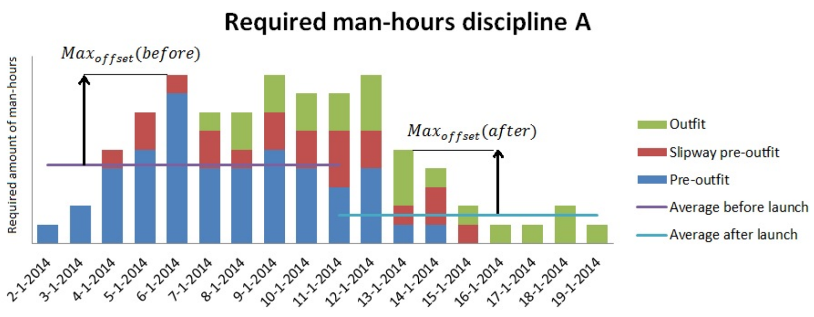


Figure 6.4: Output example - required man-hours for a specific discipline

It is assumed that the controllability of the outfitting process increases when less fluctuations within a period where the team size does not change, are noticed. In a situation where the required amount of man-hours exceeds the initial capacity, delays and waiting times might be the consequence. When judging the controllability while taking a look at the resource curve, the fluctuation of the required man-hours compared to a constant capacity is most often taken into account. Within the model, the fluctuation of the required man-hours is measured compared to the average required man-hours. Due to the changing workforce after the launch of the vessel, this average is calculated before and after the launch separately.

The following values are presented after each run for all disciplines :

- Total amount of man-hours entire project
- Total amount of man-hours POF phase
- Total amount of man-hours SWPO phase
- Total amount of man-hours outfit phase
- Average amount of man-hours required before launch
- Average amount of man-hours required after launch
- Maximum offset before launch
- Maximum offset after launch
- Standard deviation of man-hours before launch
- Standard deviation of man-hours after launch

In order to make a judgment about the required workforce over time, a planner would be interested in the relative amount of time that the required amount of man-hours is expected to be above the capacity. Small offsets are easy to handle by making overtime for a specific period or moving some workers from one job to the other. A large offset is more difficult to handle. No extra capacity is available and a subcontractor is forced to hire extra personnel. Especially short time fluctuations with large offsets are undesirable while hiring extra personnel would be impossible for such a short period of time. According to the dutch regulation a worker is allowed to work not more than 12 hours a day [21]. A subcontractor is therefore able to handle short time fluctuations with a maximum offset of 50% using the current team size. Also periods with overcapacity are undesirable where more personnel is available than necessary which has a negative effect on the efficiency. Concluding, the more constant the behavior of the required amount of man-hours, the higher the controllability within the workforce of a certain discipline.

The standard deviation of the workload is used as KPI in order to measure and judge the fluctuations. In the method of the standard deviation, large offsets have relatively a large effect on the value compared to smaller offsets due to the quadratic formula. In order to compare the value of the KPI before launch and after launch, the standard deviation is normalized by dividing it by the average. The final formula is shown below to calculate the corresponding KPI before the launch and after the launch. The lower the value of the KPI, the better.

$$KPI_{Rs}b = \frac{St.dev_b}{AVG_b} \tag{6.4}$$

where

$KPI_{Rs}b$ = KPI standard deviation resource workload

$St.dev_b$ = Standard deviation before launch

AVG_b = Average required resources before launch

$$KPI_{Rs}a = \frac{St.dev_a}{AVG_a} \tag{6.5}$$

where

$KPI_{Rs}a$ = KPI standard deviation resource workload

$St.dev_a$ = Standard deviation after launch

AVG_a = Average required resources after launch

In practice, every production scenario consist of resource fluctuations. For a planner it is interesting when judging a scenario what the largest offset or most uncontrollable period is. The KPI shown below is used in order to measure the magnitude of the maximum offset. Again, this KPI is calculates before the launch and after the launch. The lower the value of the KPI, the better.

$$KPI_{Ro}b = \frac{Max_b}{AVG_b} \quad (6.6)$$

where

$KPI_{Ro}b$ = KPI maximum offset required resources
Max_b = Maximum required resources before launch
AVG_b = Average required resources before launch

$$KPI_{Ro}a = \frac{Max_a}{AVG_a} \quad (6.7)$$

where

$KPI_{Ro}a$ = KPI maximum offset required resources
Max_a = Maximum required resources after launch
AVG_a = Average required resources after launch

Both KPI's are used to determine the controllability of each production scenario. Several possible combinations are discussed below:

	Large standard deviation	**Small standard deviation**
Large maximum offset	It can be concluded that there are many undesirable large fluctuations.	The largest offset is most likely the only one or one of the few undesirable fluctuations present in that scenario. However, during this period of under capacity more people are required to carry out all the work. When the offset period is long, a subcontractor can hire extra personnel. When this period is short, no extra personnel will be available and delays and waiting times are the result.
Small maximum offset	The production scenario most likely consist of longer periods with a significant offset. During those periods, a subcontractor can hire extra personnel in order to maintain a high level of controllability.	This describes a desirable scenario. The offsets are small and it is expected that the required resources will not fluctuate much around the average. A controllable workload is expected within this scenario.

Table 6.6: Overview different resource level options

Unit occupancy

Another aspect that influences the controllability of the outfit process is the amount of people working in a specific area. Sometimes multiple installation activities have to be carried out at the same location. Delays, rework or waiting times occur when different disciplines planned to carry out this activity at the same time. The *Planning Generator* determines the expected 'personnel density' within a unit in order to estimate the chance on such collisions. In order to improve the controllability of the outfit processes it is a challenge to organize the process in a way, by changing specific process characteristics such as POF percentages or POF phase durations so that the unit occupancy exceeds its limit as little as possible.

For each section, room and tank the density of the amount of persons working in that unit is determined. In this method the statistical chance is taken into account that a person of a specific discipline works in that unit that day. The formula shown below is used. It should be noted that the amount of persons working in a section here is most often a non-integer value.

$$N_p = \frac{Mnhrs_{total}}{Workhours_{day} * N_{days} * V_{unit}} \tag{6.8}$$

where

N_p = Total persons working in unit of that specific discipline (on average)

$Mnhrs_{total}$ = Total amount of man-hours for that activity

$Workhours_{day}$ = Amount of workhours per day for that discipline and phase

N_{days} = Number of days that the activity is carried out

V_{unit} = Volume of unit

It is assumed that the controllability of the outfit process is not in danger when the personnel density stays below a certain limit. A planner would therefore only be interested in the periods that this density exceeds the limit. According to Wei (2012), a distance in all directions of at least 2,5 meters should be available for a worker in order to carry out the job without problems caused by other jobs in that area [8]. Assuming an average deck height of 3 meters, this limit is calculated to be 0,053 persons per m^3. This value is used within this research as primary limit.

In the output scenario of the *Planning Generator* a simplification is made and the required amount of personnel is equally divided over the entire duration of an activity. However, a subcontractor most often carries out an activity within a shorter period of time with more people which leads to an increasing density. Therefore, the average amount of people within a section is multiplied by 10 and 20 to measure the effect on the controllability. These factors represent the level of concentration of personnel used by a subcontractor for an activity that needs to be carried out in a certain period. For the factor '0' the amount of working hours are equally spread over the entire period and for the higher factors '10' and '20' the subcontractor concentrates his team more at specific jobs for only a short period of time. Finally, the expected percentage of working hours exceeding the density limit is calculated for the 3 factors. It is not known what level of concentration the subcontractors use and therefore the obtained values can only be used in order to compare different outfit scenarios with each other. When a specific scenario shows a lower expected percentage of exceeding working hours, less collisions between activities are expected which increases the controllability.

A sensitivity analysis is carried out in order to determine the sensitivity of the factors chosen. The percentage of working hours within a unit that exceed the density does not have to be linear with the chosen limit. When the density in most units is most often around a specific value, the percentage exceeding that value might increase significantly when the limit is chosen just below this value. A sensitivity analysis will view this behavior.

The One-At-A-Time (OAT) method is used where a sensitivity ranking can be obtained quickly by increasing each parameter by a given percentage while leaving all others constant, and quantifying the change in the output of the model [22]. With a maximum concentration level factor of 20, a factor range between 0 and 20 is chosen for the analysis. The results are shown below in Figure 6.5.

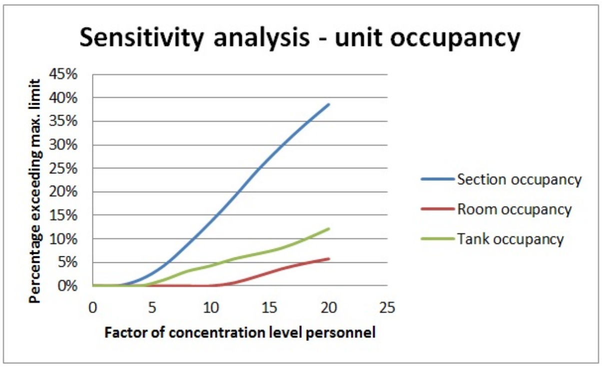


Figure 6.5: Results sensitivity analysis - unit occupancy

The results show that the sensitivity is more or less linear with the level of concentration used by the subcontractor. The figure also shows that below a level of concentration with factor '4' the personnel density in the sections is not expected to lead to collisions between activities. The personnel density in the rooms and tanks is not expected to lead to problems when the factor of the level of concentration stays below 12 and 6 in the current situation.

The following KPI is used to determine the relative amount of working hours in a unit that the density limit is exceeded. It is separately calculated for sections, rooms and tanks using their corresponding volume. The lower the value of the KPI, the better.

$$KPI_U = \frac{W_e}{W_t} \tag{6.9}$$

where

KPI_U = KPI unit occupancy: Percentage of workhours exceeding the personnel density limit

W_e = Total amount of workhours exceeding the limit during the production process for the specific unittype

W_t = Total amount of workhours during the production process within this unit type

It should be noted that the unit occupancy of rooms does not present a feasible value due to the fact that many activities that have to be carried out in the rooms during outfit phase are not included in this research. This is taken into account when drawing the final conclusions.

Crane occupancy

When the required amount of crane usage exceeds the crane capacity, specific activities can not be carried out. This results in delays and waiting times and it is therefore assumed that the crane occupancy has a significant effect on the controllability of the outfit processes.

The *Planning Generator* calculates the amount of required crane hours for each day during the production process. Within this research, only the cranes in the POF-hall are taken into account because insufficient data and time was available to determine all activities that require crane usage on the slipway. It is assumed that the outfit disciplines piping, HVAC and secondary steel require crane assistance during the installation of specific components.

At Royal IHC 6 cranes are available in the POF-hall. According to the opinion of several experts within the production at Royal IHC, the cranes are used on average 90% of the time by the section fabrication department. Assuming working days of 8 hours, 6 cranes and a crane availability of 10%, the total crane capacity for the outfit process is 4,8 crane hours per day.

For a planner it would be interesting to know the expected relative amount of exceeding crane hours for a specific scenario. This value corresponds to the expected controllability of the outfit process concerning the possible waiting times for cranes. While improving the controllability of the outfit process, it is a challenge to choose specific process characteristics such as pre-outfit percentages or pre-outfit phase duration in such a way that the required crane hours exceed the crane capacity limit as little as possible. The KPI shown below is used. The lower the value of the KPI, the better.

$$KPI_C = \frac{C_e}{C_t} \tag{6.10}$$

where

KPI_C = KPI crane occupancy: The expected percentage of crane usage exceeding the available crane capacity

C_e = Total amount of crane hours exceeding the limit during the production process

C_t = Total amount of crane hours during the production process

Floor occupancy

Most shipyard have limited area to store sections during the pre-outfit period. At Royal IHC only 14 sections can be stored in the POF-hall. At those locations, the sections are fabricated and pre-outfitted before they are transported to the conservation hall. The maximum section capacity of the hall should be taken into account during the generation of a planning of a possible production scenario.

The section fabrication in the POF hall is also taken into account while this influences the occupancy of this facility. At Royal IHC, production planners can make a feasible estimation in an early phase of the process about the duration of the fabrication of the section. It is recommended to implement this knowledge also in the *Planning Generator*. Within this research, the actual real duration for the fabrication of each specific section is used by the *Planning Generator*. The model takes this extra occupancy into account when calculating the floor occupancy in the POF Hall.

The *Planning Generator* is able to vary the duration of the POF phase of each section. It might happen that a change of this duration leads to an exceedance of the floor occupancy capacity. Therefore the model monitors at each days the amount of sections located in the POF-hall. It is a challenge to improve the outfit processes by changing process characteristics without exceeding this capacity limit.

For a planner it is interesting to see the percentage of floor occupancy exceeding the maximum limit. The amount of 'section days' in the POF-hall exceeding the limit are compared to the total amount of section days. A section day is defined as 1 day that a section is positioned in the POF-hall. The KPI's shown below are used. The lower the value of the KPI's, the better.

$$KPI_{FP} = \frac{F_e}{F_t} \tag{6.11}$$

where

$KPI_{FP} =$ The expected percentage of floor occupancy in the POF hall exceeding the available floor capacity

$F_e =$ Total amount of section days exceeding the limit during the production process

$F_t =$ Total amount of section days during the production process

$$KPI_{FC} = \frac{F_e}{F_t} \tag{6.12}$$

where

$KPI_{FC} =$ The expected percentage of floor occupancy in the section conservation hall exceeding the available floor capacity

$F_e =$ Total amount of section days exceeding the limit during the production process

$F_t =$ Total amount of section days during the production process

6.4.5 Model verification

After the creation of the *Planning Generator*, the programmed software needed to be verified and checked for possible errors. Several techniques are applied to determine the correctness of the model.

After the first run of the model the operational graphics are checked and evaluated using the different colors in the charts for different production phases.

Secondly, extreme condition tests have been performed. In order to check the models accuracy for large values of input, highest and lowest possible pre-outfit percentages have been set as well as pre-outfit phase durations.

Finally also face validity is used of project planners who gave their opinion about the production scenario output.

7 | Case study - Results and discussion

7.1 Introduction

In this chapter a case study is carried out in order to answer the main research question about the possibilities of improving the controllability of the outfit processes while maintaining the current performance of the process. In this case study the outfit processes within the production of pipe laying vessel "Sapura Onix" with yardnumber 730 are taken into account. Both models, the *Activity Loader* and the *Planning Generator* are used to determine the different activities within the processes and to find the most controllable production scenario. All possible scenarios are compared to the current scenario and the different behaviors of all types of controllability taken into account are analyzed and discussed.

Finally, the effect of changing the section erection schedule on the choice for 'best scenario' is researched. Afterwards, a certainty analysis is carried out for the results found within the case study taking all uncertainties into account throughout this research.

7.2 AS-IS situation

Currently, the outfit processes are characterized by low level planning and poor organization where the workload of the subcontractors and the interdisciplinary dependencies are most often not taken into account. Many unexpected events occur during the processes such as waiting times, delays and rework. This leads to even more delays, longer lead times and eventually higher costs. It is most often written in the contract between the yard and the subcontractor what POF percentage they can use during a specific project. However, this percentage is most often not based on thorough research. Also the POF phase duration used by the planners is not sufficiently researched in advance.

7.3 Improvement steps

The case study consists of 4 different improvement steps which are shown below:

Improvement step 1: Optimize workload controllability by varying the POF percentage per type of section

Improvement step 2: Optimize interdisciplinary controllability by varying the POF percentage per type of section

Improvement step 3: Optimize workload & interdisciplinary controllability by varying the POF phase duration per type of section

Improvement step 4: Use the results to find final improved outfit scenario

7.4 Section type analysis

The POF percentage and POF phase duration as input of the *Planning Generator* is varied for each section type for multiple production scenarios during the improvement process. All sections are divided into 3 main groups in order to reduce the amount of possible scenarios. Besides that it would also be confusing for production personnel to work with different process characteristics for each section type. With 3 possible different POF percentages and POF durations it is assumed that less mistakes are made during the production compared to a production scenario with 26 different POF percentages and POF durations. The section data of pipe laying vessel with Ynr 730 is used to determine the best distribution over the 3 groups of section types because this vessel is also used in this improvement process.

The following section characteristics are taken into account in order to divide the 26 different section types over 3 groups of sections:

- Total amount of outfit hours per section
- Location of the sections in the vessel
- 'Typical distribution' of components throughout the vessel

Finally the following distribution is chosen:
A-type sections: All double bottom mid-ship sections (excluding the moonpool section).
B-type sections: Other sections (Not A-type or C-type sections).
C-type sections: All sections in the fore-ship above the double bottom and mid-ship side sections

	Group: A-type	Group: B-type	Group: C-type
Section type numbers	1,3	2,4,6,7,10-13,20-26	5,8,9,14-19
Amount of sections	14	54	36
Average amount of outfit hours	190	524	801
Pipe spools present	Yes	Yes	Yes
HVAC components present	No	Yes	Yes
Cable trays present	No	Yes	Yes
Secondary steel components present	Yes	Yes	Yes

Table 7.1: Specifications groups of section types used during improvement process

7.5 Step 1: Varying pre-outfit percentage - Resource workload improvement

7.5.1 Method of approach

Introduction

The effect of varying POF percentages per group of section type on the controllability and performance of the outfit processes is researched within the first part of the improvement process. The AS-IS situations for the piping, HVAC, cable tray and secondary steel disciplines are first researched and discussed. Afterwards, the POF percentage for the 3 groups of section types is varied between 30%, 45%, 60%, 75% and 90% obtaining 125 different possible outfit scenarios. Each scenario is judged using the corresponding KPI's and human opinion in order to find possible ways to improve the controllability.

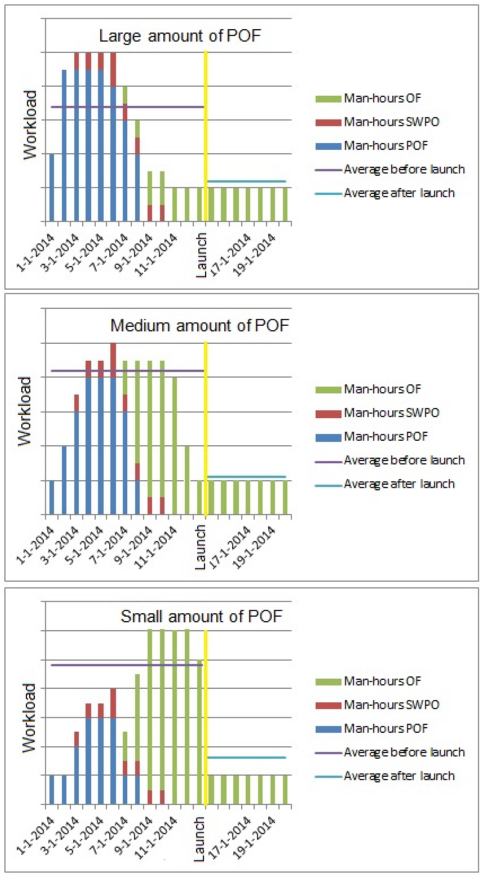


Figure 7.1: Example negative influence assumption moment of change team size

Dependency moment of changing team size

A subcontractor is able to change the size of his team during the production. The more often a team size can change the better it will fit to the required workload over time. Within this research a simplification is made and it is assumed that a subcontractor changes his team size only once at the launch of the vessel. The output of this first improvement step showed the large effect of this assumption on the KPI values obtain for a specific scenario.

A similar team size will be used during the POF period and during the start of the outfit phases in the rooms in a production scenario with one team size from the start of the production until the launch of the vessel. When a subcontractor decides to use a high POF percentage, a relatively low amount of work needs to be carried out during the first part of the outfit process in the rooms which leads to over-capacity during this period. The *Planning Generator* notifies this over-capacity as a constant offset which leads to a higher standard deviation. It would be recommended in this scenario to change the team size when the POF phase of all sections is finished. However, the *Planning Generator* always uses the assumption that the team size is changed after the launch which has a negative effect on the KPI values for a scenario with maximum POF percentages. For high POF percentages (90%), early team size changes are preferred, for medium POF percentages (60%) a team size change before the launch is preferred and for low POF percentages (30%) again an early team size change is preferred due to under-capacity after the POF period. Examples are shown in Figure 7.1.

The best moment of changing the size of a team differs per discipline and is therefore discussed in the analysis of the improved scenarios. The analysis shows that it is important to use human opinions while judging the workload over time besides the KPI's calculated by the *Planning Generator*.

It is highly recommended to do research for the best moment in time that a subcontractor changes the size of the team. A mechanism can be implemented in the *Planning Generator* that determines those best moments in time taking specific constraints into account such as 'maximal amount of team size changes' and 'minimum duration of using a team size'. Also other KPI's can be used to avoid the necessity to implement the moment of changing the size of a team. This will be discussed in chapter 9.

7.5.2 Resource leveling - Piping discipline

AS-IS scenario

Figure 7.2 presents the workload of the piping discipline over time in the current situation at Royal IHC where in all sections 60% of the work is carried out in the POF phases. Also the distribution of the number of sections per type in the POF period and the rooms in their outfit phase is shown. The amount of sections in the SWPO-phase is not shown here, due to the fact that the corresponding amount of work in the SWPO phase can not change.

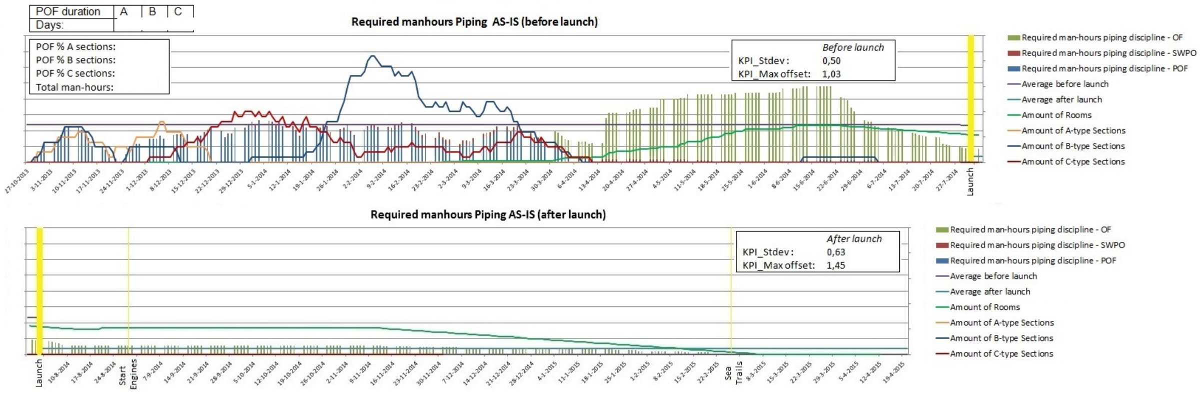


Figure 7.2: Workload piping discipline in current situation at Royal IHC during production Ynr 730

In order to improve the workload controllability in the piping discipline, it is assumed that a change of team size after the launch of the vessel can be taken into account because piping subcontractors currently use POF percentage of 60% on average. Therefore it is assumed that also the KPI values calculated by the *Planning Generator* present a feasible judgment of each scenario.

-before launch

The workload during the POF process, shown by the blue bars, does not show large fluctuations. The largest offset during the POF period is located around November 24 2013 during a period of over-capacity. A larger offset in the period before the launch of the vessel is noted during the start of the outfit phases. During this period all pipe spools are installed in rooms that have their second commissioning deadline at the launch of the vessel or at the start of the engines.

With an average of x required before launch, a standard deviation KPI of 0,50 shows that 68% of the fluctuations will stay below a maximum offset of x man-hours. The maximum offset KPI of 1,03 shows that the maximum expected offset before the launch is currently x man-hours. According to the dutch regulations [21] an employee is allowed to work not more than 12 hours a day. Using normal working days of 8 hours, 50% of extra required man-hours can be covered by the current workforce. With the average of 118 man-hours not even half of the x exceeding required man-hours can be covered by the current team. Therefore it is recommended to organize the process in such a way that this maximum expected offset decreases.

In order to improve the controllability of the workload of the piping discipline and assuming a change in team size after the launch of the vessel, the workload at the start of the POF phase should increase while the workload in the period at the start of the outfit process in the rooms should decrease. In order to increase the workload at the start of the POF period without effecting the workload at other moments in time, the amount of work in the A-type sections should increase. No C-type sections are laying in the POF hall during this period and when more work in the B-type sections would be carried out, peak workloads are expected at the end of the POF period when many B-type sections are pre-outfitted. In order to decrease the peak workload at the start of the outfit period of the rooms, more work should be shifted towards the POF period to the corresponding sections. The rooms of which the commissioning activities should be finished before the launch of the vessel or the start of the main engines are located at various parts of the vessel and are therefore linked to all sections types. Most of those rooms are located in the fore ship (C-type sections) but increasing their corresponding POF percentage will lead to higher workload peaks during the POF phase and will decrease to controllability during this period.

It is expected that an increase of the POF percentage of the A-type sections will lead to smaller workload peaks and therefore less uncontrollable fluctuations of the required amount of man-hours during the production process before the launch of the vessel.

-after launch

The average required man-hours significantly decreases after the launch of the vessel to x man-hours per day and it is expected that the subcontractor will decrease the team size at the start of this period. The average duration of offsets within this period is much longer and the offsets are significantly smaller. These circumstances give the subcontractor the ability to organize his team size in such a way that the process is more controllable.

The standard deviation KPI after the launch of 0,63 and with an average of x man-hours per day it is expected that 68% of the fluctuations will stay below a maximum offset of x man-hours per day. With 8 hour working days the maximum fluctuations will be less than 1 required person per day. The maximum offset KPI after launch shows that the maximum expected offset is 1,45 times the average which is equal to x man-hours. The maximum capacity that a team, working x man-hours a day, can handle during over-time is x hours. Still x extra man-hours are required during this period which is similar to 2 persons. It is assumed that this will not be a problem and that a subcontractor can solve this problem by shifting personnel from 1 job to the other or increases the team size when the offset last for a longer period of time. Also considering the long term offset and low amount of fluctuations within a certain period the controllability after launch is considered sufficient.

Improved scenario

The POF percentage is varied for the 3 groups of section types between 30%, 45%, 60%, 75% and 90%. An output is obtained for 125 different scenarios and is shown in Figure **??** in Appendix M.

The workload controllability after the launch of the vessel in the AS-IS situation was already considered sufficient. The output of all production scenarios calculated by the *Planning Generator* shows only little fluctuation in the controllability KPI's for this period after the launch. Therefore, main focus is only required on the workload controllability before the launch.

A higher POF percentage for A-type sections (90%), the current POF percentage for B-type sections (60%) and a slightly higher percentage for C-type sections (75%) give better controllability results as was already expected. A best value for the standard deviation and maximum offset KPI show that the workload fluctuates less and the maximum expected offset is minimized. The corresponding workload and KPI's are shown in Figure 7.3.

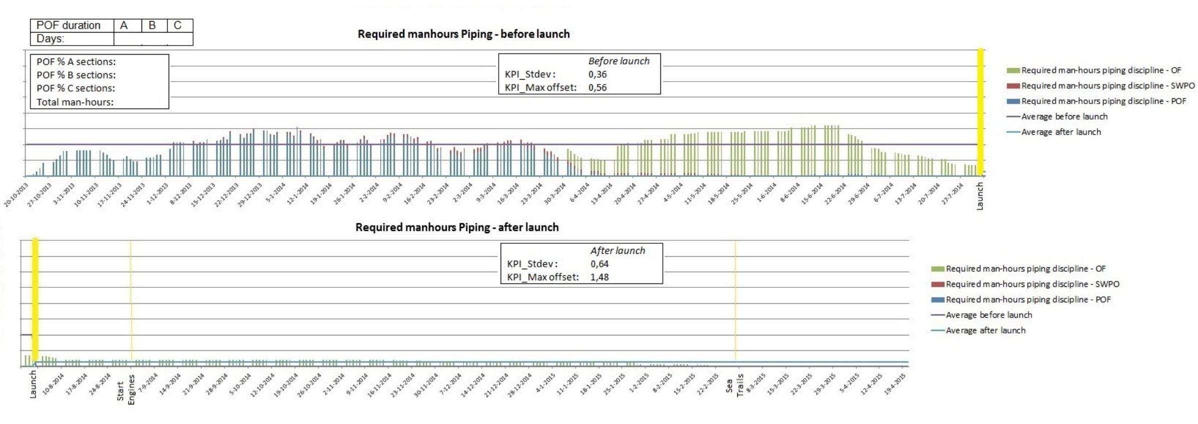


Figure 7.3: Workload piping discipline in improved situation (90% - 60% - 75%)

The standard deviation KPI before the launch of 0,36 and the average of x man-hours per day show that it is expected that 68% of the fluctuations stay below a maximum workload offset of x man-hours per day instead of 30. The maximum offset KPI of 0,56 shows that the maximum expected offset is expected to decrease from x to x man-hours per day. Also the performance improves and a reduction in man-hours of 16% can be realized.

The '90/60/75' scenario is not the only scenario that shows improvement. The controllability and performance improves for several other POF percentage combinations as well. Two other scenarios are also taken into account in the next run when the interdisciplinary effects are researched. One scenario, '75/60/75', has a smaller performance improvement compared to the best scenario but has more or less equal controllability values. The other scenario, '90/90/60' shows a higher performance improvement compared to the best scenario but has a slightly higher offset during the period before launch. The corresponding KPI's are shown in Table 7.2 below.

Scenario	*KPI_P*	*KPI_Rsbef*	*KPI_Rsaft*	*KPI_Robef*	*KPI_Roaft*
AS-IS	1	0,50	0,63	1,03	1,45
90/60/75	1,16	0,36	0,64	0,56	1,48
75/60/75	1,15	0,37	0,64	0,61	1,48
90/90/60	1,27	0,38	0,61	0,70	1,42

Table 7.2: Optional scenarios workload piping with improved performance and controllability

7.5.3 Resource leveling - HVAC discipline

AS-IS
Figure 7.4 presents the workload of the HVAC discipline over time in the current situation at Royal IHC during the production of Ynr 730. In this scenario 60% of the pipe spools and ducts are installed in the POF phases and all HVAC equipment is installed in the rooms during the outfit phase. It should be noticed that the A-type sections (double bottom midship sections) do not contain HVAC components.

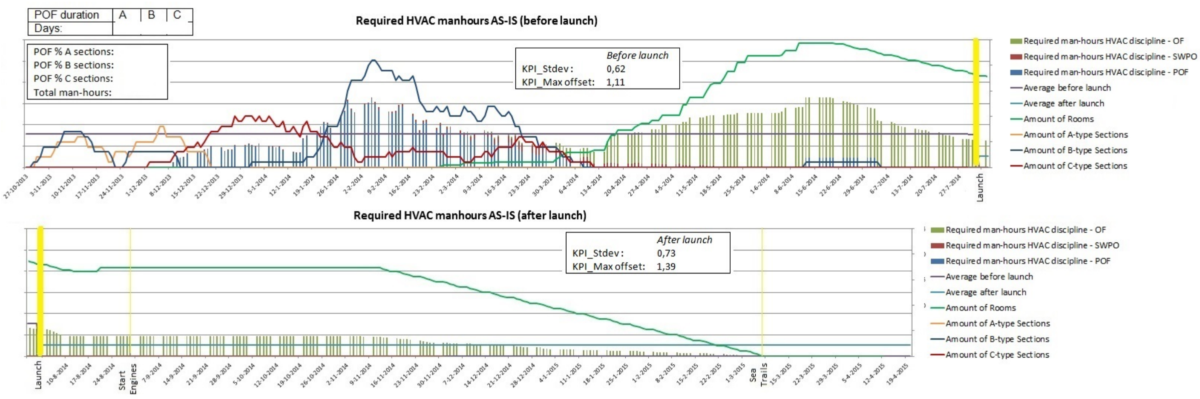


Figure 7.4: Workload HVAC discipline in current situation at Royal IHC during production Ynr 730

In order to improve the workload controllability in the HVAC discipline, a change of the team size after the launch can be taken into account because POF percentages of 60% on average are currently used by the HVAC subcontractors. Therefore it is assumed that also the KPI values calculated by the *Planning Generator* present a feasible judgment of each scenario.

-before launch
With an average of x required man-hours before the launch of the vessel, a standard deviation KPI of 0,62 shows that it is expected that 68% of the fluctuations will stay below a maximum offset of x man-hours per day. The maximum offset KPI of 1,11 shows that the maximum expected offset before the launch is x man-hours. Using normal working days of 8 hours, 50% of extra required man-hours can be covered by the standard team working extra hours. With the average of x man-hours not even half of the exceeding required man-hours can be covered by

the current team. Therefore it is recommended to organize the process in such a way that this maximum expected offset decreases.

Within the period before the launch of the vessel, 3 important fluctuations are noticed. At the start of the POF period there is over-capacity for a significant period mainly due to the fact that no HVAC components are present in the A-type sections. The second important offset is located in the middle of the POF period and is a cause of the high amount of B-type sections, containing many HVAC components, in the POF-hall around that time. The third important offset before the launch of the vessel is noticed at the start of the outfit period of the rooms. During this period all HVAC components that should be commissioned before the launch of the vessel or the start of the engines are installed.

The workload at the start of the production should increase in order to improve the controllability of the workload of the HVAC discipline assuming a change in team size after the launch of the vessel. The amount of work carried out during the POF period in the B-type sections should decrease in order to decrease the offset peak in that period. The peak at the start of the outfit period of the rooms is expected to decrease when more work is carried out in the POF period in general. Therefore, it is recommended to increase especially the amount of work during the POF period in the C-type sections.

-after launch

The average required man-hours decreases after the launch of the vessel to x man-hours per day and it is assumed that the subcontractor will decrease the team size at the start of this period. The average offset duration within this period is significantly longer and the offsets are smaller. These circumstances give the subcontractor the ability to organize his team size in such a way that the process is more controllable.

The standard deviation KPI after the launch of the vessel and the average of x man-hours per day show that it is expected that 68% of the fluctuations will stay below a maximum offset of x man-hours per day. With 8 hour working days the maximum fluctuations will be less than 2 required persons per day. The maximum KPI after launch shows that the maximum expected offset is 1,39 times the average at that time which is equal to x man-hours. The maximum capacity that a team, working x man-hours a day, can handle during over-time is x hours. Still x extra man-hours are required during this period which is similar to 1,5 person. It is assumed that this will not be a problem and that a subcontractor can solve this problem by shifting personnel from 1 job to the other. Also considering the long term offset and low amount of fluctuations within a certain period the controllability after launch is considered sufficient.

Improved

Because only the B-type and C-type sections contain HVAC components, only their POF percentage is varied between 30%, 45%, 60%, 75% and 90%. These percentages include the amount of installation work of HVAC-piping and HVAC-ducting in the POF phases while the HVAC-equipment is assumed to be always installed in the rooms during the outfit phase. An output is obtained for 125 different scenarios of which the corresponding results are shown in Figure **??** in Appendix M.

The workload controllability after the launch of the vessel in the AS-IS situation was already considered sufficient. The output of all production scenarios calculated by the *Planning Generator* shows only little fluctuation in the controllability KPI's for this period after the launch. Therefore, it is assumed that the focus is only required on the workload controllability before the launch.

As expected, lower POF percentages for the B-type sections (45%) and higher POF percentages for the C-type sections (90%) present the highest increase in controllability with an equal performance of the workload of the HVAC discipline. The corresponding workload is shown in Figure 7.5.

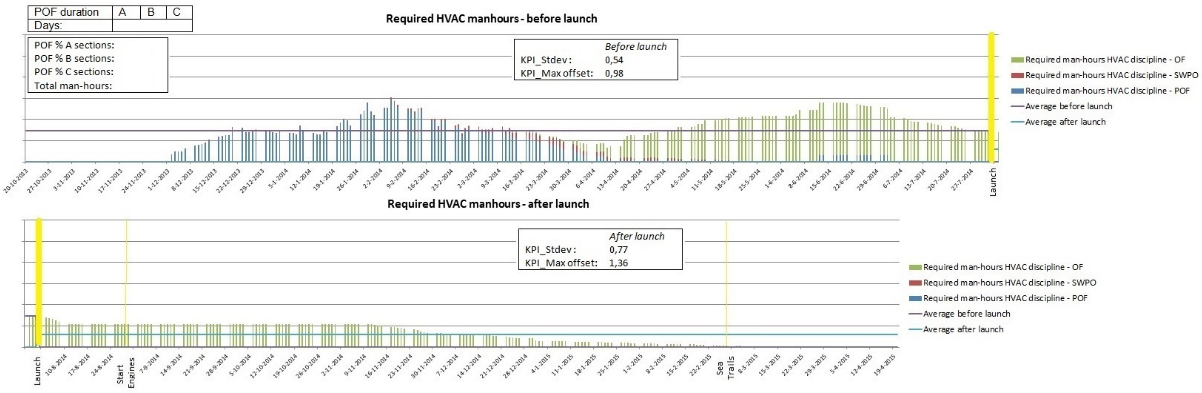


Figure 7.5: Workload HVAC discipline in improved situation (n.a. - 45% - 90%)

The standard deviation KPI before the launch of 0,54 and the average of x man-hours per day show that it is expected that 68% of the fluctuations will stay below a maximum limit of x man-hours instead of x. The maximum offset KPI of 0,98 shows that the maximum expected offset will decrease from x to x man-hours per day.

For the next improvement step where the interdisciplinary dependencies are researched, a scenario where the B-type sections have a POF percentage of 60% is also taken into account. This scenario shows a higher performance and less fluctuations before the launch of the vessel. An overview of the 2 scenarios that will be taken into account in the next improvement step is shown in Table 7.3.

Scenario	KPI_P	KPI_Rsbef	KPI_Rsaft	KPI_Robef	KPI_Roaft
AS-IS	1	0,62	0,73	1,11	1,39
n.a./45/90	1	0,54	0,77	0,98	1,36
n.a./60/90	1,05	0,58	0,75	1,36	1,39

Table 7.3: Optional scenarios workload HVAC with performance and controllability values

7.5.4 Resource leveling - Cable tray discipline

AS-IS
The current workload of the cable tray discipline at Royal IHC where currently for each section 90% of the work is carried out in the POF phases is shown in Figure 7.6. It should be noticed that the A-type sections (double bottom mid-ship sections) do not contain cable trays.

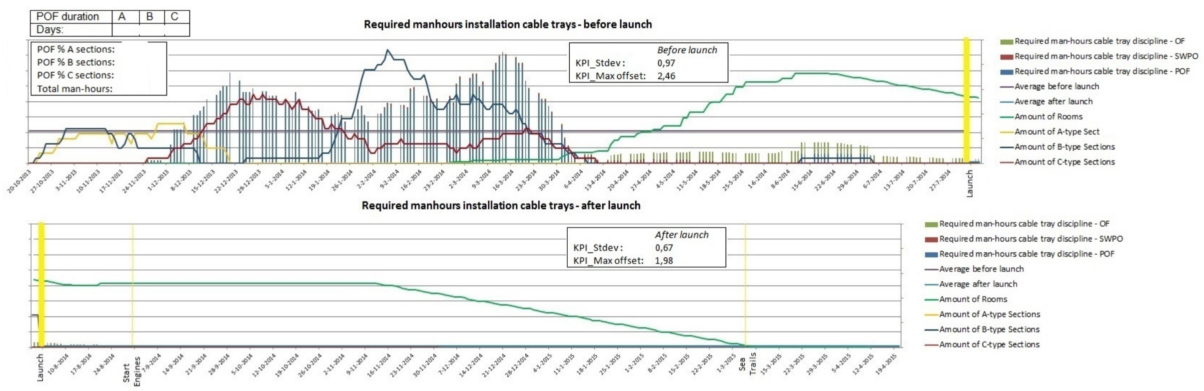


Figure 7.6: Workload cable tray discipline in current situation at Royal IHC for the production of Ynr 730 - Team size changed after launch

Currently, most cable trays are installed within the POF phase due to the beneficial fact that the trays can be painted during the section conservation and the installation of cabling can start right after the section is placed on the slipway

This outfit process in the current scenario is considered to be an uncontrollable process according to the KPI values calculated by the *Planning Generator*. However, the required workforce after the POF period does not show many fluctuations and has a more or less constant offset which should result in a scenario with a controllable workload for a subcontractor. The constant offset at the start of the outfit period increases the standard deviation which has a negative effect on the KPI. The *Planning Generator* should take a team size change into account after the POF phase in order to accept the significant lower amount of required workforce at the start of the outfit phase. This is discussed in chapter 7.5.1. Figure 7.7 shows the corresponding workload and KPI's when a change of team size after the POF period is taken into account. It is assumed that the cable tray subcontractor will change his team size after launch due to the significant difference in required man-hours when using a high rate of POF. Therefore, the KPI's are discussed that are shown in Figure 7.7

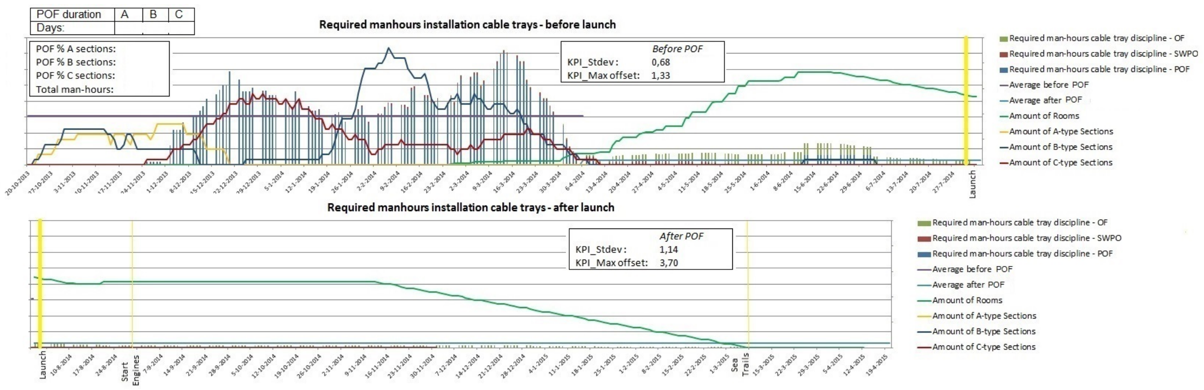


Figure 7.7: Workload cable tray discipline in current situation at Royal IHC for the production of Ynr 730 - Team size changed after POF

-POF period

The current large amount of work that is carried out in the POF phases requires a large workforce during the POF period and a relatively small required workforce during the outfit period. The required workforce during the POF phase shows large fluctuations with two large offsets. At the start of the process there is an over-capacity of man-hours because A-type sections do not contain cable trays. Most trays are installed in the front of the vessel and on the sides of the ship. These locations are covered by the C-type sections. The large amount of C-type sections at the first part of the POF phase results in the first peak. The second peak arises due to another increasing amount of C-type sections and a high amount of B-type sections with cable trays at the same time.

The KPI's calculated for a team size change after the POF period show better results for the workload fluctuations during the POF period. The standard deviation KPI shows lower expected offsets due to a higher average during this period. With an average of x required man-hours during the POF, a standard deviation KPI of 0,68 shows that it is expected that 68% of the fluctuations will stay below a maximum offset of x man-hours per day. The maximum offset KPI of 1,33 shows that the maximum expected offset during the POF is x man-hours. Using normal working days of 8 hours, 50% of extra required man-hours can be covered by the standard personnel using over-time. With the average of x man-hours not even half of the x exceeding required man-hours can be covered by the current team. Therefore it is recommended to organize the process in such a way that this maximum expected offset decreases.

The large offsets noticed during the POF period should decrease in order to improve the controllability of the workload. The performance is expected to decrease for any change in POF percentages of the section types because the current POF percentages have the highest possible value in the current scenario. It is expected that the offsets of both workload peaks decreases with a lower POF percentage for the C-type sections resulting in an increasing controllability. However, more work will be shifted towards the outfit period in the rooms which might lead to more fluctuations during that period of which the workload is relatively constant in the current situation.

-After the POF period

After the POF period the required workforce is significantly smaller and more constant. On average x man-hours per day of which most are required during the days before the launch and after the POF period. The KPI's calculated by the *Planning Generator* in a scenario with a change of the size of the team after the POF show bad values which require human opinion. The standard deviation KPI of 1,14 and with an average of x man-hours per day it is expected that 68% of the fluctuations will stay below a maximum offset of x man-hours per day. The maximum offset KPI after launch shows that the maximum expected offset is 3,7 times the average which is equal to x man-hours. The maximum capacity that 1 person, working x man-hours a day, can handle during over-time is x hours. It is assumed that the offset during this period will not be a problem and also considering the long term offset and low amount of fluctuations within a certain period the controllability after POF is considered sufficient.

Improved

The POF percentages of the B- and C-type sections are varied between 30%, 45%, 60%, 75% and 90% in order to find possible outfit scenarios with an improved controllability. The results of 125 different scenarios are shown in Figure **??** in Appendix M.

Initially, the performance may not decrease in order to improve the controllability. However, a significant increase in controllability will lead to less delays, waiting times, rework and therefore also to lower costs and a higher performance. KPI values calculated for a change of team size after the POF period and different POF percentages show that the AS-IS scenario is the best possible scenario taking the performance and controllability into account. Therefore, this scenario will be taken into account in the next improvement step.

When the subcontractor changes the team size after the launch of the vessel the most controllable scenario is considered to have a POF percentage of 45% for the B-type sections and a percentage of 75% for the C-type sections. It should be noticed that the performance in this scenario decreased. This scenario is shown in Figure 7.8 and is also taken into account in the next improvement step. The final optional scenarios for the organization of the installation of the cable trays is shown in Table 7.4.

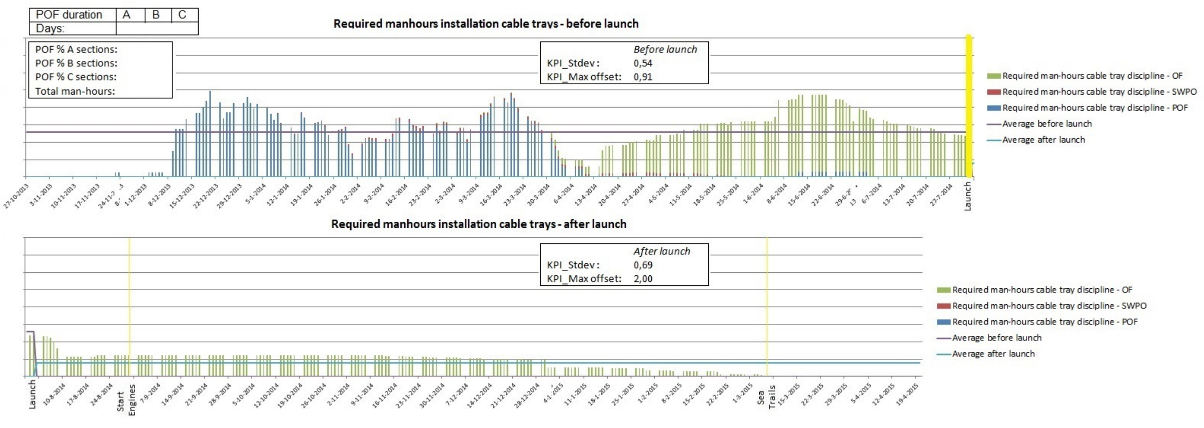


Figure 7.8: Workload cable tray discipline in improved situation (n.a. - 45% - 75%) - Team size change after launch

Scenario	*KPI_P*	*KPI_Rsbef*	*KPI_Rsaft*	*KPI_Robef*	*KPI_Roaft*	Change team size
AS-IS	1	0,68	1,14	1,33	3,70	After POF
AS-IS	1	0,97	0,67	2,46	1,98	After Launch
n.a./45/75	0,68	0,54	0,69	0,91	2,00	After Launch

Table 7.4: Optional scenarios workload installation cable trays with performance and controllability values

7.5.5 Resource leveling - Secondary steel discipline

AS-IS
The current workload of the secondary steel discipline at Royal IHC where currently for each section 90% of the work is carried out in the POF phases is shown in Figure 7.9.

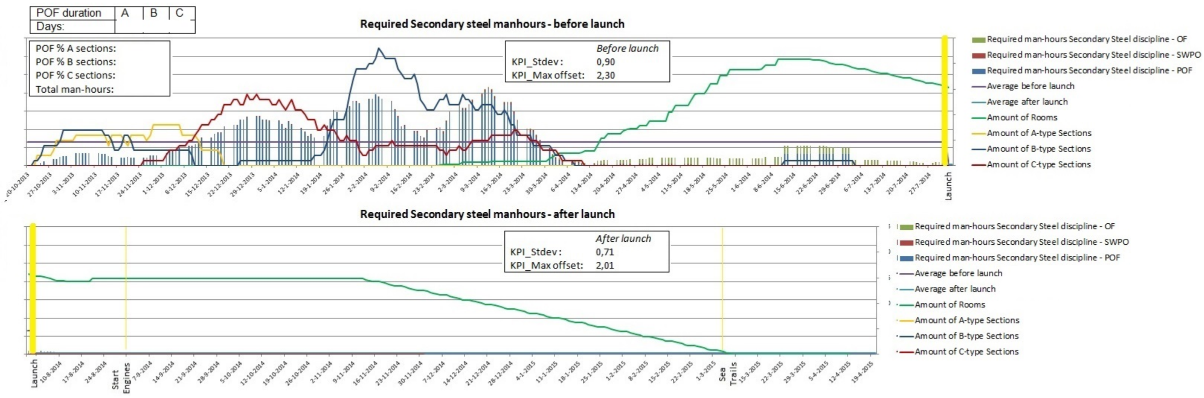


Figure 7.9: Workload secondary steel discipline in current situation at Royal IHC for the production of Ynr 730 - Team size changed after launch

Royal IHC prefers to install the secondary steel components in the POF phase due to the fact that these activities are carried out by the same personnel that fabricate a section. Therefore, some secondary steel components might sometimes even be installed before the start of the POF phase of the section.

Similar to the cable tray discipline, due to the current high POF percentage for each type of section, the required workload after the POF period is significantly lower which prefers an approach where a change of the team size after the POF period is taken into account. Because the *Planning Generator* assumes a change of the team size after the launch of the vessel, low level KPI values are obtained for the current situation. Therefore, the KPI values are discussed that are shown in Figure 7.10 corresponding to the scenario with a changing team size after the POF period.

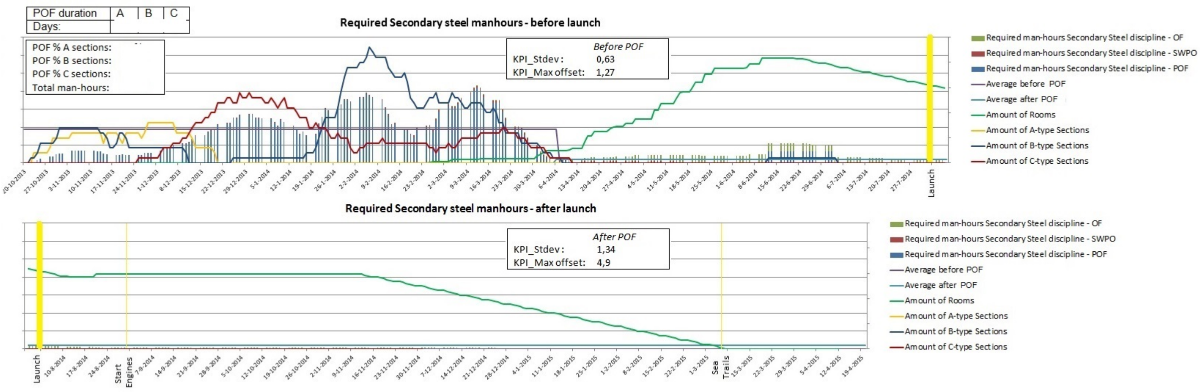


Figure 7.10: Workload secondary steel discipline in current situation at Royal IHC for the production of Ynr 730 - Team size changed after POF

-POF period
The KPI's calculated for a change of team size after the POF period show better results for the workload fluctuations during the POF period. The standard deviation KPI shows lower expected offsets due to a higher average during this period. With an average of x required man-hours during the POF, a standard deviation KPI of 0,63 shows that it is expected that 68% of the fluctuations will stay below a maximum offset of x man-hours per day.

The maximum offset KPI of 1,27 shows that the maximum expected offset during the POF is x man-hours. Using normal working days of 8 hours, 50% of extra required man-hours can be covered by the standard team working extra hours. With the average of x man-hours not even half of the x exceeding required man-hours can be covered by the current team. Therefore it is recommended to organize the process in such a way that this maximum expected offset decreases.

The performance of any other possible scenario with a different selection of POF percentages will be lower compared to the current scenario. Therefore any other interesting scenario should have a significant improved controllability and a slightly lower performance. It is expected that the controllability of the workload during the POF period will improve when the POF percentage of the B- and C-type sections decreases. However, the corresponding amount of work will be shifted towards the outfit phase of which the current controllability should be maintained.

-After the POF period
Significantly less man-hours are required during the start of the outfit phase and almost no secondary steel components are installed after the launch of the vessel. The workload after the POF period is more constant and shows less fluctuations.

The standard deviation KPI of 1,34 and with an average of x man-hours per day it is expected that 68% of the fluctuations will stay below a maximum offset of x man-hours per day. The maximum offset KPI after launch shows that the maximum expected offset is 4,91 times the average which is equal to x man-hours. The maximum capacity that 1 person, working x man-hours a day, can handle during over-time is x hours. It is assumed that the offset during this period will not be a problem and also considering the long term offset and low amount of fluctuations within a certain period the controllability after POF is considered sufficient.

Improved
The POF percentages for all type of sections are varied between 30%, 45%, 60%, 75% and 90% in order to find any possible outfit scenario with an improved controllability. The results of 125 different scenarios are shown in Figure **??** in Appendix M.

KPI values calculated for a change of team size after the POF period and different POF percentages show that the AS-IS scenario is the best possible scenario taking the performance and controllability into account. Therefore, this scenario will be taken into account in the next improvement step.

When the subcontractor changes the team size after the launch of the vessel, the most controllable scenario is considered to have a POF percentage of 90% for the A-type sections, a percentage of 90% for the B-type sections and a percentage of 60% for the C-type sections. It should be noticed that the performance in this scenario decreased. This scenario is shown in Figure 7.11 and is also taken into account in the next improvement step. The final optional scenarios for the organization of the installation of the cable trays is shown in Table 7.5.

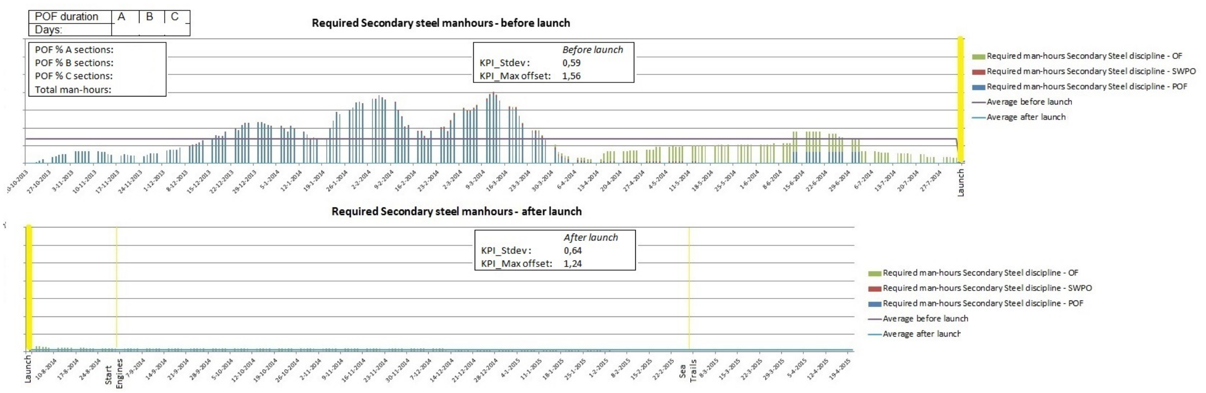


Figure 7.11: Workload Secondary steel discipline in improved situation (90% - 90% - 75%)

Scenario	KPI_P	KPI_Rsbef	KPI_Rsaft	KPI_Robef	KPI_Roaft	Change team size
AS-IS	1	0,63	1,34	1,27	4,91	After POF
AS-IS	1	0,90	0,71	2,30	2,01	After Launch
90/90/60	0,80	0,59	0,64	1,56	1,24	After Launch

Table 7.5: Optional scenarios workload installation secondary steel components with performance and controllability values

7.5.6 Resource leveling - Painting discipline

AS-IS

The required workforce over time for the painting discipline is shown in Figure 7.12. The workload for this discipline in different phases cannot be changed and it is therefore not possible to improve the corresponding controllability in this step of the research.

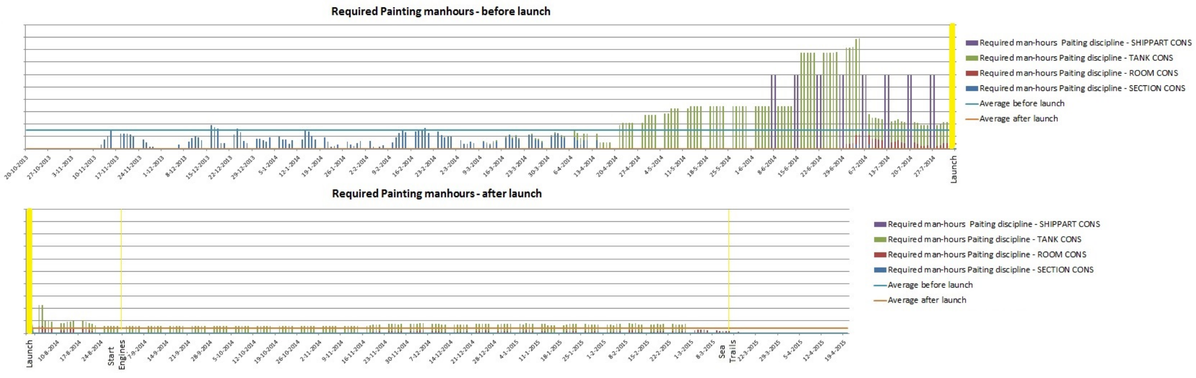


Figure 7.12: Workload painting discipline in current situation

The workload figure shows a fluctuating demand in the section conservation hall. More personnel is required for the conservation of the rooms and large offsets are expected during this period. Also an extra team of painters should be available for the conservation of large parts of the vessel during the weekend days. The workload significantly reduces after the launch of the vessel and shows less fluctuations.

7.6 Step 2: Varying pre-outfit percentage - Interdisciplinary controllability improvement

7.6.1 Introduction

The interdisciplinary effects on the controllability of the outfit processes are researched within this part of the improvement process. The controllability of the workload of each discipline is researched in the previous step and possible improved scenarios with specific POF percentages are selected. These disciplines meet each other during the production process in several areas which influences other types of controllability. The way of organizing and planning the process may improve the interdisciplinary controllability. In this step this controllability is researched for the production process of Ynr 730 at Royal IHC and possible improvements are discussed.

7.6.2 Unit occupancy

AS-IS scenario

The occupancy of each section, room and tank is measured over time by the *Planning Generator*. An estimation is made for each activity about the required amount of personnel per day using formula 6.9. The final unit occupancy is calculated by adding this number for all activities during each day in a specific unit. The unit occupancy is divided by the total volume of that unit to obtain the density (formula 6.10). It is assumed that when the unit occupancy has a density below 0,053 persons per m^3 all activities within that unit can be carried out without any collisions with other activities (see chapter 6.4.4). In order to determine the behavior of the unit occupancy when a subcontractor concentrates the amount of people more on specific days within an outfit phase, 3 different factors are used. For the factor '0' the amount of working hours are equally spread over the entire period and for the higher factors '10' and '20' the subcontractor concentrates his team more at specific jobs for only a short period of time. Finally, the expected percentage of working hours exceeding the density limit is calculated for the 3 factors. It is not known what level of concentration the subcontractors use and therefore the obtained values can only be used in order to compare different outfit scenarios with each other. When a specific scenario shows a lower expected percentage of exceeding working hours, less collisions between activities are expected which increases the controllability.

The KPI values for the unit occupancy in the current situation at Royal IHC are shown in Table 7.6 below.

Unit	factor 0	factor 10	factor 20
Sections	0%	13,60%	38,59%
Rooms	0%	0%	5,76%
Tanks	0%	4,29%	12,15%

Table 7.6: Unit occupancy in the current outfit scenario at Royal IHC during the production of Ynr 730

It is important to notice that the unit occupancy in the rooms does not include all activities. Some activities such as the installation of large equipment are not taken into account. Specific peaks in the room occupancy are therefore not shown in this output and it is recommended to expand this research with all missing outfit activities.

According to the output of the *Planning Generator* and the assumed maximum density limit, no collisions are expected when each subcontractor levels the amount of personnel over the entire POF phase. However, this calculation takes non-integer values into account for the amount of personnel which is not realistic. It is therefore important to look at the factors for level of concentration.

Improved scenario

The unit occupancy is calculated by the *Planning Generator* for all possible combinations of the optional improved outfit scenarios of each discipline determined in the previous step. The corresponding KPI values for each output are given in Figure 7.13 below.

Output no.	Total performance	Section occupancy f 0	f 10	f 20	Room occupancy f 0	f 10	f 20	Tank occupancy f 0	f 10	f 20	Piping POF % A	B	C	HVAC POF % A	B	C	Cable Trays POF % A	B	C	Secondary steel POF % A	B	C
Output 2.21		0,00%	19,73%	46,25%	0,00%	0,00%	0,00%	0,00%	4,29%	12,16%	90%	90%	60%	60%	60%	90%	90%	90%	90%	90%	90%	90%
Output 2.17		0,00%	19,72%	46,05%	0,00%	0,00%	1,49%	0,00%	4,29%	12,16%	90%	90%	60%	60%	45%	90%	90%	90%	90%	90%	90%	90%
Output 2.22		0,00%	19,50%	45,49%	0,00%	0,00%	0,00%	0,00%	4,29%	12,16%	90%	90%	60%	60%	60%	90%	90%	90%	90%	90%	90%	60%
Output 2.18		0,00%	19,48%	45,28%	0,00%	0,00%	1,33%	0,00%	4,29%	12,16%	90%	90%	60%	60%	45%	90%	90%	90%	90%	90%	90%	60%
Output 2.5		0,00%	14,53%	42,63%	0,00%	0,00%	6,71%	0,00%	4,29%	12,16%	90%	60%	75%	60%	60%	90%	90%	90%	90%	90%	90%	90%
Output 2.13		0,00%	14,67%	41,75%	0,00%	0,00%	6,70%	0,00%	4,29%	12,16%	75%	60%	75%	60%	60%	90%	90%	90%	90%	90%	90%	90%
Output 2.1		0,00%	14,54%	42,60%	0,00%	0,00%	8,13%	0,00%	4,29%	12,16%	90%	60%	75%	60%	45%	90%	90%	90%	90%	90%	90%	90%
Output 2.9		0,00%	14,68%	41,70%	0,00%	0,00%	8,12%	0,00%	4,29%	12,16%	75%	60%	75%	60%	45%	90%	90%	90%	90%	90%	90%	90%
Output 2.6		0,00%	14,14%	41,73%	0,00%	0,00%	6,08%	0,00%	4,29%	12,16%	90%	60%	75%	60%	60%	90%	90%	90%	90%	90%	90%	60%
Output 2.14		0,00%	14,28%	40,82%	0,00%	0,00%	6,07%	0,00%	4,29%	12,16%	75%	60%	75%	60%	60%	90%	90%	90%	90%	90%	90%	60%
Output 2.2		0,00%	14,14%	41,69%	0,00%	0,00%	7,43%	0,00%	4,29%	12,16%	90%	60%	75%	60%	45%	90%	90%	90%	90%	90%	90%	60%
Output 2.10		0,00%	14,28%	40,76%	0,00%	0,00%	7,42%	0,00%	4,29%	12,16%	75%	60%	75%	60%	45%	90%	90%	90%	90%	90%	90%	60%
Output 2.23		0,00%	19,10%	43,44%	0,00%	0,00%	1,19%	0,00%	4,29%	12,16%	90%	90%	60%	60%	60%	90%	90%	45%	75%	90%	90%	90%
Output 2.19		0,00%	19,24%	43,38%	0,00%	0,00%	2,64%	0,00%	4,29%	12,16%	90%	90%	60%	60%	45%	90%	90%	45%	75%	90%	90%	90%
Output 2.24		0,00%	18,84%	42,66%	0,00%	0,00%	1,07%	0,00%	4,29%	12,16%	90%	90%	60%	60%	60%	90%	90%	45%	75%	90%	90%	60%
AS-IS		**0,00%**	**13,60%**	**38,59%**	**0,00%**	**0,00%**	**5,76%**	**0,00%**	**4,29%**	**12,16%**	**60%**	**60%**	**60%**	**60%**	**60%**	**60%**	**90%**	**90%**	**90%**	**90%**	**90%**	**90%**
Output 2.20		0,00%	18,98%	42,60%	0,00%	0,00%	2,41%	0,00%	4,29%	12,16%	90%	90%	60%	60%	45%	90%	90%	45%	75%	90%	90%	60%
Output 2.7		0,00%	14,02%	39,48%	0,00%	1,15%	9,62%	0,00%	4,29%	12,16%	90%	60%	75%	60%	60%	90%	90%	45%	75%	90%	90%	90%
Output 2.15		0,00%	14,15%	38,49%	0,00%	1,14%	9,61%	0,00%	4,29%	12,16%	75%	60%	75%	60%	60%	90%	90%	45%	75%	90%	90%	90%
Output 2.3		0,00%	14,10%	39,61%	0,00%	1,53%	11,36%	0,00%	4,29%	12,16%	90%	60%	75%	60%	45%	90%	90%	45%	75%	90%	90%	90%
Output 2.11		0,00%	14,24%	38,60%	0,00%	1,53%	11,34%	0,00%	4,29%	12,16%	75%	60%	75%	60%	45%	90%	90%	45%	75%	90%	90%	90%
Output 2.8		0,00%	13,64%	38,47%	0,00%	1,05%	8,87%	0,00%	4,29%	12,16%	90%	60%	75%	60%	60%	90%	90%	45%	75%	90%	90%	60%
Output 2.16		0,00%	13,78%	37,44%	0,00%	1,05%	8,86%	0,00%	4,29%	12,16%	75%	60%	75%	60%	60%	90%	90%	45%	75%	90%	90%	60%
Output 2.4		0,00%	13,72%	38,59%	0,00%	1,41%	10,53%	0,00%	4,29%	12,16%	90%	60%	75%	60%	45%	90%	90%	45%	75%	90%	90%	60%
Output 2.12		0,00%	13,86%	37,54%	0,00%	1,41%	10,52%	0,00%	4,29%	12,16%	75%	60%	75%	60%	45%	90%	90%	45%	75%	90%	90%	60%

Figure 7.13: Unit occupancy for different outfit scenarios at Royal IHC for the production of Ynr 730

It should be noticed that the tank occupancy stays equal within each scenario. Only conservation activities are carried out within the tanks of which the amount of work is not affected by the changing POF percentages. The planner should increase the duration of these corresponding tank conservation phases in order to decrease the tank occupancy.

Looking at the different output scenarios, a tendency is noticed where the unit occupancy in sections increases for a decreasing total required amount of man-hours while the unit occupancy in the rooms decreases (see Figure 7.14). The logic is simple: work is transfered from rooms to sections which results in less required man-hours, a higher section occupancy and a lower room occupancy. Especially the section occupancy shows high percentages of man-hours exceeding the maximum density limit. This should be monitored in order to maintain a high controllability within the POF phases.

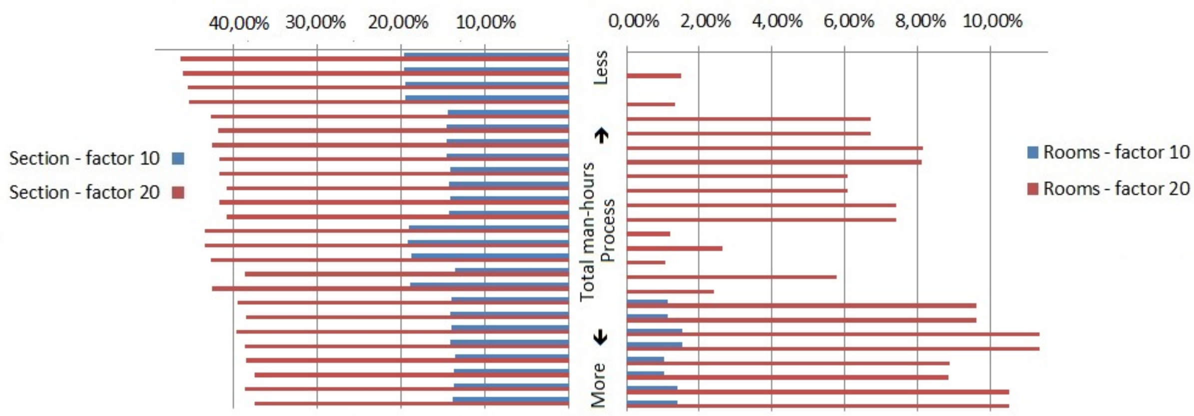


Figure 7.14: Unit occupancy for different outfit scenarios at Royal IHC for the production of Ynr 730

Especially for the concentration level with factor 10, the different outputs show a significant increase in section occupancy for high POF percentages within the piping discipline. When most of the pipe spools are installed in the POF phase of a section, the expected unit occupancy exceeding the density limit is 1,5 times as high. At the same time, the room occupancy is significantly lower for these scenarios due to the fact that the installation activities are transfered from the outfit phase in the rooms to the POF phase. The fluctuations of the section and room occupancy for the fluctuations of POF percentages of other disciplines are smaller. This shows that it is important to determine the expected unit occupancy for all possible POF percentages in advance in order to choose a set of POF percentages for each discipline that maintains a sufficient controllability.

The results show that the room occupancy is relatively low when a concentration factor of 10 is used. This occupancy only exceeds the density limit for output scenarios with relatively low POF percentages and where larger amounts of work is carried out in the outfit phase in the room. However, the room occupancy does not show 'complete' feasible values while many activities in the rooms are missing due to the exclusion of specific outfit disciplines. The fact that the room occupancy is significantly lower compared to the section occupancy shows that there is relatively more space for the other missing activities.

It is concluded that less collisions between activities in one working area are expected to occur when the selection of POF percentages per type of section and per discipline is chosen by taking the interdisciplinary controllability values into account. In order to judge the different output scenarios, only the section occupancy is taken into account within this research due to the incomplete room occupancy. The current scenario shows the best controllability for an average performance compared to the other optional output scenarios with an improved disciplinary workload controllability. Specific scenarios with a much higher section occupancy should be avoided while other scenarios with slightly higher section occupancy but also a higher performance might be preferred.

Within this case study it turns out that it is difficult to choose specific selections of POF percentages in a way that the unit occupancy decreases. However, it is expected that a change in POF phase durations will have a larger effect on the occupancy which will be taken into account in the next improvement step. The unit occupancy analysis in this step shows that it is important to exclude specific scenarios with unacceptable unit occupancy levels for specific POF percentage selections per discipline.

7.6.3 Crane occupancy

AS-IS scenario

Several piping, HVAC and secondary steel activities require crane assistance. The crane occupancy is measured over time by the *Planning Generator* and the percentage of crane hours exceeding the available crane capacity is calculated. Figure 7.15 shows the crane occupancy and the available crane capacity for the current outfit processes at Royal IHC during the production of Ynr 730.

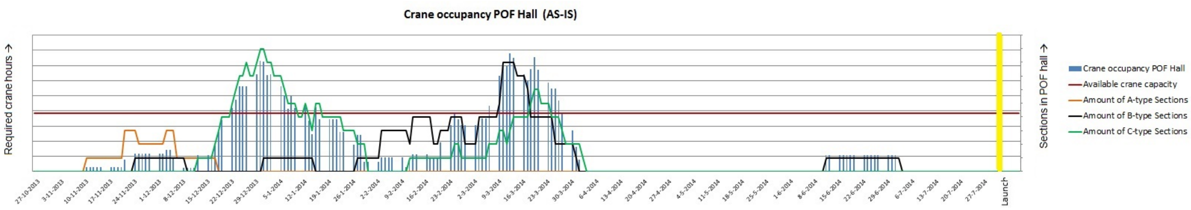


Figure 7.15: Crane occupancy cranes POF hall at Royal IHC during the production process of Ynr 730

The *Planning Generator* shows that in the current outfit scenario 20% of the crane hours exceeds the possible crane capacity (see chapter 6.4.4 for calculation capacity). During these periods of under-capacity it is likely that specific outfit activities can not start because they have to wait for available crane capacity. This percentage should decrease in order to reduce delays and waiting times and improve the controllability. g

The graph shows that the crane occupancy is not leveled over the entire POF period and that there are other periods in which the crane occupancy is significantly lower or higher. During the POF period of the A-type sections (double bottom mid-ship sections) only little crane assistance is required. During the POF period of the B and C-type sections significantly more crane assistance is required due to the high amount of outfit components and relatively more components that required crane assistance. It is expected that the POF percentages for each discipline chosen to improve the workload also influence the crane occupancy over time in a positive way. These percentages decreased the workload peaks at specific moments where many activities where planned. With a decrease of the amount of work at those moments also the required amount of crane assistance is expected to decrease.

Improved scenario

The crane occupancy is measured over time by the *Planning Generator* for all possible combinations of the optional outfit scenarios of each discipline determined in the previous improvement step. The corresponding KPI values for each output are given in Figure 7.16 below.

Output no.	Total performance	Crane occupancy hrs above	% above cap	Piping POF % A	B	C	HVAC POF % A	B	C	Cable Trays POF % A	B	C	Secondary steel POF % A	B	C
Output 2.21		362	21,7%	90%	90%	60%	60%	60%	90%	90%	90%	90%	90%	90%	90%
Output 2.17		362	21,7%	90%	90%	60%	60%	45%	90%	90%	90%	90%	90%	90%	90%
Output 2.22		215	14,8%	90%	90%	60%	60%	60%	90%	90%	90%	90%	90%	90%	60%
Output 2.18		215	14,8%	90%	90%	60%	60%	45%	90%	90%	90%	90%	90%	90%	60%
Output 2.5		370	22,2%	90%	60%	75%	60%	60%	90%	90%	90%	90%	90%	90%	90%
Output 2.13		370	22,3%	75%	60%	75%	60%	60%	90%	90%	90%	90%	90%	90%	90%
Output 2.1		370	22,2%	90%	60%	75%	60%	45%	90%	90%	90%	90%	90%	90%	90%
Output 2.9		370	22,3%	75%	60%	75%	60%	45%	90%	90%	90%	90%	90%	90%	90%
Output 2.6		219	15,1%	90%	60%	75%	60%	60%	90%	90%	90%	90%	90%	90%	60%
Output 2.14		219	15,2%	75%	60%	75%	60%	60%	90%	90%	90%	90%	90%	90%	60%
Output 2.2		219	15,1%	90%	60%	75%	60%	45%	90%	90%	90%	90%	90%	90%	60%
Output 2.10		219	15,2%	75%	60%	75%	60%	45%	90%	90%	90%	90%	90%	90%	60%
Output 2.23		362	21,7%	90%	90%	60%	60%	60%	90%	90%	45%	75%	90%	90%	90%
Output 2.19		362	21,7%	90%	90%	60%	60%	45%	90%	90%	45%	75%	90%	90%	90%
Output 2.24		215	14,8%	90%	90%	60%	60%	60%	90%	90%	45%	75%	90%	90%	60%
AS-IS		**319**	**20,2%**	**60%**	**60%**	**60%**	**60%**	**60%**	**60%**	**90%**	**90%**	**90%**	**90%**	**90%**	**90%**
Output 2.20		215	14,8%	90%	90%	60%	60%	45%	90%	90%	45%	75%	90%	90%	60%
Output 2.7		370	22,2%	90%	60%	75%	60%	60%	90%	90%	45%	75%	90%	90%	90%
Output 2.15		370	22,3%	75%	60%	75%	60%	60%	90%	90%	45%	75%	90%	90%	90%
Output 2.3		370	22,2%	90%	60%	75%	60%	45%	90%	90%	45%	75%	90%	90%	90%
Output 2.11		370	22,3%	75%	60%	75%	60%	45%	90%	90%	45%	75%	90%	90%	90%
Output 2.8		219	15,1%	90%	60%	75%	60%	60%	90%	90%	45%	75%	90%	90%	60%
Output 2.16		219	15,2%	75%	60%	75%	60%	60%	90%	90%	45%	75%	90%	90%	60%
Output 2.4		219	15,1%	90%	60%	75%	60%	45%	90%	90%	45%	75%	90%	90%	60%
Output 2.12		219	15,2%	75%	60%	75%	60%	45%	90%	90%	45%	75%	90%	90%	60%

Figure 7.16: Crane occupancy scenarios POF hall at Royal IHC for the production of Ynr 730

The expectation that the crane usage can improve when the outfit process is organized in another way is confirmed by the output of the optional scenarios. The percentage of under-capacity of the cranes is for several selections of POF percentages significantly lower. This percentage is calculated by dividing the total amount of crane hours that exceed the maximum available crane capacity by the total crane hours used in the POF hall during the entire process. For several selections, the total amount of exceeding crane hours stays equal but the amount of total required crane hours during the process differs. The results show that the POF percentages used by the secondary steel discipline in the C-type sections have a large influence. Changing the amount of piping, and HVAC activities in the POF period does only have a small effect on the percentage of crane under-capacity. This can be explained by the fact that the amount of pipe spools that require crane assistance is lower compared to the amount of secondary steel components. Besides that, the two optional selections of POF percentages for the secondary steel discipline have a large difference in the amount of work that should be carried out in the C-type sections.

It is expected that an optimal organization of the amount of work carried out by the secondary steel discipline in the POF phase may improve the crane controllability during this period. In the best output scenario, the amount of installation jobs of secondary steel components in C-type sections is relatively low and it is expected that the amount of delays and waiting times due to lack of crane capacity will decrease by more than 5%. The crane occupancy analysis in this step shows that the chosen selection of POF percentages does have a significant influence on the expected crane occupancy exceeding the maximum available crane capacity. It is therefore considered important to choose the selection of POF percentages for each discipline in a way that the crane occupancy is kept as low as possible.

7.6.4 Floor occupancy

AS-IS scenario

The floor occupancy during the outfit processes is measured over time by the *Planning Generator* for the POF hall and conservation hall. In this part of the research the floor occupancy is not expected to change because it will only change when specific phase durations change or when the section erection sequence changes. The floor occupancy will be discussed in more detail in the next improvement step where the duration of the POF phases is varied.

The floor occupancy of the POF hall is shown in Figure 7.17 below and the floor occupancy of the conservation hall is shown in Figure 7.18.

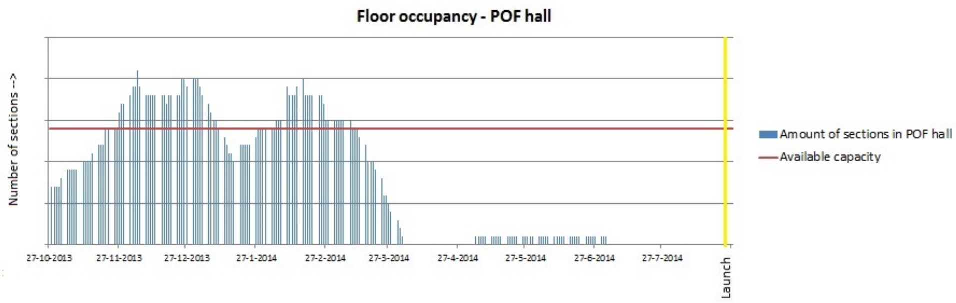


Figure 7.17: Floor occupancy POF hall at Royal IHC during production process of Ynr 730

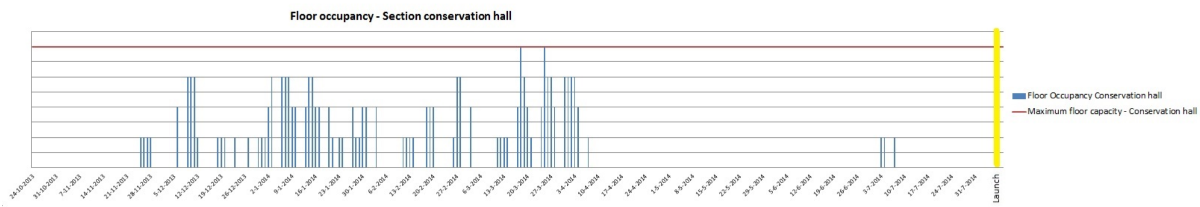


Figure 7.18: Floor occupancy section conservation hall at Royal IHC during production process of Ynr 730

Figure 7.17 shows that the floor occupancy in the current scenario exceeds the available capacity significantly. At Royal IHC, specific places outside the POF-hall or in the panel hall are sometimes used to built and outfit sections. Therefore, the maximum capacity limit does not seem to be a hard constraint that can never be exceeded. However, when changing specific input information in this research such as POF phase durations, it should always be checked whether the proposed schedule and occupancy are feasible. If not, the planner should choose for another schedule or strategy or he should consider outsourcing specific sections.

The floor occupancy in the section conservation hall does not exceed the maximum capacity in the current situation at Royal IHC. This was expected due to the fact that the initial section erection schedule and standard durations are used by the *Planning Generator* which were made by experienced planners at Royal IHC, resulting in a feasible production scenario.

7.6.5 Chosing best scenario

After researching different controllability areas the best outfit strategy can be chosen. The selection of POF percentages per type of section and discipline already contain workload controllability improvements. In this second step the best selection should be chosen taking the unit occupancy and crane occupancy into account. Assuming the fact that the performance may not decrease, the total amount of required man-hours for the process should be less or similar to the current situation.

It was concluded that it is difficult to improve the unit occupancy by choosing a specific set of POF percentages for each discipline. However, several scenarios with significantly high sections occupancies should be excluded. It is concluded that the crane occupancy is more influenced by the selected POF percentages. An improvement in this type of controllability can be made. The floor occupancy within the POF hall and painting hall is not effected when varying the POF percentage.

For an increasing performance, output scenario number 2.6 shows similar unit occupancy values compared to the current situation. This same scenario also shows a significant improvement in the crane occupancy. The corresponding values are shown in Figure 7.19 below.

Output no.	Total required man-hours	Section occupancy			Room occupancy			Tank occupancy			Crane occup. % above cap	Floor Occup. - POF % above lim	Floor Occup. - Cons % above lim	Piping POF %			HVAC POF %			Cable Trays POF %			Secondary steel POF %		
		f 0	f 10	f 20	f 0	f 10	f 20	f 0	f 10	f 20				A	B	C	A	B	C	A	B	C	A	B	C
AS-IS		0,00%	13,60%	38,59%	0,00%	0,00%	5,76%	0,00%	4,29%	12,16%	20,2%	0,00%	0,00%	60%	60%	60%	60%	60%	60%	90%	90%	90%	90%	90%	90%
Output 2.6		0,00%	14,14%	41,73%	0,00%	0,00%	6,08%	0,00%	4,29%	12,16%	15,1%	0,00%	0,00%	90%	60%	75%	60%	60%	90%	90%	90%	90%	90%	90%	60%

Figure 7.19: Process characteristics current scenario and improved outfit scenario - improvement step 2

The following results are expected when using similar phase durations but changing the POF percentages of the disciplines per type of section according to output scenario number 2.6:

- Increasing total performance by a reduction of the total amount of man-hours
- Increasing performance per discipline by reduction of their total required amount of man-hours
- Workload controllability improvement for each discipline
- More or less similar expected personnel densities in the sections compared to the current situation
- Less expected crane under-capacities in the POF hall during the project

7.7 Step 3: Varying pre-outfit duration - Total controllability improvement

7.7.1 Introduction

The effect of the POF phase duration on the controllability is researched in this third improvement step. The initial POF phase durations for a section is currently 2 weeks or 10 days. This duration is varied between 1 week (5 working days), 2 weeks (10 working days) and 3 weeks (15 working days) per type of section in order to research the behavior of the controllability of the workload, the unit occupancy, crane occupancy and floor occupancy during the outfit processes.

In this improvement step it is again assumed that a subcontractor changes the size of his team after the launch of the vessel. The effect of this assumption on the results of each run is already discussed in chapter 7.5. Specific possible consequences within the cable tray and secondary steel disciplines will be discussed below.

7.7.2 Resource leveling

Figure 7.20 below shows the results of the workload controllability KPI's for each discipline for different scenarios with varying POF phase durations per type of section.

Output no.	Total performance	Piping Avg_b	KPI_ro	KPI_rs	HVAC Avg_b	KPI_ro	KPI_rs	Cable Trays Avg_b	KPI_ro	KPI_rs	Secondary steel Avg_b	KPI_ro	KPI_rs	Durations POF phase Sect A	Sect B	Sect C
AS-IS			1,03	0,50		1,11	0,62		2,46	0,97		2,30	0,90	10	10	10
Output 3.1			0,98	0,50		1,24	0,61		2,39	0,99		2,60	0,91	5	5	5
Output 3.2			0,98	0,49		1,04	0,59		2,61	0,95		2,48	0,89	5	5	10
Output 3.3			0,98	0,49		1,13	0,58		2,43	0,92		2,55	0,87	5	5	15
Output 3.4			1,03	0,51		1,30	0,64		2,47	1,01		2,68	0,93	5	10	5
Output 3.5			1,03	0,50		1,11	0,62		2,46	0,97		2,30	0,90	5	10	10
Output 3.6			1,03	0,50		1,22	0,61		2,52	0,94		2,24	0,88	5	10	15
Output 3.7			1,08	0,53		1,38	0,66		2,56	1,03		2,77	0,95	5	15	5
Output 3.8			1,08	0,52		1,15	0,65		2,44	0,98		2,37	0,91	5	15	10
Output 3.9			1,08	0,52		1,26	0,64		2,43	0,96		2,31	0,89	5	15	15
Output 3.10			1,03	0,53		1,30	0,64		2,47	1,02		2,70	0,94	10	5	5
Output 3.11			1,03	0,52		1,09	0,62		2,70	0,98		2,57	0,91	10	5	10
Output 3.12			1,03	0,52		1,18	0,61		2,52	0,95		2,64	0,89	10	5	15
Output 3.13			1,03	0,51		1,30	0,64		2,47	1,01		2,68	0,93	10	10	5
Output 3.14			1,03	0,50		1,22	0,61		2,52	0,94		2,24	0,87	10	10	15
Output 3.15			1,08	0,53		1,38	0,66		2,56	1,03		2,77	0,94	10	15	5
Output 3.16			1,08	0,52		1,15	0,65		2,44	0,98		2,37	0,91	10	15	10
Output 3.17			1,08	0,52		1,26	0,64		2,43	0,96		2,31	0,89	10	15	15
Output 3.18			1,08	0,55		1,36	0,66		2,56	1,04		2,79	0,96	15	5	5
Output 3.19			1,08	0,54		1,15	0,65		2,79	1,00		2,66	0,93	15	5	10
Output 3.20			1,08	0,54		1,24	0,64		2,61	0,97		2,73	0,91	15	5	15
Output 3.21			1,08	0,54		1,36	0,66		2,56	1,03		2,78	0,95	15	10	5
Output 3.22			1,08	0,53		1,16	0,65		2,54	0,99		2,38	0,92	15	10	10
Output 3.23			1,08	0,52		1,27	0,64		2,61	0,97		2,32	0,90	15	10	15
Output 3.24			1,08	0,53		1,38	0,66		2,56	1,03		2,77	0,94	15	15	5
Output 3.25			1,08	0,52		1,15	0,65		2,44	0,98		2,37	0,91	15	15	10
Output 3.26			1,08	0,51		1,26	0,64		2,43	0,96		2,31	0,89	15	15	15

Figure 7.20: Workload KPI's different outfit scenarios with varying POF phase duration per type of section at Royal IHC for production Ynr 730

The initial performance in each different output scenario will not change while the amount of work in each outfit phase is fixed. The real performance might change in practice due to a changing controllability that affects the total required amount of man-hours. However, the *Planning Generator* does not take this effect into account.

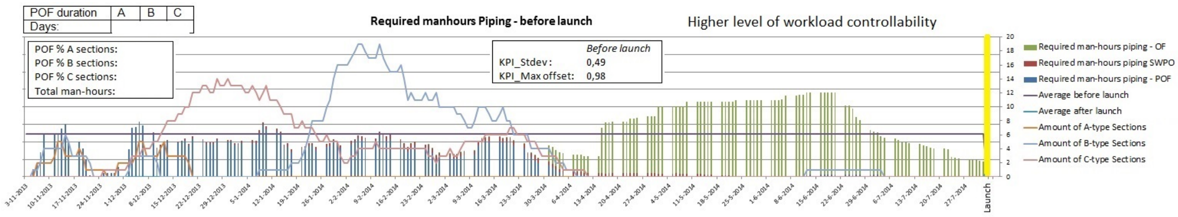
The varying duration of the POF phases only affect the process characteristics such as workload, unit occupancy or crane occupancy within the POF period. The amount of work and duration within other phases remains the same and does not change. Therefore, only the KPI's of the processes before the launch are taken into account.

It should be noted that the averages change due to a changing project duration. Longer POF phase durations for A or B type sections result in a longer project duration due to the fact that the start date of the project depends on the start date of the POF phase of several sections of these types.When the duration of the POF phase of the A-type sections is for example extended with a week, the whole project start a week earlier and the project duration is extended with a week. Sometimes the maximum workload offset does not change but only the average changes which changes the KPI of the maximum offset. The standard deviation changes for every output scenario.

Workload piping discipline

The results in Figure 7.20 show that the maximum offset during the period before the launch does not change when the POF phase durations is varied. The maximum workload of the piping discipline is located after the POF period during the outfitting in the rooms which is shown in Figure 7.2. This maximum offset does not change when the POF phase duration is varied. The maximum offset KPI however does change due to small changes in the average amount of man-hours before the launch of the vessel. The standard deviation KPI does not show significant changes for different POF-durations. This shows that the POF phase duration for sections does not have a large influence on the amount and size of fluctuations in workload of the piping discipline.

The lowest maximum offset and smallest amount and size of workload fluctuations are found for an outfit scenario with relatively long POF durations for sections with much pipe installation work such as the C-type sections. An example of this controllable scenario is shown in Figure 7.21. A high maximum offset and many fluctuations with a larger size are found for outfit scenarios with relatively short POF durations for the sections with much pipe installation work and longer durations for sections with less installation work such as A-type sections. An example of this scenario is also shown in Figure 7.21.



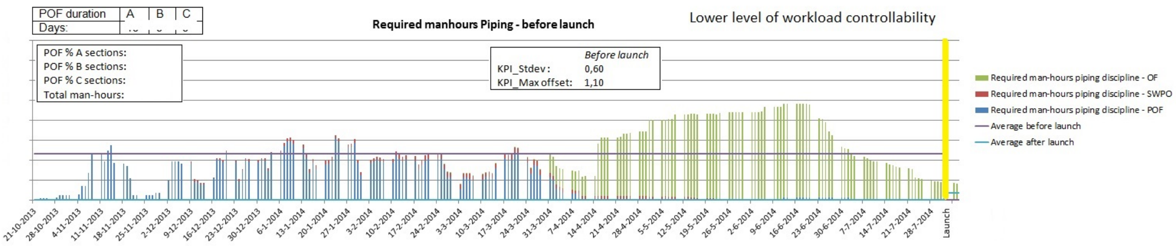


Figure 7.21: High and low level controllability scenarios for the workload within the piping discipline for specific POF phase durations

Scenario	Duration A-type sections	Duration B-type sections	Duration C-type sections
Best scenario	5	5	15
Worst scenario	15	5	5

Table 7.7: POF phase durations for best and worst workload controllability within the piping discipline

Looking at the results of the varies output scenarios it can be concluded that the POF phase duration does not have a large influence on the workload controllability in the piping discipline. The POF percentage researched in the first improvement step had a relative larger influence.

Workload HVAC discipline

It should be noticed that only the POF phase durations of the B and C type sections directly influence the workload controllability while no HVAC components are located in the A-type sections. However, small differences can be noticed when changing the POF phase duration of the A-type sections because this changes the total project duration with a week which affects the average required man-hours before launch and therefore the KPI values.

The maximum workload offset does change here because of the fact that the largest offset is located in the POF period (see Figure 7.4). Especially scenarios with short POF phase durations for C-type sections show large offsets. The standard deviation does not fluctuate that much although short POF phase durations for the C-type sections lead to a workload with relatively more and larger fluctuations.

The lowest workload offset is measured for outfit scenarios with relatively long POF phase durations for sections with much HVAC installation work such as the C-type sections and relatively short POF phase durations for sections with less HVAC work such as the B-type sections. Long POF phase durations for the B-type sections and short POF phase durations for the C-type sections lead to a low workload controllability level. The best and worst scenario considering the workload controllability of the HVAC discipline are shown in Table 7.8 below.

Scenario	Duration A-type sections	Duration B-type sections	Duration C-type sections
Best scenario	5	5	15
Worst scenario	10	15	5

Table 7.8: POF phase durations for best and worst workload controllability within the HVAC discipline

Looking at the results of the varies output scenarios it can be concluded that the POF phase duration does not have a large influence on the workload controllability in the HVAC discipline. The POF percentage researched in the first improvement step had a relative larger influence.

Workload cable tray discipline
It should be noticed that within the cable tray discipline only the POF phase durations of the B and C type sections directly influence the workload controllability while no cable trays are located in the A-type sections. However, a changing POF phase duration of the A-type sections slightly influences the KPI values due to a changing project duration.

Maximum offset does change here because of the fact that the highest offset is located in the POF period. Especially for phase durations of 5 days for B-type sections and 10 days for C-type sections, significant large offsets are noted. The standard deviation doesn't fluctuate that much but shows bad values for short POF phase durations times for C-type sections. Best values are noted for long POF phases for B-type sections and 10 or 15 days for the C-type sections. The worst scenario does have short POF phase durations for B-type sections and when the C-type sections have a POF phase duration of 10 days. Both scenarios are listed in Table 7.9 below.

Scenario	Duration A-type sections	Duration B-type sections	Duration C-type sections
Best scenario	5	15	15
Worst scenario	15	5	10

Table 7.9: POF phase durations for best and worst workload controllability within the cable tray discipline

As already discussed in the first improvement step, it may be preferable for this discipline to change the size of the team after the POF phase instead of changing the size after the launch of the vessel due to the relatively high POF percentage preferably used. However, the *Planning Generator* only takes a change in team size after the launch into account. The KPI values corresponding to a scenario in which a subcontractor is able to change the size of his team after the POF period are also calculated in order to check whether the improved scenario is also valid for that situation. The scenarios are shown in Table 7.10 below.

Scenario	KPI StDev_bef	KPI MaxOff_bef	Moment of team size change
AS-IS	0,97	2,46	After launch
AS-IS	0,68	1,33	After POF
5 / 15 / 15	0,96	2,43	After launch
5 / 15 / 15	0,70	1,11	After POF

Table 7.10: Optional scenarios workload cable tray discipline with improved controllability

Workload Secondary steel discipline
The maximum offset between the average workload in the secondary steel discipline and the maximum workload within this discipline changes when the POF phase duration for the 3 types of sections is varied. All 3 types of sections contain secondary steel components and the maximum workload is currently located in the POF period (see Figure 7.9). A changing POF phase duration therefore influences the maximum offset. The amount and size of workload fluctuations, monitored my the standard deviation KPI does not change much for different POF phase durations.

The results show that the effect of varying the POF phase duration from the A-type sections on the controllability is small. The variance of the POF phase duration of the B-type and C-type sections has a larger effect on the controllability. The most controllable outfit scenario is found when the C-type sections, containing the most secondary steel components, have the longest possible POF phase duration of 3 weeks and when the B-type section have a 'normal' POF phase duration of 2 weeks or 10 days. However, this scenario does only show a small improvement of the amount and size of the workload fluctuations compared to the current scenario. The worst scenario is found when only a little amount of time is available in the POF phase for the installation of the secondary steel components in the sections that contain many components. The best and worst scenario, considering the workload controllability of the secondary steel discipline, are shown in Table 7.11 below.

Even as the cable trays discipline, the secondary steel discipline installs currently most of the components in the POF phase. Therefore a change of team size after the POF period is preferred. The KPI values corresponding to a scenario in which a subcontractor is able to change the size of his team after the POF period are also calculated in order to check whether the improved scenario is also valid for that situation. The scenarios are shown in Table 7.10 below.

Scenario	Duration A-type sections	Duration B-type sections	Duration C-type sections
Best scenario	5	10	15
Worst scenario	15	5	5

Table 7.11: POF phase durations for best and worst workload controllability within the secondary steel discipline

Scenario	KPI StDev_bef	KPI MaxOff_bef	Moment of team size change
AS-IS	0,90	2,30	After launch
AS-IS	0,63	1,27	After POF
5 / 10 / 15	0,89	2,31	After launch
5 / 10 / 15	0,59	1,23	After POF

Table 7.12: Optional scenarios workload secondary steel discipline with improved controllability

Looking at the results of the varies output scenarios it can be concluded that the POF phase duration does not have a large influence on the workload controllability in the secondary steel discipline. The POF percentage researched in the first improvement step had a relative larger influence.

7.7.3 Unit occupancy

Figure 7.22 below shows the unit occupancy of different output scenarios for varying POF phase durations per type of section. While only the POF phase duration is adjusted the amount of work in the outfit period in the rooms and tanks and their phase duration will not change. Therefore the unit occupancy in the rooms and tanks will not change for each outfit scenario in this improvement step.

	Total	Section occupancy			Room occupancy			Tank occupancy			Durations POF phase		
Output no.	performance	f 0	f 10	f 20	f 0	f 10	f 20	f 0	f 10	f 20	Sect A	Sect B	Sect C
AS-IS		0,00%	13,60%	38,59%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	10	10	10
Output 3.1		0,00%	32,92%	54,39%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	5	5	5
Output 3.2		0,00%	22,82%	46,34%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	5	5	10
Output 3.3		0,00%	20,19%	39,91%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	5	5	15
Output 3.4		0,00%	26,30%	49,91%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	5	10	5
Output 3.5		0,00%	16,20%	41,86%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	5	10	10
Output 3.6		0,00%	13,57%	35,43%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	5	10	15
Output 3.7		0,00%	22,10%	45,71%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	5	15	5
Output 3.8		0,00%	12,00%	37,66%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	5	15	10
Output 3.9		0,00%	9,37%	31,23%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	5	15	15
Output 3.10		0,00%	30,32%	51,12%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	10	5	5
Output 3.11		0,00%	20,22%	43,07%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	10	5	10
Output 3.12		0,00%	17,59%	36,64%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	10	5	15
Output 3.13		0,00%	23,70%	46,64%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	10	10	5
Output 3.14		0,00%	10,97%	32,16%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	10	10	15
Output 3.15		0,00%	19,50%	42,44%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	10	15	5
Output 3.16		0,00%	9,40%	34,40%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	10	15	10
Output 3.17		0,00%	6,77%	27,97%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	10	15	15
Output 3.18		0,00%	30,32%	49,02%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	15	5	5
Output 3.19		0,00%	20,22%	40,98%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	15	5	10
Output 3.20		0,00%	17,59%	34,54%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	15	5	15
Output 3.21		0,00%	23,70%	44,54%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	15	10	5
Output 3.22		0,00%	13,60%	36,50%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	15	10	10
Output 3.23		0,00%	10,97%	30,07%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	15	10	15
Output 3.24		0,00%	19,50%	40,35%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	15	15	5
Output 3.25		0,00%	9,40%	32,30%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	15	15	10
Output 3.26		0,00%	6,77%	25,87%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	15	15	15

Figure 7.22: Unit occupancy KPI's different outfit scenarios with varying POF phase duration per type of section at Royal IHC for production Ynr 730

The results show that the duration of the POF period has a significant effect on the expected amount of personnel in a section. The B-type and especially the C-type sections need a relatively long POF period in order to keep the percentage of exceeding personnel density in the units as low as possible. These sections contain many outfit components which leads to a higher expected personnel density during the POF period.

The behavior of the varying POF phase durations in this improvement step shows that the personnel density decreases when the duration of the phase increases. With a similar amount of work and a longer duration, less persons are required per day when the amount of work is spread equally over this period. The scenario with the lowest section occupancy contains maximum POF phase durations of 3 weeks for each type of section. The outfit scenario with the worst POF phase duration contains minimum POF phase durations of 1 week for each type of sections.

When the yard wants to improve the controllability and reduce the amount of delays and waiting time by lowering the chance on collisions between activities in a unit, it should strive for maximum POF phase durations in the B and C-type sections. The controllability shows sufficient unit occupancy values for scenarios with an average or short POF phase duration for the A-type sections.

7.7.4 Crane occupancy

Figure 7.23 below shows the different output scenarios for varying POF phase durations per type of section. The results show that the durations of the POF phases have a significant effect on the crane occupancy in the POF hall.

Output no.	Total performance	Crane occupancy % above capacity	Durations POF phase Sect A	Sect B	Sect C
AS-IS		20,2%	10	10	10
Output 3.1		23,0%	5	5	5
Output 3.2		20,6%	5	5	10
Output 3.3		17,7%	5	5	15
Output 3.4		23,5%	5	10	5
Output 3.5		20,2%	5	10	10
Output 3.6		17,7%	5	10	15
Output 3.7		23,3%	5	15	5
Output 3.8		19,8%	5	15	10
Output 3.9		17,5%	5	15	15
Output 3.10		23,0%	10	5	5
Output 3.11		20,6%	10	5	10
Output 3.12		17,7%	10	5	15
Output 3.13		23,5%	10	10	5
Output 3.14		17,7%	10	10	15
Output 3.15		23,3%	10	15	5
Output 3.16		19,8%	10	15	10
Output 3.17		17,5%	10	15	15
Output 3.18		23,0%	15	5	5
Output 3.19		20,6%	15	5	10
Output 3.20		17,7%	15	5	15
Output 3.21		23,5%	15	10	5
Output 3.22		20,2%	15	10	10
Output 3.23		17,7%	15	10	15
Output 3.24		23,3%	15	15	5
Output 3.25		19,8%	15	15	10
Output 3.26		17,5%	15	15	15

Figure 7.23: Crane occupancy KPI's different outfit scenarios at Royal IHC for the production of Ynr 730

With a decreasing POF phase duration in a section, the same activities are carried out in a shorter period of time. This increases the required crane hours per day. Figure 7.15 in the second improvement step showed the current crane occupancy including the amount of sections per type over time during the production of Ynr 730 at Royal IHC. The crane occupancy does not exceed the maximum crane capacity during the POF phases of the A-type sections. Therefore, shortening the POF phase of these sections does not lead to (extra) exceeding crane hours. The crane occupancy shows peak loads on the cranes during periods when especially C-type sections are pre-outfitted in the hall. It is expected that the crane occupancy is better leveled when the POF phase duration of the C-type sections is longer which results in a lower amount of required crane occupancy per day for activities within these sections.

This behavior is confirmed by the various outputs shown in Figure 7.23. Changing the POF phase duration of the A-type section does not have any effect on the exceeding percentage of crane hours. The B-type sections have a small effect on the exceeding percentage while the C-type section have a significant effect.

It can be concluded that the POF phase duration of the B and especially the C-type section should be chosen as long as possible in order to improve the controllability of the crane occupancy. The A-type sections do not influence this controllability according to the results using the current section erection schedule.

7.7.5 Floor occupancy

With a change of the POF phase duration, only the floor occupancy within the POF hall changes. The floor occupancy in the section conservation hall does not change while the start and end times of the painting phases of the sections are not affected. The floor occupancy in the current situation is shown in Figure 7.17.

The expected amount of sections within the POF hall at a certain moment in time changes when the POF phase duration of specific sections are extended or shortened. This amount should be monitored in order to avoid impossible planning scenarios where more sections are planned to be positioned in the POF hall than possible. In case of such unfeasible production scenarios a planner can take the following actions in order to solve the problem:

- Change the erection schedule
- Outsource sections
- Choose another production scenario

Figure 7.24 below shows the corresponding floor occupancy KPI values for different outfit scenarios with varying POF phase durations. These results show that the amount of section days exceeding the POF hall capacity depend heavily on the chosen POF phase duration. The amount of exceeding section days changes significantly when the POF phase duration of the B-type and C-type sections change due to a high floor occupancy during the period where these sections are located in the POF hall. At the start of the project, when most of the A-type sections are built and pre-outfitted in the POF hall, relatively much floor capacity is left before the maximum capacity is exceeded. Therefore the POF phase duration of this type of section does not significantly influence the total amount of exceeding section days.

	Total man-	Floor occupancy POF Hall	Durations POF phase		
Output no.	hours	*% above capacity*	Sect A	Sect B	Sect C
AS-IS		12,2%	10	10	10
Output 3.1		7,3%	5	5	5
Output 3.2		10,6%	5	5	10
Output 3.3		13,5%	5	5	15
Output 3.4		9,2%	5	10	5
Output 3.5		12,3%	5	10	10
Output 3.6		15,4%	5	10	15
Output 3.7		11,0%	5	15	5
Output 3.8		14,3%	5	15	10
Output 3.9		17,1%	5	15	15
Output 3.10		7,1%	10	5	5
Output 3.11		10,3%	10	5	10
Output 3.12		13,1%	10	5	15
Output 3.13		9,2%	10	10	5
Output 3.14		15,3%	10	10	15
Output 3.15		10,9%	10	15	5
Output 3.16		14,1%	10	15	10
Output 3.17		17,0%	10	15	15
Output 3.18		7,0%	15	5	5
Output 3.19		10,1%	15	5	10
Output 3.20		12,8%	15	5	15
Output 3.21		9,0%	15	10	5
Output 3.22		12,0%	15	10	10
Output 3.23		14,9%	15	10	15
Output 3.24		10,8%	15	15	5
Output 3.25		14,0%	15	15	10
Output 3.26		16,9%	15	15	15

Figure 7.24: Floor occupancy KPI's POF hall different outfit scenarios at Royal IHC for the production of Ynr 730

Figure 7.25 below shows the ’worst’ production scenario of output number 9 in which the A-type sections have a POF phase duration of 5 days and the B and C-type sections a duration of both 15 days. This figure shows that the maximum number of sections in the POF hall stays the same in the scenario with longer POF durations while the amount of sections exceeding the floor capacity increases. According to the current AS-IS situation, it is possible for Royal IHC to store 21 sections at the same time on the yard for fabrication and POF. If this is possible during the entire project, it is assumed that also this ’worst scenario’ is feasible.

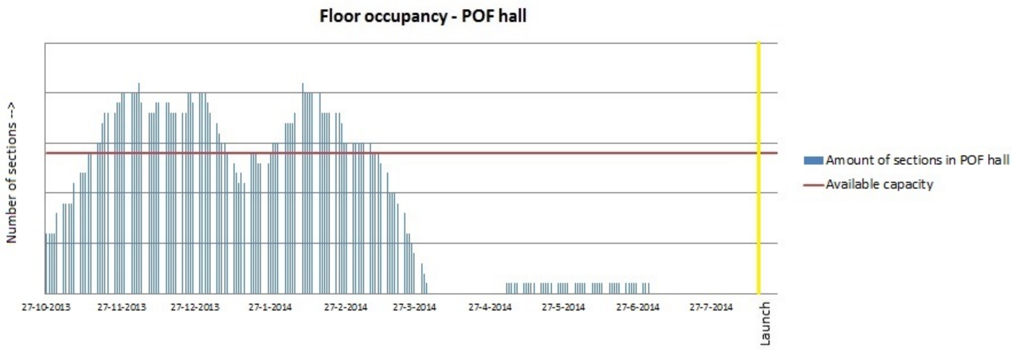


Figure 7.25: Floor occupancy POF hall production scenario 9 at Royal IHC for the production of Ynr 730

It is recommended to implement the real maximum floor occupancy limit in the *Planning Generator* in order to be able to determine easily whether a specific scenario is feasible or not. Otherwise, the usage of an extra KPI is recommended where the maximum sections in the POF hall is measured to determine the feasibility of each scenario.

7.7.6 Chosing best scenario

The controllability of the workload of all discipline, the unit occupancy, the crane occupancy and the floor occupancy is taken into account in this third improvement step for various POF phase duration combinations. In order to improve the outfit processes for the production of Ynr 730 the best scenario should be chosen.

It was found that the workload controllability only showed small fluctuations for changing POF phase durations. For all disciplines it was found that their most controllable scenario had long POF phase duration for the C-type and preferably the B-type sections. The A-type sections that contain only a low amount of outfit components can have a shorter POF phase duration when necessary. Although major improvements in this controllability can not be achieved by changing the POF phase duration, specific uncontrollable output scenarios can be excluded in this step.

The longer the POF phase durations for each type of sections, the lower the unit occupancy of the sections. It was found in this step that the B-type and especially the C-type sections have the largest influence on the expected unit occupancy exceeding the maximum density limit and this type of controllability. A similar behavior is found for the crane occupancy where also longer POF phase durations for the B-type and especially the C-type sections where preferred.

The floor occupancy depends significantly on the chosen POF phase duration and is mostly affected by the B and C-type sections. Long durations for these sections lead to more section days exceeding the available floor capacity. However, the worst scenario cases found show similar maximum required floor capacity values compared to the current (feasible) AS-IS situation.

According to the workload, the unit occupancy, the crane occupancy and the floor occupancy controllability the 2 possible selections of POF phase durations shown in Figure 7.26 below present the best results:

Output no.	Total required manhours	Piping			HVAC			Cable Trays			Secondary steel			Durations POF phase		
		Avg_b	KPI_ro	KPI_rs	Avg_b	KPI_ro	KPI_rs	Avg_b	KPI_ro	KPI_rs	Avg_b	KPI_ro	KPI_rs	Sect A	Sect B	Sect C
AS-IS		118,7	1,03	0,50	31,4	1,11	0,62	42,9	2,46	0,97	26,6	2,30	0,90	10	10	10
Output 3.6		118,7	1,03	0,50	31,4	1,22	0,61	42,9	2,52	0,94	26,6	2,24	0,88	5	10	15
Output 3.9		115,8	1,08	0,52	30,6	1,26	0,64	41,8	2,43	0,96	26,0	2,31	0,89	5	15	15

Output no.	Total required manhours	Section occupancy			Room occupancy			Tank occupancy			Crane occup.	Floor Occup. - POF	Floor Occup. - Section cons.	Durations POF phase		
		f 0	f 10	f 20	f 0	f 10	f 20	f 0	f 10	f 20	% exceed	% above lim	% above lim	Sect A	Sect B	Sect C
AS-IS		0,00%	13,60%	38,59%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	20,2%	12,2%	0,00%	10	10	10
Output 3.6		0,00%	13,57%	35,43%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	17,7%	15,4%	0,00%	5	10	15
Output 3.9		0,00%	9,37%	31,23%	0,00%	0,00%	5,76%	0,00%	4,29%	12,15%	17,5%	17,1%	0,00%	5	15	15

Figure 7.26: Process characteristics current scenario and improved outfit scenario - improvement step 3

7.8 Step 4: Varying pre-outfit duration and percentage - TO-BE scenario

7.8.1 Introduction

General knowledge is gained in the first 3 steps about the behavior of the controllability and performance for different POF percentages and POF phase durations used in the outfit processes. The best possible POF percentages are selected in the first and second step considering the current POF phase duration of 2 weeks for each section. In the third step, the best possible POF phase durations are chosen considering the POF percentages used at Royal IHC in the current situation. In order to determine the best outfit strategy for Royal IHC, both the POF percentages and POF durations should be taken into account simultaneously.

7.8.2 Possible TO-BE situation

In the first and second step, 1 best output scenario with a specific set of POF percentages was selected. In the third step, 2 best output scenarios with specific POF phase durations were selected. Combining these possible percentages and durations provides 2 outfit scenarios shown in Table 7.27 of which the results are shown in Table 7.28 below.

Scenario	Durations POF phase (days)			POF percentage piping			POF percentage HVAC			POF percentage cable trays			POF percentage secondary steel		
	Sect A	Sect B	Sect C	Sect A	Sect B	Sect C	Sect A	Sect B	Sect C	Sect A	Sect B	Sect C	Sect A	Sect B	Sect C
AS-IS	10	10	10	60%	60%	60%	60%	60%	60%	60%	60%	60%	90%	90%	90%
Scenario 1	5	10	15	90%	60%	75%	60%	60%	90%	90%	90%	90%	90%	90%	60%
Scenario 2	5	15	15	90%	60%	75%	60%	60%	90%	90%	90%	90%	90%	90%	60%

Figure 7.27: POF phase durations and POF percentages per scenario

Scenario	Total Required man-hours	Section occupancy			Room occupancy			Tank occupancy			Crane occup.	Floor occup. - Section cons	Floor occup. - POF hall
		f 0	f 10	f 20	f 0	f 10	f 20	f 0	f 10	f 20	% above cap.	% above lim	% above lim
AS-IS		0,0%	13,6%	38,6%	0,0%	0,0%	5,8%	0,0%	4,3%	12,2%	20,2%	0,0%	12,2%
Scenario 1		0,0%	15,8%	38,4%	0,0%	0,0%	6,1%	0,0%	4,3%	12,2%	12,7%	0,0%	15,4%
Scenario 2		0,0%	11,8%	34,4%	0,0%	0,0%	6,1%	0,0%	4,3%	12,2%	12,5%	0,0%	17,1%

Scenario	Piping						HVAC						Cable Trays						Secondary steel					
	Avg_b	Avg aft	KPI_ro bef	KPI_ro aft	KPI_rs bef	KPI_rs aft	Avg_b	Avg aft	KPI_ro bef	KPI_ro aft	KPI_rs bef	KPI_rs aft	Avg_b	Avg aft	KPI_ro bef	KPI_ro aft	KPI_rs bef	KPI_rs aft	Avg_b	Avg aft	KPI_ro bef	KPI_ro aft	KPI_rs bef	KPI_rs aft
AS-IS	119	18	1,03	1,45	0,5	0,63	31	11	1,11	1,39	0,62	0,73	43	2	2,46	1,98	0,97	0,67	27	1	2,3	2,01	0,9	0,71
Scenario 1	103	14	0,58	1,48	0,36	0,64	30	10	1,48	1,39	0,56	0,75	43	2	2,52	1,98	0,94	0,67	31	4	1,60	1,24	0,58	0,64
Scenario 2	101	14	0,60	1,48	0,37	0,64	29	10	1,53	1,39	0,59	0,75	42	2	2,43	1,98	0,96	0,67	30	4	1,51	1,24	0,60	0,64

Figure 7.28: Final process characteristics per scenario

Both scenarios show an improvement of the performance and most controllability areas. Depending on the opinion of the project manager, a specific scenario can be chosen.

7.8.3 Recommendations

In order to find the best outfit scenario for a project, it is recommended to use the Planning Generator and run scenarios for multiple different POF percentages and POF phase durations simultaneously. Within this case study 5ˆ12 x 27 = 6591796875 different output scenarios can be calculated taking 3 groups of section types, 4 disciplines, 5 different POF percentages and 3 different POF phase durations into account. It would costs more than 250.000 years to run this simulation with a current average run-time of 20 minutes. Therefore the following iteration process is recommended:

Step 1: Calculate the process characteristics of the current situation
Step 2: Calculate the process characteristics for varying POF percentages for each discipline separately
Step 3: Fix the new POF percentages of the discipline with the best improvement results
Step 4: Calculate the process characteristics for varying POF phase durations
Step 5: Fix the POF phase durations of the best output scenario
Step 6: Go back to step 2 until all disciplines have their optimal POF percentages

7.9 Effect of changing erection schedule

7.9.1 Introduction

For most shipbuilding project a more or less standard section erection sequence is used. Complex sections that require longer lead times, such as engineroom sections, are placed on the slipway as soon as possible. The erection of sections of a pipe laying vessel starts for example most often with the moonpool section and from there other sections are coupled in each direction.

After the analysis of the production of Ynr 730 with only 1 section erection schedule, another erection schedule is used in order to see the effect of this schedule on the controllability and performance of the outfitting processes. The section erection sequence of the production of Ynr 733 is used. This pipe laying vessel is a copy of Ynr 730 and is built at location Kinderdijk. The vessel is built with the fore ship pointing to the water while Ynr 730 was built at location Krimpen with its stern in the direction of the water. This influenced the erection sequence. At the start of the erection of the sections of Ynr 730 main focus is first put on the sections in the fore ship while during the erection of the sections of Ynr 733 besides focus on the fore ship sections, relatively more focus was put on sections in the mid ship of the vessel. Another difference between both schedules is that during the production of Ynr 733, the accommodation sections have assembled first. After the launch, the whole accommodation is lifted on the vessel. Appendix N gives an overview of both section erection schedules.

7.9.2 Effect on the workload

With the new erection schedule, the same sections need to be outfitted and the same amount of work per unit needs to be carried out. Only the start and end times of the phases and activities within the outfit planning changed. This leads to a change in workload over time for each discipline. An example is shown in Figure 7.29 below that presents the new workload of the cable tray discipline.

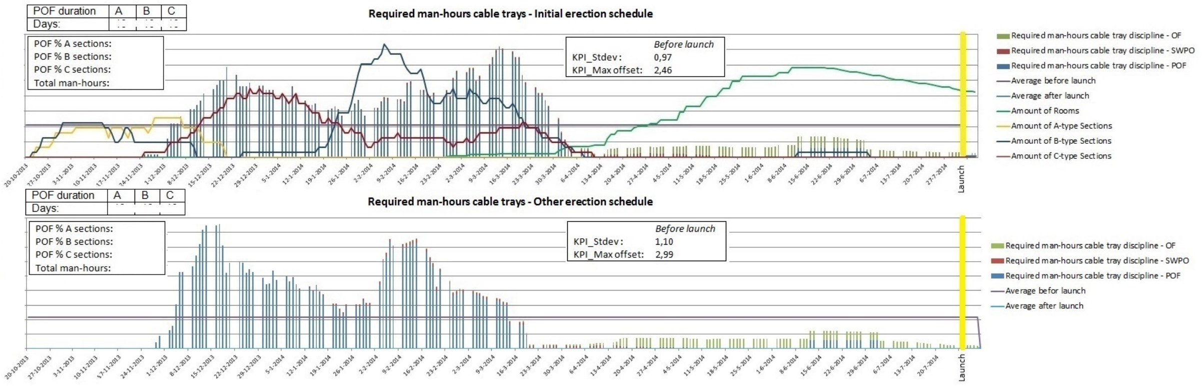


Figure 7.29: Results workload changes after implementation new section erection schedule

Differences in the distribution of the workload are noticed compared to the situation with the initial erection sequence which also results in different expected controllability KPI values. However, the total amount of required man-hours does not change while the amount of work carried out in each phase stays equal. Also, the main workload distribution stays the same while the basis of both erection schedules does not differ much.

7.9.3 Effect on the unit occupancy

The unit occupancy remains the same while the phase durations are similar as well as the amount of work that needs to be carried out in each section, room, tank or ship part.

7.9.4 Effect on the crane occupancy

For different erection sequences, the amount of sections and type of sections positioned at a certain moment in time in the POF hall changes which effects the required crane capacity over time. Therefore also a change in the erection sequence effect the crane occupancy. The influence of the new erection sequence is shown in Figure 7.30 below.

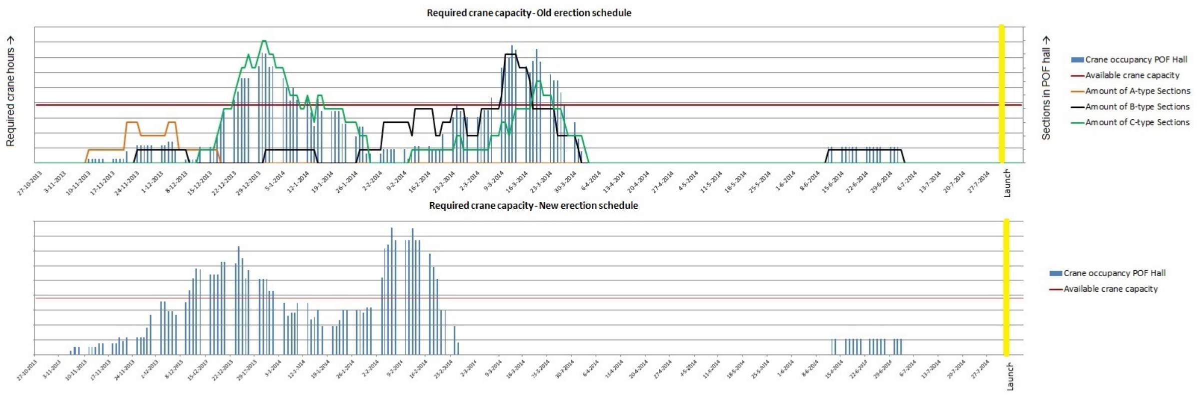


Figure 7.30: Results crane occupancy changes after implementation new section erection schedule

Significant differences in required crane occupancy are noticed between both production scenarios. This shows that the erection sequence does have a large influence on the crane occupancy controllability.

7.9.5 Effect on the floor occupancy

Also the floor occupancy changes when adjustments are made within the erection planning. The section erection planning is required for the generation of an outfit planning by the *Planning Generator*. This erection planning is made by a project planner that also takes the floor occupancy into account. It is therefore expected that the floor occupancy will not exceed the available capacity when using standard phase durations.

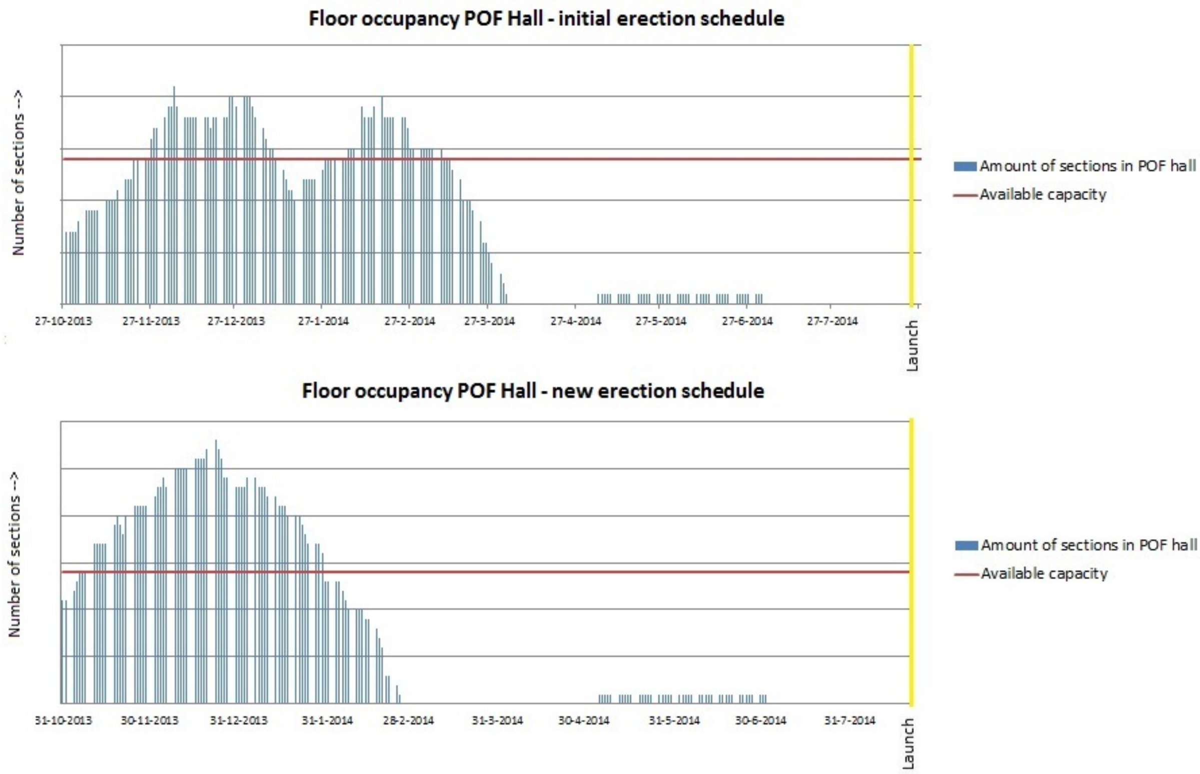


Figure 7.31: Results floor occupancy changes after implementation new section erection schedule

Significant differences in the required floor occupancy are noticed when changing the erection planning.

7.9.6 Conclusions

The section erection sequence does have a large influence on the workload, the crane occupancy and the floor occupancy. It does not influence the performance and the unit occupancy. However, due to a more of less standard erection strategy used by the yard, it is expected that main shape of the occupancy graphs will remain.

This part of the research also shows that the outsource strategy has a large influence on the controllability of the outfit processes. Having an outfit planning in an early phase using the Activity Loader and the Planning Generator enables a project planner to take the controllability of the outfitting processes into account for the determination of the outsource strategy.

7.10 Certainty analysis

7.10.1 Introduction

The estimations given in the first part of the research and the production scenario generated in the second part contain a level of uncertainty. The possible offset of the required man-hours for each discipline is already discussed in the first part but is measured within this case study for Ynr 730. This uncertainty contains the possible offset between the estimated amount of work and the real amount of work in a section or room. The following steps are taken in order to determine the 68% certainty level and 95% certainty level.

Step 1: The specific standard deviations (expected offsets) for each section type are calculated in the first part of the research.

Step 2: For each section and specific activity, the standard deviation of the man-hours (offset for 68% certainty) is added to the initial amount of man-hours required for that activity.

Step 3: The new production scenario with the increased amount of man-hours is generated by the *Planning Generator*.

Step 4: For each activity the offset in man-hours is calculated by subtracting the initial estimated man-hours from the man-hours calculated in the new scenario.

Step 5: 'The concept of propagation' [1] is used where the final upper and lower limit of the 68% certainty boundary is found during each day for each specific discipline.

Step 6: In order to calculate the upper and lower boundary of the certainty level of 95%, step 2 until 5 are taken using an offset of twice the standard deviation.

7.10.2 Certainty: Workload Piping

Figure 7.32 below shows certainty range of 68% and 95% for the amount of man-hours required for the installation of piping.

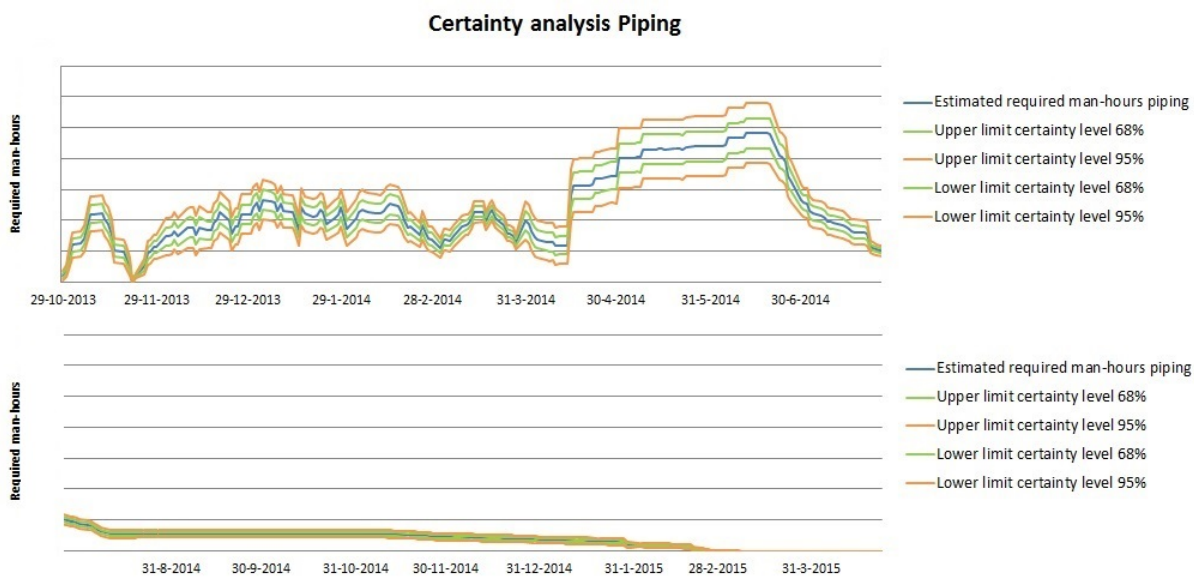


Figure 7.32: Results certainty analysis workload piping discipline

[1]When the quantity whished to specify is not directly measured, but is calculated from two or more directly measured quantities, the uncertainty in the derived quantity must be determined from the uncertainties in the measured quantities from which it is calculated [23]

The uncertainty varies over time and depends on the type and amount of sections or rooms in which outfit activities are carried as well as the amount of work carried out in each phase. The largest uncertainty is noticed at the start of the outfit phase in the rooms. The large amount of rooms in which outfit activities take place results in a large total uncertainty. The highest offset within a certainty range of 68% is x man-hours and x man-hours for a certainty range of 95%. This is similar to x or x extra required workers. After the first commissioning dead lines (launch of the vessel and the start of the engines) less rooms are outfitted which results in a relatively low uncertainty. The uncertainty during the POF period is more constant and seems to be most effected by the amount of sections in the POF hall.

The uncertainty does have a high effect on the controllability while it might lead to an unexpected increase of the required amount of persons at a specific moment during the project. Therefore, it is highly recommended to improve the quality of the method used in order to increase the level of certainty.

7.10.3 Certainty: Workload HVAC

Figure 7.33 below shows certainty range of 68% and 95% for the amount of man-hours required for the installation of HVAC piping and ducting.

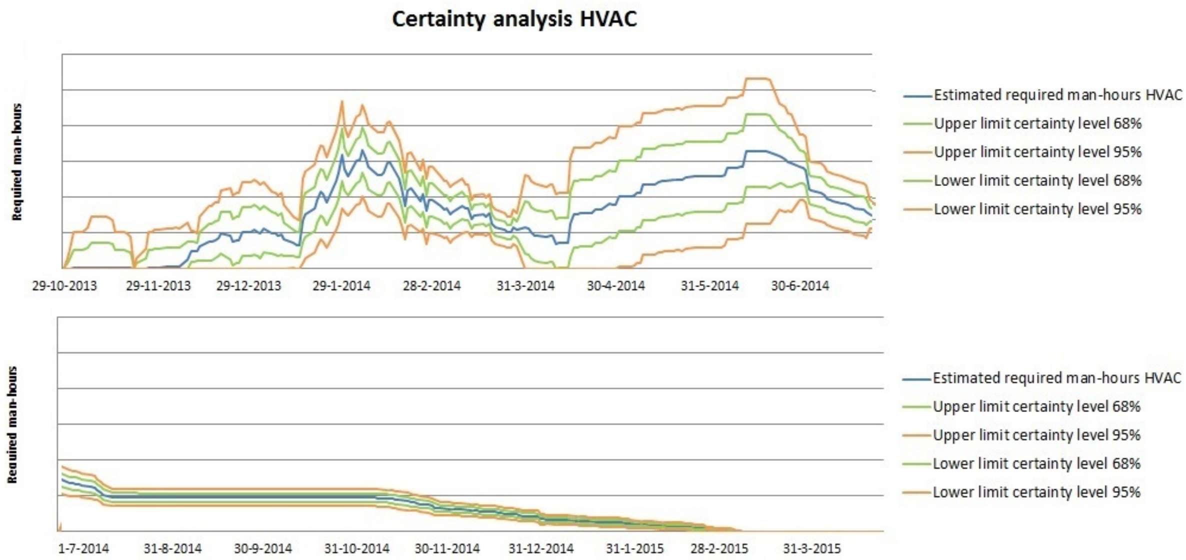


Figure 7.33: Results certainty analysis workload HVAC discipline

The uncertainty varies over time and depends on the type and amount of sections or rooms in which outfit activities are carried out as well as the amount of work carried out in each phase. The largest uncertainty is noticed at the start of the outfit phase in the rooms. The large amount of rooms in which outfit activities take place results in a large total uncertainty. The highest offset within a certainty range of 68% is x man-hours and x man-hours for a certainty range of 95%. This is similar to x or x extra required workers. After the first commissioning dead lines (launch of the vessel and the start of the engines) less rooms are outfitted which results in a relatively low uncertainty. The uncertainty during the POF period fluctuates and seems to be effected by the amount and type of sections in the POF hall.

The uncertainty does have a high effect on the controllability while it might lead to an unexpected increase of the required amount of persons at a specific moment during the project. Therefore, it is highly recommended to improve the quality of the method used in order to increase the level of certainty.

7.10.4 Certainty: Workload Cable Trays

Figure 7.34 below shows certainty range of 68% and 95% for the amount of man-hours required for the installation of cable trays.

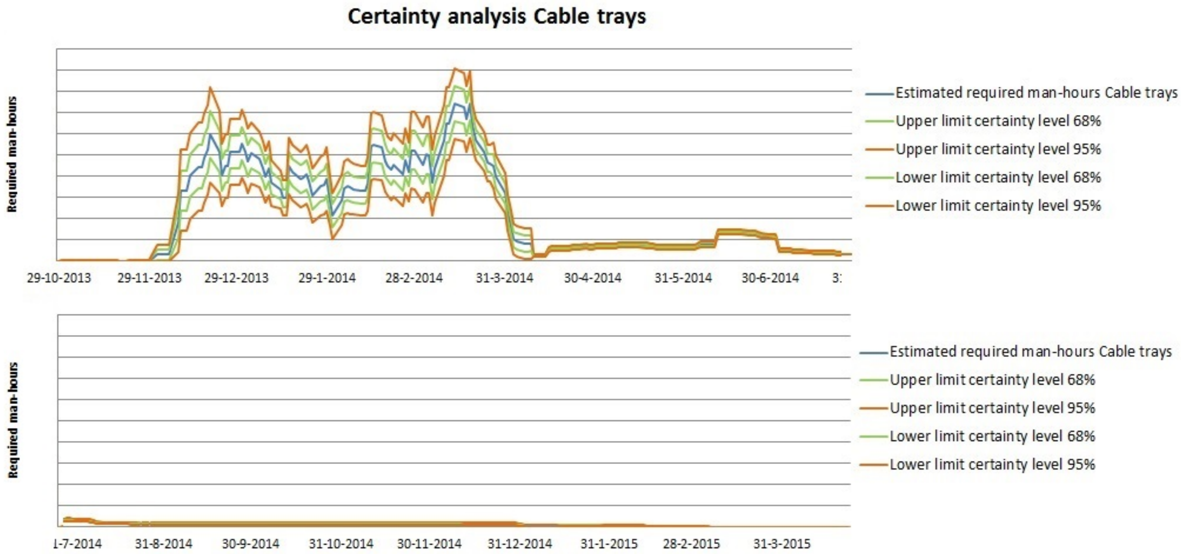


Figure 7.34: Results certainty analysis workload Cable trays discipline

The uncertainty varies over time and depends on the type and amount of sections or rooms in which outfit activities are carried out as well as the amount of work carried out in each phase. The largest uncertainty is noticed during the POF period. The large amount of work due to a high POF percentage (90%) results in a large total uncertainty. The highest offset within a certainty range of 68% is x man-hours and x man-hours for a certainty range of 95%. This is similar to x or x extra required workers. The uncertainty during the outfit period in the rooms is significantly smaller due to only little amount of work that needs to be carried (5%).

The uncertainty does have a high effect on the controllability while it might lead to an unexpected increase of the required amount of persons at a specific moment during the project. Therefore, it is highly recommended to improve the quality of the method used in order to increase the level of certainty.

7.10.5 Certainty: Workload Secondary steel

Figure 7.35 below shows certainty range of 68% and 95% for the amount of man-hours required for the installation of secondary steel components.

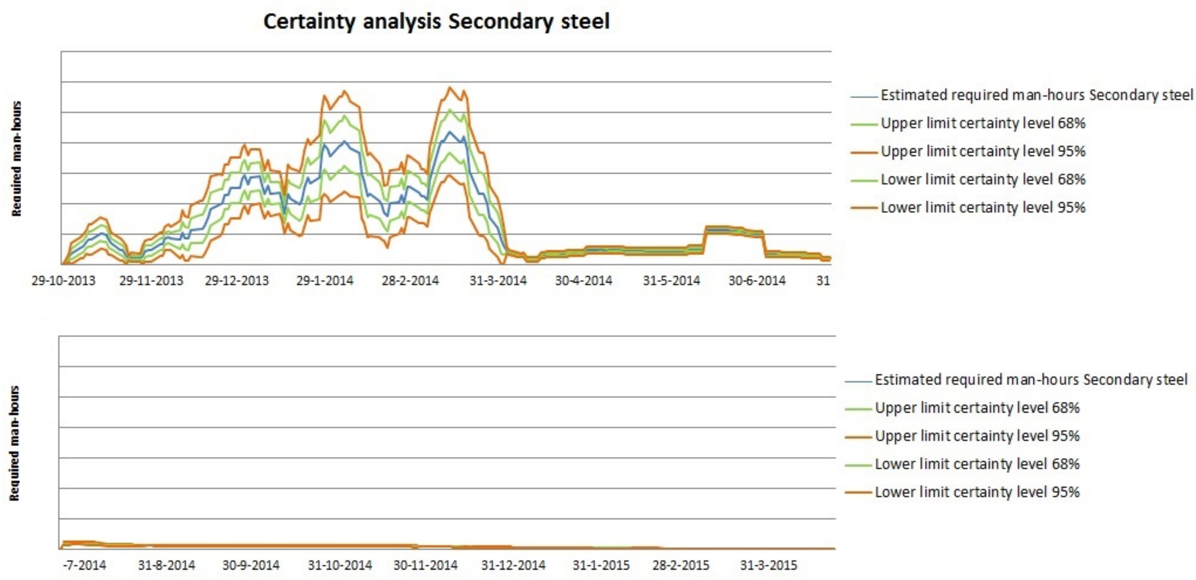


Figure 7.35: Results certainty analysis workload Secondary steel discipline

The uncertainty varies over time and depends on the type and amount of sections or rooms in which outfit activities are carried out as well as the amount of work carried out in each phase. The largest uncertainty is noticed during the POF period. The large amount of work due to a high POF percentage (90%) results in a large total uncertainty. The highest offset within a certainty range of 68% is x man-hours and x man-hours for a certainty range of 95%. This is similar to x or x extra required workers. The uncertainty during the outfit period in the rooms is significantly smaller due to only little amount of work that needs to be carried (5%).

The uncertainty does have a high effect on the controllability while it might lead to an unexpected increase of the required amount of persons at a specific moment during the project. Therefore, it is highly recommended to improve the quality of the method used in order to increase the level of certainty.

7.10.6 Certainty conclusions

The figures shown for each discipline show that the uncertainty depends on the amount and type of sections and rooms but also on the amount of work that should be carried out per phase. For the piping and HVAC disciplines a relative large uncertainty is noticed at the start of the outfit phases in the rooms while the uncertainty during this period is significantly smaller for the cable trays and secondary steel discipline.

Other possible uncertainties are not taken into account within this analysis. Most important uncertainties such as the uncertainty in the man-hour factors between different outfit phases or the uncertainty within the crane occupancy should be further researched.

It is recommended to also determine the uncertainty within the unit occupancy and crane occupancy values. In order to determine the uncertainty in the unit occupancy, the uncertainty values of the disciplinary workload can be used. Due to the fact that models created in this research only obtain the activities of 6 disciplines, the room occupancy does not give feasible values and can therefore not be taken into account. For the determination of the uncertainty of the crane occupancy, further research should be carried out to validate the methods and values used for the determination of the required crane hours per activity in order to obtain expected offsets.

Currently, no sufficient data exists to perform a full validation for the required amount of man-hours of each discipline, the unit occupancy and crane occupancy during the entire project. However, it would be interesting to test the output of the model with such data in order to see the offset. It is therefore recommended to the Yard to collect as much data as possible, maybe even in cooperation with the subcontractor, in order to improve the controllability of the processes.

8 | Conclusions

Outfit planning in shipbuilding is currently not sufficiently investigated. The outfitting processes are characterized by low level planning and poor organization. Interferences, disturbances, great interdependencies and different surrounding area requirements lead to delays, longer lead times, higher costs, more rework and a lower quality. In this research possible ways are developed to increase the controllability of these processes in order to reduce the number of unexpected events. Initially, it was intended to take the whole outfitting process into account. However, due to insufficient time, main focus is put on the controllability of the outfit processes within the pre-outfit phase.

In order to choose a specific 'best' production scenario within the pre-contract phase of a shipbuilding project, with the highest expected controllability and performance, at first the outfit activities should be known. The *Activity Loader* is able to create a list providing all required information about the outfit activities including the corresponding certainty range using only basic vessel specifications, a section plan and a first version of the general arrangement and tank arrangement.

After the obtainment of an overview of all outfit work to be carried out during the project, the project planner and project manager should select the production scenario with the preferred planning characteristics using the *Planning Generator* in order to optimize the controllability and performance of the outfitting processes during the project. The controllability decreases in case of an undesirable behavior of the workload, when collisions between activities occur, when the crane occupancy exceeds the available crane capacity but also when more floor space is required than available. The *Planning Generator* is able to determine in an early phase the chance of occurrence of those events by measuring and judging the workload, the unit occupancy and the crane and floor occupancy over time. The generation of an outfit planning containing a higher level of controllability for a similar or lower total amount of required man-hours results in less expected delays, waiting times and rework and lead to lower unexpected costs.

This research showed that the chosen pre-outfit percentage per discipline and per section influences the controllability and performance of the outfit processes. Also the duration of the pre-outfit phase of each section has a significant influence on specific process characteristics influencing the controllability. It is therefore important that the project planner and project manager make a substantiated choice about the pre-outfit percentage and pre-outfit duration in an early phase.

For each project, best planning characteristics should be selected separately instead of using a specific tendency for all shipbuilding projects due to the large influence of the section erection schedule on the controllability.

The case study of the production of Ynr 730 showed that it is possible to improve the workload, the section occupancy and the crane occupancy in the pre-outfit hall for a scenario with a feasible floor occupancy. The following lessons are learned and tendencies are discovered during the case study:

- The POF percentage and POF phase duration chosen for each type of section influence all the types of controllability taken into account.
- The workload controllability is more influenced by the selected POF percentages compared to the selected POF phase durations.
- The unit occupancy controllability is more influenced by the selected POF phase durations compared to the selected POF percentages.
- The crane occupancy controllability is more influenced by the selected POF percentages compared to the selected POF phase durations.
- The floor occupancy is only influenced by the POF phase durations.
- It is preferred to use lower POF percentages for complex sections with more outfit work and higher POF percentages for sections with less outfit work in order to improve the controllability.

- It is preferred to use longer POF phase durations for complex sections with more outfit work and shorter POF phase durations for sections with less outfit work in order to improve the controllability.

9 | Recommendations

Within this chapter 3 types of recommendation are given. At first, recommendations to Royal IHC are given. Secondly, recommendations are given for further research where after also recommendations are given for the improvement of both the *Activity Loader* and the *Planning Generator*.

9.1 Recommendations to Royal IHC

It is recommended to Royal IHC to use computerized estimation tools, such as the *Activity Loader* and the *Planning Generator*, to obtain an outfit planning with preferable process characteristics in an early phase of the process. During the strategy determination process of the production scenario specific strategies can be researched that influence the controllability and performance such as outsourcing sections, changing the erection sequence but also changing the POF percentages and POF phase durations. After the obtainment of this planning, discussions should be held between al parties involved in an early phase in order to discuss the strategy in more detail and prevent for specific difficult uncontrollable situations. The main planning and the planning of each subcontractor becomes transparent before starting the actual outfit activities and agreements can be made between yard and subcontractors but also between the subcontractors themselves.

The uncertainty within both models still has a significant high level. In order to decrease the uncertainty and obtain ore feasible output scenarios it is recommended to Royal IHC to start recording production data within the outfitting processes. Below, specific process characteristics which should be recorded for each yardnumber from now on are listed:

- For each discipline the total amount of components per section and room
- For each activity the start and end time and the required amount of man-hours when possible
- The crane occupancy for each activity when crane usage is required

It is recommended to Royal IHC to implement a 'feedback loop' in the process that notices uncontrollable situations and provides possible improvements for the future. The planner should research the direct cause of a delay, a rework activity or waiting time when these are noticed. The situation should be compared with the planning and it should be determined whether this event could have been prevented by choosing another strategy in the beginning or not. After each project, the project team should discuss these events in order to locate specific tendencies and find possible improvement for future projects. The total amount of information obtained within this 'feedback loop' can finally also be used to determine whether the controllability is improved as it was expected by the output of the model. This method can be used as validation of the assumptions made within this research.

9.2 Recommendations for further research

The conceptual models found in the first part of this research have a certain uncertainty which is unacceptable in some cases. Therefore it is recommended to carry out further research for the improvement of the estimation methods used in order to decrease the uncertainty of the estimation.

It is recommended to perform a detailed research to the factors multiplying the amount of man-hours in each phase. In this research 1 factor is used per discipline but the factor differs in real-life per component type and might therefore be different for each section, dependent on the type of components in that unit.

In order to complete the production scenario and to obtain a feasible picture of the outfit period in the rooms, it is recommended to carry out research to the conceptual models of the missing disciplines.

It is recommended to research the possibilities for the creation of similar models with conceptual models and estimation methods for the engineering and purchasing department. While these departments are heavily interdependent with the production department it is recommended to create 1 model that obtains all different departments.

It is recommended to carry out further research to the best selection of sections forming groups when using the *Planning Generator*. These sections all have the same POF percentages and POF phase durations and the specific selection of groups influences therefore the potentiality of the improvements.

9.3 Recommendations for model improvement

This researched showed that the workload controllability for each subcontractor is significantly influenced by the moment that the subcontractor changes the size of his team. Within the *Planning Generator* only once, either after the POF period or after the launch, the size of the team is changed. However, in the real situation more team size changes occur which leads to a higher controllability. Therefore a method should be implemented in the *Planning Generator* that calculates the best moments to change te size of the teams using the workload over time of each discipline and specific constraints such as 'the maximum amount of team size changes per project' or 'the minimum duration of the usage of 1 team size'.

It is a challenge to find a KPI that measures the controllability of the workload without the need of a human opinion. Preferably the required amount of man-hours changes as little as possible. Therefore it might be interesting to use the second derivative of the workload graph. The total surface under the graph would be the value presented by the KPI.

Currently, it takes 30 minutes to run the *Planning Generator* in order to obtain the output of a full production scenario using a duo core 5 year old laptop. In this run, the complete production process is (re)calculated. When a run is carried out where multiple production scenarios are calculated for varying input values, it might take a few days to finish the run. It is recommended to change the model in such a way that only specific process characteristics change within the planning obtained after the first run, instead of building a whole new planning. This would save a significant amount of time.

New functional requirements model

Functional requirements of the *Activity Loader* are:

- The *Activity Loader* automatically generates input sheets using only limited vessel information.
- The *Activity Loader* estimates the required amount of outfit work for all units (sections, rooms, tanks and ship parts).
- The *Activity Loader* translates the amount of work per activity into the required amount of man-hours.
- The *Activity Loader* estimates the required amount of crane-hours for each activity.
- The *Activity Loader* creates section, room, tank and ship part outfit activity lists including specific activity characteristics such as start and end constraints.
- The *Activity Loader* is able to export the final output to the *Planning Generator*.

Functional requirements of the *Planning Generator* are:

- The *Planning Generator* divides the amount of work that should be carried out over all phases using the outfit percentages per phase and the specific rooms that belong to a section.
- The *Planning Generator* inserts scaffolding activities where required.
- The *Planning Generator* inserts commissioning activities where required.
- The *Planning Generator* inserts start dates, end dates and durations for all activities using the given constraints and other input information.

- The *Planning Generator* creates a complete outfit planning including all outfit activities in all units (sections, rooms, tanks and ship parts).
- The *Planning Generator* determines the best amount and best moments of team size changes for each subcontractor using the constraints.
- The *Planning Generator* calculates most important outfit process characteristics and KPI's.
- The *Planning Generator* draws figures that present the behavior of the workload over time per discipline, the unit occupancy over time, the crane occupancy over time and the floor occupancy over time.
- The *Planning Generator* consists of a mechanism that is able to run multiple different scenarios, by only changing specific process characteristics in the initial planning, and saves all different outputs in order to locate possible improvements in the outfit process.

Appendices

A | Appendix: Vessels used

This Appendix shows the specifications of all vessels used within this research

B | Appendix: Figures literatuur review

The figures below show for specific disciplines the world wide installation strategy. The figures are based on a research carried out by the RAND organization about possible POF strategies. [1]

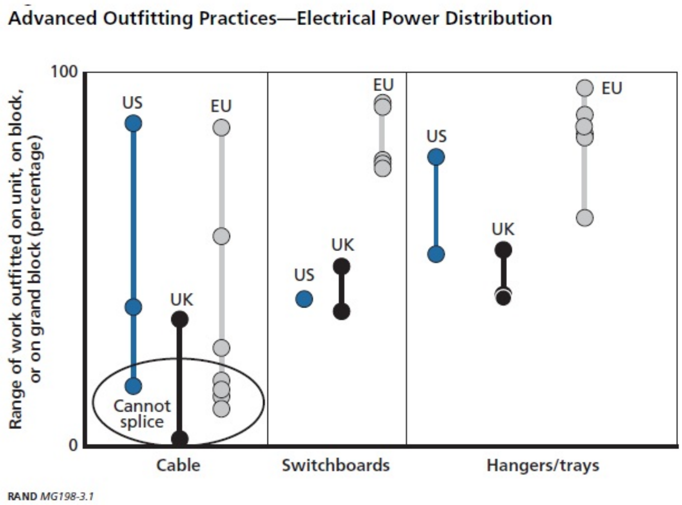


Figure B.1: Worldwide strategy POF percentages of components within the electrical discipline [1]

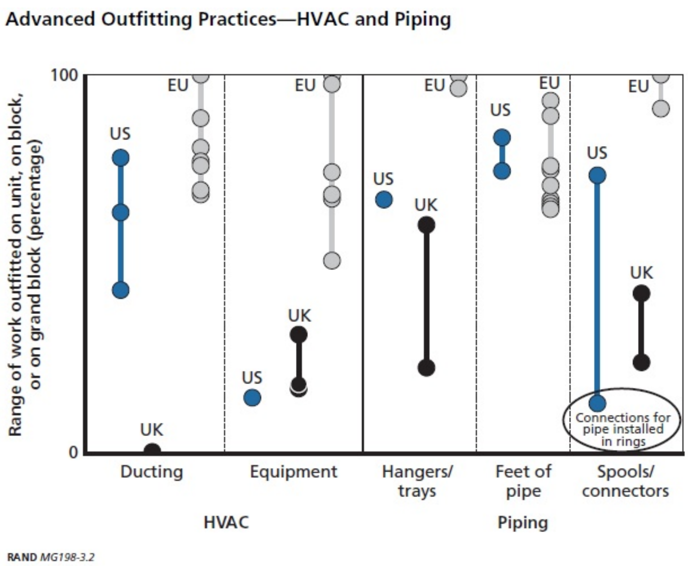


Figure B.2: Worldwide strategy POF percentages of components within the HVAC and piping discipline [1]

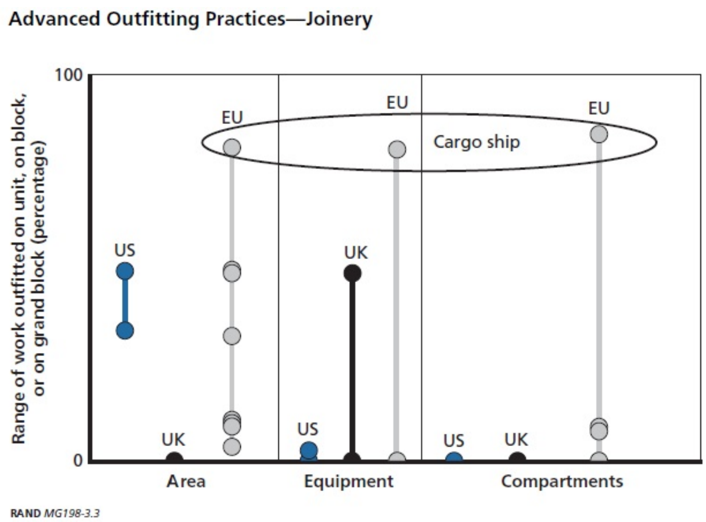


Figure B.3: Worldwide strategy POF percentages of components within the joinery discipline [1]

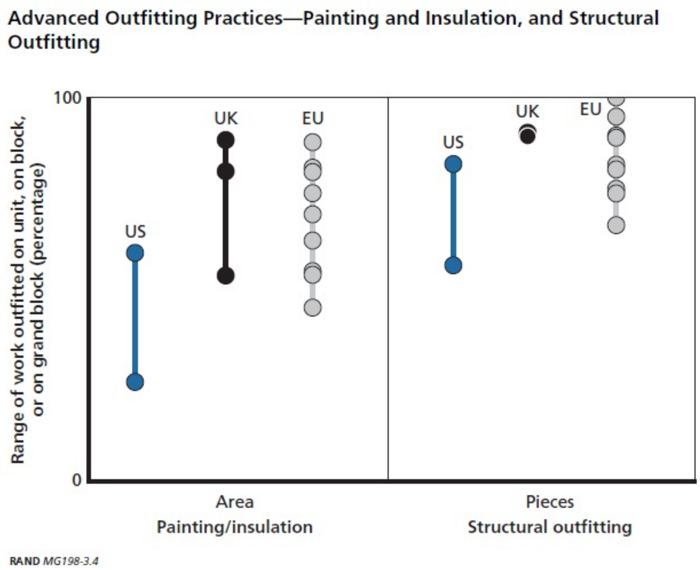


Figure B.4: Worldwide strategy POF percentages of components within the painting, insulation and secondary steel work discipline [1]

C | Appendix: Statistics

Regression analysis

After obtaining a suitable dataset of historical projects, a valid and applicable statistical method should be selected depending on the type of data and the desired type of output. Regression analysis are most often carried out in order to define relationships with correct feasible parameter values.

Regression analysis is a statistical tool for the investigation of relationships between variables. Using this technique, data is assembled on the underlying variables of interest and is used to estimate the quantitative effect of the causal variables upon the variable that they influence. Afterwards the investigator most often assesses the degree of confidence that the true relationship is close to the estimated relationship [24].

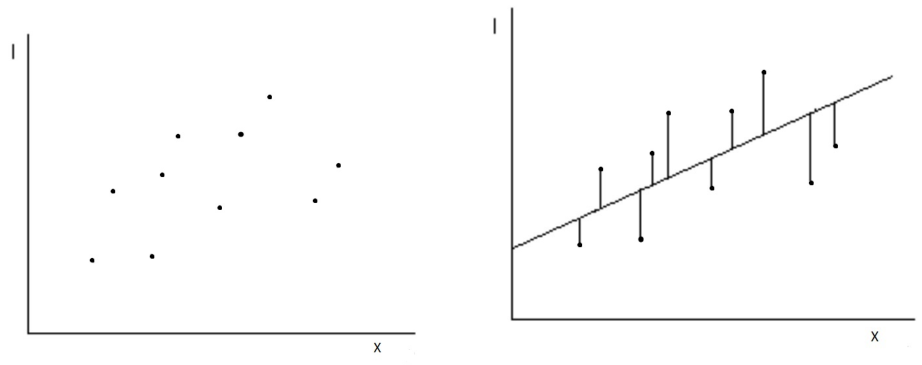
A simple regression analysis starts with a dataset containing data from a real life problem. At the outset of any regression study, one formulates some hypotheses about the relationship between the variables of interest. Afterwards, the data is drawn in a graph with the specific variables on the X- and Y-axis. An example is shown in Figure C.1a. Due to the fact that all data points are most often not positioned on one straight line, a formula has to be defined to estimate the relationships between the variables. A simple hypothesized linear relationship between the variables might be written as [24]:

$$I = \alpha X + \beta + \varepsilon \tag{C.1}$$

where

$I =$ quantity to be estimated
$\alpha =$ The effect of one variable on the other
$X =$ dependent variable
$\beta =$ A constant amount
$\varepsilon =$ The "noise" of other influences which are not taken into account

In regression analysis, the noise term has most often no systematic property but is on average equal to zero. The line which is described by the formula shown above can be drawn in the graph. An example is shown in Figure C.1b.



(a) Example of dataset in graph

(b) Example of offset after regression through given data

Figure C.1: Regression analysis

Sometimes multiple variables influence each other and the relationship can only be determined when all variables are taken into account. For multiple regression the following formula is used:

$$I = \alpha X + \beta Y + \gamma + \varepsilon \tag{C.2}$$

where

$\alpha =$ The effect of one variable on the others

$\beta =$ The effect of one variable on the others

$\gamma =$ A constant amount

$\varepsilon =$ The "noise" of other influences which are not taken into account

The difference with the simple regression is that a line in a two dimensional diagram can not be used - with two explanatory variables a third dimension is required. Instead of estimating a line, here a plane is estimated.

Determination of dependent variable - correlation coefficient

In order to determine the quality of the relationship between two variables, the linear correlation coefficient 'r' can be used. This coefficient measures the strength and the direction of a linear relationship between two variables [16]. The mathematical formula for computing the value of 'r' is:

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{n(\sum x^2) - (\sum x)^2}\sqrt{n(\sum y^2) - (\sum y)^2}} \text{ where}$$

$n =$ pairs of data

$x =$ Variable X

$y =$ Variable Y

- The value of r is such that $-1 \leq r \geq 1$
- When r does have a value of 1 it means that there is a perfect positive correlation between the variables taken into account.
- When r does have a value of -1 it means that there is a perfect negative correlation between the variables taken into account.
- A coefficient close to zero indicates that no systematic co-varying exists between the variables.
- A correlation greater than 0.8 is generally described as *strong*, whereas a correlation less than 0.5 is generally described as *weak* [16].

Least square method

One of the ways to calculate the linear regression is to apply the least square method. The method of least squares is a procedure to determine the best fit line to the data. Simple calculus and linear algebra are used in this method. The basic problem is to find the best fit straight line $y = ax + b$ for the dataset $n\varepsilon\{1, ...N\}$ with pairs x_n, y_n. The associated error may be defined as [25]:

$$E(a,b) = \frac{1}{N}\sum_{n=1}^{N}(y_n - (ax_n + b))^2 \tag{C.3}$$

The goal is to find the values for α and β that minimize the error. This is done by finding the corresponding values such that the differentials are equal to zero [25]:

$$\frac{\delta E}{\delta \alpha} = 0 \tag{C.4}$$
$$\frac{\delta E}{\delta \beta} = 0 \tag{C.5}$$
$$\tag{C.6}$$

Further solving this problem gives the formula shown below with which the final values for a minimal error can easily be calculated [25]:

$$\begin{pmatrix} \alpha \\ \beta \end{pmatrix} = \begin{pmatrix} \sum_{n=1}^{N} (x_n)^2 & \sum_{n=1}^{N} x_n \\ \sum_{n=1}^{N} x_n & \sum_{n=1}^{N} 1 \end{pmatrix}^{-1} \begin{pmatrix} \sum_{n=1}^{N} x_n y_n \\ \sum_{n=1}^{N} y_n \end{pmatrix} \tag{C.7}$$

In most of the researches the least square method is applied to find values for the corresponding parameters.

Standard deviation and average of absolute values

After obtaining a 'best fit line' for a given data set, the goodness of the fit must be determined. The calculated parameters are most often applied on a given dataset and the estimated values are compared with the real data. This small validation is than rated using the standard deviation or the average of the absolute difference in order to get an idea about the magnitude of the error.

In statistics the standard deviation is most often used to quantify the variation of a set of values. It can be calculated with the formula shown below:

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \bar{x})^2} \tag{C.8}$$

When the standard deviation is known, the estimator is able to say something about the certainty of the method used. The value of the standard deviation is the range in which the certainty is 68%. Figure C.2 explains this principle.

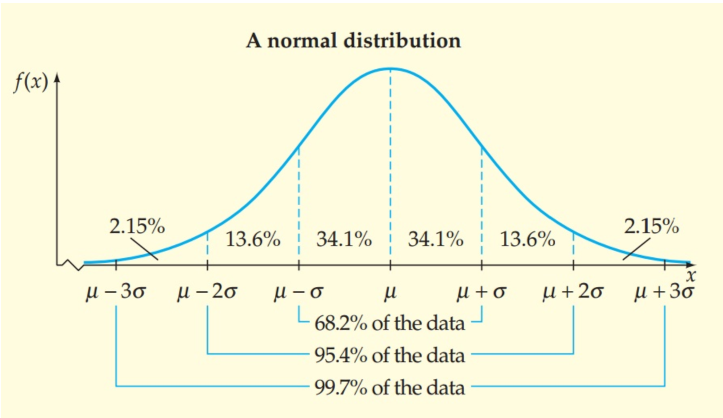


Figure C.2: Usage of standard deviation [7]

Another method of the analysis of the difference between the estimated values and the real values if the average of the absolute average. An advantage here is that cancellation of error is avoided due to the fact that all error are considered positive. The following formula is used:

$$avg = \frac{1}{N}\sum_{i=1}^{N} \mid (x_i - \bar{x}) \mid \tag{C.9}$$

No standard rules exist for a maximum allowable value for the standard deviation. For each situation it needs to be determined what the maximum allowable error is.

D | Appendix: Section types and room types

This Appendix shows the different types of sections defined in this research for pipe laying vessels and hopper dredgers. Also the room types used in this research for both vessel types are shown.

Part of vessel	Including double bottom	Mid or side sections	Aux	Description	No.
Mid ship					
	Sections incl. DB				
		Mid sections			
			With/Without Aux		
				Normal	1
				Moonpoolsection	2
		Side sections			
			With/Without Aux		
				Normal	3
	Sections above DB				
		Mid sections			
			With/Without Aux		
				Normal	4
				Moonpoolsection	5
				Deck sections	6
				Section against fore ship	7
		Side sections			
			With/Without Aux		
				Normal	8
				Section against fore ship	9
Fore ship	Sections incl. DB				
		Mid sections			
			Zonder aux		
				Boegsection	12
				Under ER	10
			Met aux		
				Under ER	10
				Bowthruster section	11
				Bowsection	12
		Side sections			
			With/Without Aux	Normal	13
	Sections above DB				
		Mid sections			
			With/Without Aux		
				Normaal	14
				Section with accommodation spaces	15
				Forecastle section	16
				Deck section	17
				Bowsection	18
		Side sections			
			With/Without Aux	Normal	19
				Section with accommodation spaces	15
				Deck section	17
Aft ship					
	Sections incl. DB				
		Mid / Side sections			
			With/Without Aux		
				Incl bottom plating, excl double bottom	20
				Normal	21
	Sections above DB				
		Mid sections			
			With/Without Aux		
				Normal	22
		Side sections			
			With/Without Aux		
				Normal	23
Accomodation					
	Sections above DB				
		Mid / Side sections			
				Section with accommodation spaces	24
				Wheelhouse	25
				Section on top of wheelhouse	26

Figure D.1: Overview section types pipelaying vessel

Part of vessel	Including double bottom	Mid or side sections	Aux	Description	No.
Midship					
	Sections incl. DB				
		Mid sections	With/Without Aux	Normal (Kippenkooi)	1
				At end of hopper (Kippenkooi)	2
				Under or incl pumproom / pump control room	3
				Sides midsections hopper (no sides of hull)	4
		Side sections	With/Without Aux	Include more deck above	5
				Next to pump room	6
				Normal (only tanktop)	7
	Sections above DB				
		Mid sections	With/Without Aux	Normal	8
				'Hatch sectiion, hanging over hopper'	9
				Section on deck	33
		Side sections	Without aux	Normal	10
			With aux	Normal	11
				Section where ladder is connected	12
Foreship	Sections incl. DB				
		Mid sections	With/Without Aux	Normal	13
				Bowsection	14
				Bowthrustersection	15
				Bulbsection	16
		Side sections	With/Without Aux	Normal	17
	Sections above DB	Mid/Side sections	Without aux	Normal	18
				Section with accommodation spaces	19
				Forecastle section	20
				Bowsection	14
				Bulbsection	16
			With aux	Normal	21
Aftship	Sections incl. DB	Mid/Side sections	With/Without Aux	Normal	22
				Under or incl ER / aux space	23
				Stearing gear section	24
	Sections above DB	Mid/Side sections	Without aux	Normal	25
				Deck section	26
				Section with accommodation spaces	33
			With aux	Normal	27
				Deck section	28
Accomodation	Sections above DB	Mid/Side sections		Section with accommodation spaces	29
				Section under wheelhouse "hondenhok"	30
				Wheelhouse section	31
				Section on top of wheelhouse	32

Figure D.2: Overview section types hopper dredger

	Room type		Pipelayer	Dredger
TECHNICAL SPACE	Thrusterroom		X	X
	Engineroom (ER)	*Deck 1*	X	X
		Deck 2	X	X
		Deck 3	X	X
	HPU room		X	X
	Pump room	*Jet pump room*		X
		Gland pump room		X
		Dredging pump room		X
	Pump motor room			X
	Winch room		X	X
	Switchboardroom		X	X
	Trafo room		X	
	Pipe flushing room		X	
			X	X
	Seperator room (FO treatment room)		X	X
	AC room		X	X
	Generator room		X	X
	Incinerator room		X	X
	Hydraulic room			X
	Steering gear room			X
	Chemical room		X	X
	Technical space	*Large*		X
		Small	X	X
NON-TECHNICAL ROOM	Control room	*Engine control room (ECR)*	X	X
		ROV control room	X	X
		Other control room	X	X
	Storage room	*Technical storage room*	X	X
		General storage room	X	X
	Workshop room	*Technical workshop room*	X	X
		General workshop room	X	X
	Accomodation room	*Changing room*	X	X
		Office	X	X
		Galley	X	X
		Mess room	X	X
		Recreation room	X	X
		Cabin	X	X
		Laundry room	X	X
		Gym	X	X
	Wheelhouse		X	X
OTHER SPACES	Alleyway		X	X
	Stairs		X	X
	Funnel		X	X
	Carroussel hold		X	
	Elevator		X	X
	Hopper area			X

Figure D.3: Overview room types pipelaying vessels and hopper dredgers

E | Appendix: Results outfitting - Piping

This Appendix shows figures used in the outfit research of the piping discipline. Also final results and output figures are shown.

Figures process characteristics piping

Item	Content	Time on average (minute)
Prepare documents and tools	Read 3D and 2D drawings	10
	Think and make the decision which is the next spool to be installed	10
	Search the spool in a pipe tray	10
Transport a pipe spool	Negotiate with the current user of a crane	5
	Wait for the crane	20
	Transport the pipe spool from the pipe tray to a steel section and place the pipe spool on its position	15
Make one support	Figure out the position of this support	2
	Measure and write down the distance from the center of the pipe spool to its nearby steel structure	3
	Walk to a workshop and make the support	15
	Pick up bolts and nuts in a storehouse and walk back to the steel section	5
	Weld the support on the steel structure and put the pipe spool on the support	5

Figure E.1: Values used for the estimation of the mounting time of a pipespool [8]

Type	Phase	Weight	Support
1	POF	≤ 50	1
2	POF	≤ 51	2
3	POF	≤ 52	3
4	POF	>50	1
5	POF	>50	2
6	POF	>50	3
7	SWPO	≤ 50	1
8	SWPO	≤ 51	2
9	SWPO	≤ 52	3
10	SWPO	>50	1
11	SWPO	>50	2
12	SWPO	>50	3
13	OF	≤ 50	1
14	OF	≤ 51	2
15	OF	≤ 52	3
16	OF	>50	1
17	OF	>50	2
18	OF	>50	3

Figure E.2: Definition different pipetypes used in research

Figures results, verification and validation hopper dredgers

Below, Figures are shown including the results of the research of the amount of pipe spools in sections of a hopper dredger.

System Type:		Air, Filling & Sound	Cooling water (Fresh and Auxiliary)	Bilge and ballast	Black water	Deck scupper and scupper piping	Driptray and sludge	Firefighting system and deckwash	Fuel oil lines (Service and Transfer)	Grey water
Depend on:		*Depth*	*Power*	*Length*	*Constant*	*LxB*	*Power*	*LxBxD*	*LxBxD*	*LxBxD*
Factor normal	*alpha (α)*	85,882	0,0195	3,5939	0	0,0374	0,0062	0,003	0,0097	0,0052
	constant (β)	-151,48	702,69	108,3	211,5	14,547	97,777	135,45	224,66	-61,491
Max line	*alpha (α)*	85,882	0,0195	3,5939	0	0,0374	0,0062	0,003	0,0097	0,0052
	constant (β)	-102,407	841,391	182,6357	296	41,2384	97,777	147,477115	404,6758	-61,491
Min line	*alpha (α)*	85,882	0,0195	3,5939	0	0,0374	0,0062	0,003	0,0097	0,0052
	constant (β)	-200,4678	605,825	57,212965	127	-37,4664	97,777	125,52625	120,40016	-61,491
Difference range	Ps	49	97	51	85	52	0	10	104	0
Min difference (1270)	%	0,42%	0,83%	0,44%	0,73%	0,45%	0,00%	0,09%	0,90%	0,00%
Max difference (7720)	%	1,59%	3,14%	1,66%	2,74%	1,69%	0,00%	0,32%	3,38%	0,00%
Correlation coefficient r	-	0,99	0,87	0,95	<0,80	0,94	0,94	0,98	0,95	0,99

System Type:		Hydraulic pipelines	Lubrication oil lines (Aux, transfer, service)	SANITARY FRESHWATER (hot/cold potable water)	SERVICE AIR	Starting air	Tank sounding	Gland flushing and degassing	Jetwater	Thermal oil
Depend on:		*Power*	*Length*	*Constant*	*Length*	*Constant*	*LxBxD*	*Deadweight*	*Hopper cap*	*Constant*
Factor normal	*alpha (α)*	0,0961	3,9565	0	0,901	0	0,0001	0,0167	0,0149	0
	constant (β)	301,73	-18,732	172,3333333	-20,711	53,23664738	16,822	106,64	317,53	1218
Max line	*alpha (α)*	0,0961	3,9565	0	0,901	0	0,0001	0,0167	0,0149	0
	constant (β)	1020,1218	148,9595	216	21,32435	170	21,8214	221,9442	379,85	1454
Min line	*alpha (α)*	0,0961	3,9565	0	0,901	0	0,0001	0,0167	0,0149	0
	constant (β)	-311,907	-138,692	143	-50,357	39	14,7825705	-103,04	225,2	982
Difference range	Ps	614	120	29	30	14	2	210	92	236
Min difference (1270)	%	5,27%	1,03%	0,25%	0,25%	0,12%	0,02%	1,80%	0,79%	2,03%
Max difference (7720)	%	19,90%	3,89%	0,95%	0,96%	0,46%	0,07%	6,80%	2,99%	7,65%
Correlation coefficient r	-	0,84	0,85	<0,80	0,82	<0,80	0,88	0,88	0,89	<0,80

Figure E.3: Step 1 - Results estimation parameters total amount of pipe spools per system - Hopper Dredgers

	Type	Aft ship	Mid ship	Fore ship	Accomodation	DB	Above DB	Mid	Side	AVG %	Min %	Max %	St dev (%)	New avg
Midship	1 tot 12		x			x	x	x	x	42,65846	38,98906	48,20428	3,989220367	42,7976
Foreship	13 tot 21			x		x	x	x	x	13,61478	10,02351	18,60774	3,641963103	13,65918
Aftship	22 tot 28 + 33					x	x	x	x	40,49652	36,37562	45,71105	3,888837933	40,62861
Accomodation	29 tot 32					n.a.	x	x	x	2,905127	2,508055	3,207029	0,293182428	2,914603
Totaal										*99,67488*				*100*
Group 1	1 tot 4		x			x		x		8,529765	7,611587	9,004616	0,649377082	8,557587
Group 2	5 tot 7		x			x			x	21,06274	17,40802	23,23382	2,599470087	21,13144
Group 3	8 tot 12		x				x	x	x	13,06596	8,143659	21,82317	6,208179387	13,10858
Group 4	13 tot 17			x		x		x	x	4,938457	2,238091	9,754656	3,413917136	4,954565
Group 5	18 tot 21			x			x	x	x	8,676319	7,785422	9,390445	0,667063438	8,704619
Group 6	22 tot 28 + 33	x				x	x	x	x	40,49652	36,37562	45,71105	3,888837933	40,62861
Group 7	29 tot 32				x		x	x	x	2,905127	2,508055	3,207029	0,293182428	2,914603
Totaal										*99,67488*				*100*

Figure E.4: Step 2 - Results pipe spool distribution in ship parts and groups - Hopper Dredgers

						Validation for group		
Sectiontype	**Group nr**	**Group tot %**	**Friendship**	**Leader?**	**Percentage calculated**	**St.dev (%)**	**Min difference**	**Max difference**
1	1	8,56%	A	Yes	0,99%	0,39%	0,00%	0,92%
2	1	8,56%	A	No	3,06%	0,39%	0,00%	0,92%
3	1	8,56%	A	No	3,48%	0,39%	0,00%	0,92%
4	1	8,56%	A	No	1,02%	0,39%	0,00%	0,92%
5	2	21,13%	B	Yes	19,85%	1,91%	0,02%	2,10%
6	2	21,13%	B	No	0,64%	1,91%	0,02%	2,10%
7	2	21,13%	B	No	0,64%	1,91%	0,02%	2,10%
8	3	13,11%	C	Yes	2,23%	2,89%	0,01%	6,49%
9	3	13,11%	C	No	0,00%	2,89%	0,01%	6,49%
10	3	13,11%	D	Yes	10,56%	2,89%	0,01%	6,49%
11	3	13,11%	D	No	0,00%	2,89%	0,01%	6,49%
12	3	13,11%		n.a.	0,32%	2,89%	0,01%	6,49%
13	4	4,95%	E	No	2,11%	1,60%	0,00%	4,06%
14	4	4,95%	F	No	0,02%	1,60%	0,00%	4,06%
15	4	4,95%	F	No	0,00%	1,60%	0,00%	4,06%
16	4	4,95%	F	No	0,32%	1,60%	0,00%	4,06%
17	4	4,95%	E	No	2,50%	1,60%	0,00%	4,06%
18	5	8,70%		n.a.	3,21%	0,65%	0,02%	1,02%
19	5	8,70%		n.a.	1,39%	0,65%	0,02%	1,02%
20	5	8,70%		n.a.	0,57%	0,65%	0,02%	1,02%
21	5	8,70%		n.a.	3,53%	0,65%	0,02%	1,02%
22	6	40,63%	G	No	0,00%	3,18%	0,49%	6,13%
23	6	40,63%	G	Yes	15,15%	3,18%	0,49%	6,13%
24	6	40,63%		n.a.	2,43%	3,18%	0,49%	6,13%
25	6	40,63%	H	No	0,00%	3,18%	0,49%	6,13%
26	6	40,63%	H	No	7,71%	3,18%	0,49%	6,13%
27	6	40,63%	H	No	7,51%	3,18%	0,49%	6,13%
28	6	40,63%	H	No	7,83%	3,18%	0,49%	6,13%
29	7	2,91%		n.a.	2,28%	2,20%	0,03%	0,41%
30	7	2,91%	I	No	0,30%	2,20%	0,03%	0,41%
31	7	2,91%	I	No	0,13%	2,20%	0,03%	0,41%
32	7	2,91%		n.a.	0,20%	2,20%	0,03%	0,41%
33	6	40,63%	H	No	0,00%	3,18%	0,49%	6,13%

Figure E.5: Step 2 - Results pipe spool distribution over section types including verification - Hopper Dredgers

	7720	11483	ps			718	9105	ps			1269	6766	ps		
Sectiontype			DIFF	ABS(DIFF)	Diff (ps)	REAL	ESTIMATE	DIFF	ABS(DIFF)	Diff (ps)	REAL	ESTIMATE	DIFF	ABS(DIFF)	Diff (ps)
1			0,00%	0,00%	0			0,00%	0,00%	0			0,02%	0,02%	1
2			-0,46%	0,46%	27			-0,42%	0,42%	19			0,92%	0,92%	62
3			0,00%	0,00%	0			0,00%	0,00%	0			0,00%	0,00%	0
4			0,02%	0,02%	0			0,00%	0,00%	0			0,00%	0,00%	0
5			-1,37%	1,37%	13			3,71%	3,71%	26			-2,10%	2,10%	18
6			0,00%	0,00%	0			0,02%	0,02%	1			0,00%	0,00%	0
7			-0,05%	0,05%	3			0,00%	0,00%	0			0,00%	0,00%	0
8			1,18%	1,18%	68			-1,32%	1,32%	30			0,31%	0,31%	21
9			0,00%	0,00%	0			0,00%	0,00%	0			0,00%	0,00%	0
10			2,67%	2,67%	19			-6,49%	6,49%	39			4,65%	4,65%	39
11			0,00%	0,00%	0			0,00%	0,00%	0			0,00%	0,00%	0
12			0,02%	0,02%	3			-0,90%	0,90%	82			0,01%	0,01%	0
13			0,85%	0,85%	49			0,00%	0,00%	0			-0,39%	0,39%	26
14			0,00%	0,00%	0			0,00%	0,00%	0			-0,36%	0,36%	24
15			0,00%	0,00%	0			0,00%	0,00%	0			0,00%	0,00%	0
16			0,00%	0,00%	0			0,02%	0,02%	2			0,00%	0,00%	0
17			1,86%	1,86%	53			2,11%	2,11%	64			-4,06%	4,06%	92
18			0,52%	0,52%	9			0,00%	0,00%	0			-0,27%	0,27%	5
19			0,41%	0,41%	16			-0,35%	0,35%	8			0,00%	0,00%	0
20			0,00%	0,00%	0			0,62%	0,62%	56			-0,91%	0,91%	62
21			-0,02%	0,02%	0			-0,99%	0,99%	23			1,02%	1,02%	17
22			0,00%	0,00%	0			0,00%	0,00%	0			0,00%	0,00%	0
23			1,96%	1,96%	28			-3,84%	3,84%	58			2,22%	2,22%	38
24			0,77%	0,77%	44			1,03%	1,03%	47			-1,46%	1,46%	99
25			0,00%	0,00%	0			0,00%	0,00%	0			0,00%	0,00%	0
26			0,49%	0,49%	6			-1,72%	1,72%	22			0,00%	0,00%	0
27			-4,87%	4,87%	80			6,13%	6,13%	279			-2,25%	2,25%	22
28			-3,43%	3,43%	49			0,00%	0,00%	0			0,00%	0,00%	0
29			0,41%	0,41%	8			-0,04%	0,04%	1			-0,27%	0,27%	6
30			-0,01%	0,01%	1			0,00%	0,00%	0			0,15%	0,15%	10
31			0,08%	0,08%	5			-0,32%	0,32%	30			0,03%	0,03%	2
32			-0,07%	0,07%	4			0,00%	0,00%	0			0,00%	0,00%	0
33			0,00%	0,00%	0			0,00%	0,00%	0			2,72%	2,72%	61
Average			*0,65%*		*15*			*0,91%*		*24*			*0,73%*		*18*
Min			*0,00%*					*0,00%*					*0,00%*		
Max			*4,87%*					*6,49%*					*4,65%*		
Stdev			*1,30%*					*1,91%*					*1,41%*		

Figure E.6: Results parameter and value verification - Hopper Dredgers

Section types									**Pipetypes**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
1	17,50%	0,86%	0,14%	44,91%	0,00%	0,00%	5,31%	2,15%	0,86%	2,58%	0,00%	0,00%	8,90%	3,44%	0,00%	13,34%	0,00%	0,00%
2	17,86%	2,88%	0,00%	14,01%	0,55%	0,00%	13,87%	1,37%	0,00%	7,14%	0,00%	0,00%	30,22%	3,98%	0,41%	7,69%	0,00%	0,00%
3	15,77%	4,10%	0,95%	10,09%	0,63%	0,00%	2,52%	0,00%	0,00%	0,63%	0,00%	0,00%	45,74%	6,94%	2,84%	9,46%	0,32%	0,00%
4	9,57%	0,00%	0,00%	20,87%	8,70%	0,00%	0,00%	0,00%	0,00%	11,30%	4,35%	0,00%	0,00%	0,00%	0,00%	37,39%	7,83%	0,00%
5	32,10%	13,40%	0,15%	13,79%	0,64%	0,00%	7,60%	2,35%	0,10%	2,06%	0,02%	0,00%	18,35%	5,00%	0,07%	4,14%	0,22%	0,00%
6	7,02%	0,00%	0,00%	35,09%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	24,56%	5,26%	0,00%	24,56%	3,51%	0,00%
7	46,84%	7,59%	0,00%	12,66%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	31,65%	1,27%	0,00%	0,00%	0,00%	0,00%
8	20,99%	2,71%	0,00%	14,22%	0,23%	0,00%	6,09%	0,68%	0,23%	2,03%	0,00%	0,00%	43,12%	8,35%	0,23%	0,68%	0,45%	0,00%
9	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
10	24,52%	7,97%	0,57%	10,04%	0,65%	0,04%	5,33%	0,89%	0,00%	1,50%	0,24%	0,00%	28,59%	11,71%	2,24%	5,49%	0,20%	0,00%
11	24,52%	7,97%	0,57%	10,04%	0,65%	0,04%	5,33%	0,89%	0,00%	1,50%	0,24%	0,00%	28,59%	11,71%	2,24%	5,49%	0,20%	0,00%
12	40,00%	2,76%	1,38%	6,90%	4,14%	0,00%	2,07%	1,38%	1,38%	2,76%	0,00%	0,00%	26,21%	6,90%	1,38%	1,38%	1,38%	0,00%
13	47,92%	2,78%	0,00%	10,42%	0,69%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	29,86%	0,00%	0,69%	7,64%	0,00%	0,00%
14	33,82%	7,35%	0,00%	8,82%	0,00%	0,00%	14,71%	5,88%	0,00%	0,00%	0,00%	0,00%	13,24%	11,76%	0,00%	4,41%	0,00%	0,00%
15	33,82%	7,35%	0,00%	8,82%	0,00%	0,00%	14,71%	5,88%	0,00%	0,00%	0,00%	0,00%	13,24%	11,76%	0,00%	4,41%	0,00%	0,00%
16	33,82%	7,35%	0,00%	8,82%	0,00%	0,00%	14,71%	5,88%	0,00%	0,00%	0,00%	0,00%	13,24%	11,76%	0,00%	4,41%	0,00%	0,00%
17	27,15%	0,99%	0,00%	4,64%	0,00%	0,00%	4,30%	0,66%	0,00%	5,63%	0,00%	0,00%	46,69%	0,66%	0,00%	9,27%	0,00%	0,00%
18	48,64%	4,23%	0,60%	5,14%	0,00%	0,00%	4,53%	0,60%	0,60%	0,00%	0,60%	0,00%	27,19%	3,02%	2,42%	2,11%	0,30%	0,00%
19	46,79%	0,77%	0,00%	7,46%	0,26%	0,00%	5,91%	0,77%	0,00%	0,77%	0,00%	0,00%	33,93%	3,08%	0,00%	0,26%	0,00%	0,00%
20	21,74%	0,00%	0,00%	5,43%	0,00%	0,00%	11,96%	0,00%	0,00%	2,17%	0,00%	0,00%	44,57%	9,78%	4,35%	0,00%	0,00%	0,00%
21	41,99%	4,38%	0,21%	4,38%	0,43%	0,00%	1,28%	0,32%	0,11%	0,96%	0,21%	0,00%	35,26%	3,95%	0,00%	6,52%	0,00%	0,00%
22	35,02%	2,81%	0,03%	6,23%	0,09%	0,00%	18,46%	1,76%	0,00%	1,70%	0,00%	0,00%	29,16%	1,23%	0,00%	3,51%	0,00%	0,00%
23	35,02%	2,81%	0,03%	6,23%	0,09%	0,00%	18,46%	1,76%	0,00%	1,70%	0,00%	0,00%	29,16%	1,23%	0,00%	3,51%	0,00%	0,00%
24	25,47%	3,14%	0,00%	0,00%	0,94%	0,00%	20,13%	7,86%	0,63%	0,00%	0,00%	0,00%	35,53%	6,29%	0,00%	0,00%	0,00%	0,00%
25	36,25%	3,48%	0,00%	10,66%	0,17%	0,00%	6,29%	0,73%	0,00%	1,74%	0,00%	0,00%	32,94%	2,41%	0,11%	5,11%	0,11%	0,00%
26	29,17%	3,74%	0,05%	3,07%	0,42%	0,00%	10,14%	0,31%	0,00%	0,88%	0,00%	0,00%	44,05%	3,95%	0,62%	3,59%	0,00%	0,00%
27	36,25%	3,48%	0,00%	10,66%	0,17%	0,00%	6,29%	0,73%	0,00%	1,74%	0,00%	0,00%	32,94%	2,41%	0,11%	5,11%	0,11%	0,00%
28	39,29%	4,64%	0,23%	6,11%	0,39%	0,00%	14,31%	0,77%	0,00%	1,86%	0,23%	0,00%	26,84%	2,86%	0,54%	1,86%	0,08%	0,00%
29	30,56%	1,16%	0,00%	0,00%	0,00%	0,00%	22,45%	1,85%	0,23%	0,00%	0,23%	0,00%	40,28%	2,08%	0,00%	0,93%	0,23%	0,00%
30	75,00%	0,00%	0,00%	0,00%	0,00%	0,00%	2,78%	0,00%	0,00%	0,00%	0,00%	0,00%	22,22%	0,00%	0,00%	0,00%	0,00%	0,00%
31	46,91%	2,47%	0,00%	1,23%	0,00%	0,00%	6,17%	0,00%	0,00%	2,47%	0,00%	0,00%	40,74%	0,00%	0,00%	0,00%	0,00%	0,00%
32	41,94%	12,90%	0,00%	9,68%	0,00%	0,00%	12,90%	0,00%	0,00%	0,00%	0,00%	0,00%	19,35%	0,00%	0,00%	3,23%	0,00%	0,00%
33	46,79%	0,77%	0,00%	7,46%	0,26%	0,00%	5,91%	0,77%	0,00%	0,77%	0,00%	0,00%	33,93%	3,08%	0,00%	0,26%	0,00%	0,00%

Figure E.7: Step 4 - Results percentage of pipetype for each section type - Hopper dredger

Figures results, verification and validation pipe laying vessels

Below, Figures are shown including the results of the research of the amount of pipe spools in sections of a pipe laying vessel.

System type:		Air, Filling & Sounding	Cooling water (Fresh and Auxiliary)	Bilge and ballast	Black water	Deck scupper and scupper piping	Driptray and sludge	Firefighting system and deckwash	Fuel oil lines (Service and Transfer)	Grey water
Depend on:		*Depth*	*Power*	*Length*	*Constant*	*LxB*	*Power*	*LxBxD*	*LxBxD*	*LxBxD*
Factor normal	*alpha (α)*	85,882	0,0195	3,5939	0	0,0374	0,0062	0,003	0,0097	0,0052
	constant (β)	4,3	702,7	592,3	232,0	445,4	97,8	312,8	224,7	398,2
Max line	*alpha (α)*	85,882	0,0195	3,5939	0	0,0374	0,0062	0,003	0,0097	0,0052
	constant (β)	53,4	841,4	666,6	316,5	472,1	97,8	324,8	404,7	398,2
Min line	*alpha (α)*	85,882	0,0195	3,5939	0	0,0374	0,0062	0,003	0,0097	0,0052
	constant (β)	-44,7	605,8	541,2	147,5	393,4	97,8	302,9	120,4	398,2
Difference range	**Ps**	98,1	235,6	125,4	169,0	78,7	0,0	22,0	284,3	0,0
Min difference (727)	**%**	0,64%	1,27%	0,67%	1,11%	0,68%	0,00%	0,13%	1,37%	0,00%
Max difference (7719)	**%**	0,35%	0,70%	0,37%	0,61%	0,38%	0,00%	0,07%	0,75%	0,00%

		Hydraulic pipelines	Lubrication oil lines (Aux, transfer, service)	SANITARY FRESHWATER (hot/cold potable water)	SERVICE AIR	Starting air	Tank sounding	Thermal oil
		Power	*Length*	*Acco*	*Length*	*Constant*	*LxBxD*	*Constant*
		0,0961	3,9565	0	0,901	0	0,0001	0
		301,7	-18,7	357,6	-20,7	53,2	106,3	1218,0
		0,0961	3,9565	0	0,901	0	0,0001	0
		1020,1	149,0	401,3	21,3	170,0	111,3	1454,0
		0,0961	3,9565	0	0,901	0	0,0001	0
		-311,9	-138,7	328,3	-50,4	39,0	104,3	982,0
		1332,0	287,7	73,0	71,7	131,0	7,0	472,0
		8,07%	1,58%	0,39%	0,39%	0,19%	0,03%	3,10%
		4,43%	0,87%	0,21%	0,21%	0,10%	0,01%	1,70%

Figure E.8: Step 1 - Results estimation parameters total amount of pipe spools per system - Pipelaying vessel

	Type	Aft ship	Mid ship	Fore ship	Accomodation	DB	Above DB	Mid	Side	AVG %	Min %	Max %	St dev (%)
Midship	1 tot 9		x			x	x	x	x	25,24%	23,24%	27,24%	2,00%
Foreship	10 tot 19 (excl 15)			x		x	x	x	x	47,64%	47,53%	47,75%	0,11%
Aftship	20 tot 23	x				x	x	x	x	10,97%	10,21%	11,73%	0,76%
Accomodation	15 + 24 tot 26				x		x	x	x	16,14%	14,79%	17,49%	1,35%
										100,00%			
Group 1	1 tot 3		x			x		x	x	5,40%	4,78%	6,02%	0,62%
Group 2	4 tot 9		x				x	x	x	19,84%	17,22%	22,46%	2,62%
Group 3	10 tot 13			x		x		x	x	14,57%	12,83%	16,32%	1,75%
Group 4	14 tot 19 (excl 15)			x			x	x	x	33,07%	31,21%	34,93%	1,86%
Group 5	20 tot 23	x				x	x	x	x	10,97%	10,21%	11,73%	0,76%
Group 6	15 & 24				x		x	x	x	13,91%	12,84%	14,98%	1,07%
Group 7	25 & 26				x		x	x	x	*2,23%*	1,95%	2,52%	0,28%
										100,00%			

Figure E.9: Step 2 - Results pipe spool distribution in ship parts and groups - Pipelaying vessel

						Validation for group		
Sectiontype	Group nr	Group tot %	Friendship	Leader?	Percentage calculated	St.dev (%)	Min difference	Max difference
1	1	5,40%	A	No	0,69%	0,25%	-0,31%	0,21%
2	1	5,40%		n.a.	0,95%	0,25%	-0,31%	0,21%
3	1	5,40%	A	No	3,76%	0,25%	-0,31%	0,21%
4	2	19,84%	B	No	1,84%	1,25%	-1,85%	2,20%
5	2	19,84%		n.a.	1,71%	1,25%	-1,85%	2,20%
6	2	19,84%	B	No	3,90%	1,25%	-1,85%	2,20%
7	2	19,84%	C	No	0,10%	1,25%	-1,85%	2,20%
8	2	19,84%	B	No	7,67%	1,25%	-1,85%	2,20%
9	2	19,84%	C	No	4,63%	1,25%	-1,85%	2,20%
10	3	14,57%	D	No	5,11%	0,65%	-1,10%	0,67%
11	3	14,57%	E	No	1,92%	0,65%	-1,10%	0,67%
12	3	14,57%	E	No	0,20%	0,65%	-1,10%	0,67%
13	3	14,57%	D	No	7,35%	0,65%	-1,10%	0,67%
14	4	33,07%	F	No	16,02%	0,61%	-0,90%	1,12%
15	7	13,91%		n.a.	7,49%	0,71%	-0,99%	0,99%
16	4	33,07%		n.a.	0,83%	0,61%	-0,90%	1,12%
17	4	33,07%		n.a.	3,82%	0,61%	-0,90%	1,12%
18	4	33,07%		n.a.	1,26%	0,61%	-0,90%	1,12%
19	4	33,07%	F	No	11,15%	0,61%	-0,90%	1,12%
20	5	10,97%	G	No	3,72%	1,60%	-1,81%	2,62%
21	5	10,97%	G	No	2,01%	1,60%	-1,81%	2,62%
22	5	10,97%	H	No	2,40%	1,60%	-1,81%	2,62%
23	5	10,97%	H	No	2,84%	1,60%	-1,81%	2,62%
24	7	13,91%		n.a.	6,42%	0,71%	-0,99%	0,99%
25	6	16,47%		n.a.	1,15%	0,18%	-0,25%	0,25%
26	6	16,47%		n.a.	1,08%	0,18%	-0,25%	0,25%

Figure E.10: Step 2 - Results pipe spool distribution over section types including verification - Pipelaying vessel

	727	13208	ps			7719	7059	ps			730	14502	ps			
Sectiontype	REAL	ESTIMATE	DIFF	Abs (diff)	Diff (ps)	REAL	ESTIMATE	DIFF	Abs (diff)	Diff (ps)	REAL	ESTIMATE	DIFF	Abs (diff)	Diff (ps)	St.dev (mhrs)
1			0,21%	0,21%	7			0,00%	0,00%	0			0,24%	0,24%	9	20
2			0,21%	0,21%	28			-0,66%	0,66%	46			0,68%	0,68%	99	122
3			0,20%	0,20%	3			0,04%	0,04%	1			0,46%	0,46%	7	23
4			-1,38%	1,38%	0			0,00%	0,00%	0			0,00%	0,00%	0	0
5			-0,31%	0,31%	42			0,66%	0,66%	47			-1,70%	1,70%	246	307
6			0,56%	0,56%	9			0,71%	0,71%	0			2,99%	2,99%	54	68
7			-1,95%	1,95%	0			0,00%	0,00%	0			0,00%	0,00%	0	0
8			2,22%	2,22%	33			-0,95%	0,95%	11			1,51%	1,51%	24	112
9			-1,76%	1,76%	116			2,20%	2,20%	78			-1,89%	1,89%	137	191
10			0,67%	0,67%	29			0,00%	0,00%	0			0,01%	0,01%	0	132
11			0,41%	0,41%	54			-0,64%	0,64%	22			0,18%	0,18%	26	16
12			0,00%	0,00%	0			0,19%	0,19%	0			-0,01%	0,01%	1	3
13			0,67%	0,67%	15			-1,10%	1,10%	39			-1,26%	1,26%	30	111
14			-0,90%	0,90%	13			0,00%	0,00%	0			-1,36%	1,36%	22	125
15			0,07%	0,07%	0			-0,07%	0,07%	2			0,90%	0,90%	22	50
16			-0,33%	0,33%	44			0,56%	0,56%	39			0,49%	0,49%	71	67
17			0,09%	0,09%	4			0,13%	0,13%	0			-2,05%	2,05%	99	202
18			0,18%	0,18%	24			0,04%	0,04%	3			0,71%	0,71%	102	96
19			-0,90%	0,90%	15			1,12%	1,12%	11			-1,16%	1,16%	21	136
20			-1,78%	1,78%	78			2,62%	2,62%	185			-3,15%	3,15%	152	185
21			0,82%	0,82%	36			-1,56%	1,56%	37			0,74%	0,74%	36	71
22			1,06%	1,06%	35			0,00%	0,00%	0			0,80%	0,80%	29	34
23			0,65%	0,65%	22			-1,81%	1,81%	64			0,02%	0,02%	1	14
24			0,99%	0,99%	7			-0,99%	0,99%	4			2,12%	2,12%	20	40
25			0,25%	0,25%	11			-0,25%	0,25%	9			0,33%	0,33%	16	18
26			0,03%	0,03%	4			-0,03%	0,03%	1			0,39%	0,39%	56	54
Average	Average		0,72%		24 ps			0,63%		23			0,97%		49	
Min	Min		0,00%					0,00%					0,00%			
Max	Max		2,22%					2,62%					3,15%			
Stdev	StDev		0,95%					0,96%					1,31%			

Figure E.11: Results parameter and value verification and validation - Pipelaying vessel

Section type									*Pipetype*									
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	12,50%	0,00%	0,00%	14,06%	0,00%	0,00%	10,94%	1,56%	0,00%	3,13%	1,56%	0,00%	45,31%	0,00%	0,00%	10,94%	0,00%	0,00%
2	6,60%	0,00%	0,00%	1,89%	0,00%	0,00%	0,47%	0,00%	0,00%	0,00%	0,00%	0,00%	50,94%	4,25%	0,00%	33,49%	2,36%	0,00%
3	12,50%	0,46%	0,00%	10,19%	0,15%	0,00%	10,49%	0,62%	0,00%	6,48%	0,77%	0,00%	34,26%	0,77%	0,00%	22,99%	0,31%	0,00%
4	30,87%	1,27%	0,42%	10,57%	1,27%	0,00%	4,44%	0,21%	0,00%	2,33%	0,00%	0,00%	36,58%	2,75%	0,42%	8,67%	0,21%	0,00%
5	14,37%	0,88%	0,00%	0,59%	0,00%	0,00%	2,35%	0,29%	0,29%	1,47%	0,29%	0,00%	55,43%	13,20%	5,87%	4,69%	0,29%	0,00%
6	19,40%	2,14%	0,53%	15,30%	0,36%	0,00%	6,58%	2,14%	0,36%	2,31%	0,00%	0,00%	29,18%	16,90%	3,02%	1,07%	0,71%	0,00%
7	39,69%	5,45%	0,00%	11,28%	0,78%	0,00%	8,56%	0,00%	0,00%	1,95%	0,00%	0,00%	22,96%	5,45%	1,17%	2,72%	0,00%	0,00%
8	41,07%	5,54%	0,79%	17,34%	2,50%	0,00%	2,97%	0,13%	0,26%	0,86%	0,13%	0,00%	20,11%	2,37%	0,99%	4,61%	0,33%	0,00%
9	25,31%	3,77%	0,00%	8,21%	1,55%	0,00%	21,74%	4,06%	0,29%	3,19%	0,48%	0,00%	22,03%	4,83%	1,06%	2,90%	0,48%	0,10%
10	19,28%	2,05%	0,34%	5,29%	0,00%	0,00%	0,85%	0,00%	0,00%	0,00%	0,00%	0,00%	57,68%	4,61%	0,00%	9,73%	0,17%	0,00%
11	33,12%	1,89%	0,16%	5,84%	0,63%	0,00%	11,20%	0,95%	0,00%	9,15%	0,32%	0,00%	29,81%	1,58%	0,16%	5,21%	0,00%	0,00%
12	23,08%	7,69%	0,00%	23,08%	0,00%	0,00%	11,54%	0,00%	0,00%	0,00%	0,00%	0,00%	23,08%	11,54%	0,00%	0,00%	0,00%	0,00%
13	7,62%	0,87%	0,00%	1,87%	0,31%	0,00%	10,49%	0,25%	0,00%	3,31%	0,06%	0,00%	59,24%	2,50%	0,00%	13,42%	0,06%	0,00%
14	45,52%	2,15%	0,00%	4,16%	0,09%	0,00%	9,49%	0,36%	0,04%	0,76%	0,00%	0,00%	33,30%	1,92%	0,45%	1,75%	0,00%	0,00%
15	16,78%	2,96%	0,00%	0,33%	0,00%	0,00%	29,28%	3,62%	0,00%	0,33%	0,00%	0,00%	44,08%	2,63%	0,00%	0,00%	0,00%	0,00%
16	54,65%	2,33%	0,00%	7,56%	1,16%	0,00%	3,49%	0,00%	0,00%	0,00%	0,00%	0,00%	26,74%	0,00%	0,00%	4,07%	0,00%	0,00%
17	26,57%	3,65%	0,20%	4,06%	0,41%	0,20%	4,87%	0,20%	0,00%	0,20%	0,00%	0,00%	43,20%	9,33%	3,25%	3,65%	0,00%	0,20%
18	41,26%	0,00%	0,00%	0,00%	0,00%	0,00%	1,40%	0,00%	0,00%	0,00%	0,00%	0,00%	46,85%	3,50%	2,10%	4,90%	0,00%	0,00%
19	30,34%	1,86%	0,09%	4,78%	0,58%	0,00%	12,43%	0,35%	0,00%	2,15%	0,09%	0,00%	41,12%	1,83%	0,00%	4,16%	0,20%	0,00%
20	34,58%	1,74%	0,00%	4,60%	0,12%	0,00%	1,99%	0,00%	0,00%	0,37%	0,00%	0,00%	51,00%	3,73%	0,12%	1,49%	0,00%	0,25%
21	36,81%	3,30%	0,00%	22,71%	1,10%	0,37%	1,47%	0,37%	0,00%	5,13%	0,00%	0,00%	14,29%	1,65%	0,00%	12,82%	0,00%	0,00%
22	38,42%	4,52%	0,00%	14,69%	0,56%	0,00%	3,39%	0,00%	0,00%	0,56%	0,00%	0,00%	33,90%	3,39%	0,00%	0,56%	0,00%	0,00%
23	39,97%	2,66%	0,51%	10,91%	1,90%	0,00%	4,44%	0,63%	0,13%	2,03%	0,00%	0,00%	30,84%	1,90%	0,00%	4,06%	0,00%	0,00%
24	41,98%	0,96%	0,00%	4,82%	0,14%	0,00%	18,01%	0,25%	0,00%	1,07%	0,14%	0,00%	30,01%	0,64%	0,04%	1,93%	0,00%	0,00%
25	32,57%	4,59%	0,00%	10,09%	0,00%	0,00%	1,38%	0,00%	0,00%	0,00%	0,00%	0,00%	44,50%	0,92%	0,00%	5,96%	0,00%	0,00%
26	45,41%	1,38%	0,00%	7,34%	0,00%	0,00%	0,92%	0,00%	0,00%	0,00%	0,00%	0,00%	40,37%	0,92%	0,00%	3,21%	0,46%	0,00%

Figure E.12: Step 4 - Results percentage of pipetype for each section type - Pipelaying vessel

	11003			11024			13001		
Pipe type no.:	Real %	Estimated %	Difference %	Real %	Estimated %	Difference %	Real %	Estimated %	Difference %
Type 1,7,13			27,84%			-12,07%			-10,40%
Type 2,8,14			-2,98%			7,88%			3,78%
Type 3,9,15			-9,09%			1,10%			-0,21%
Type 4,10,16			-17,33%			0,48%			6,47%
Type 5,11,17			1,56%			2,51%			0,12%
Type 6,12,18			0,00%			0,10%			0,25%

Figure E.13: Validation results step 4 - Percentage of pipe types for 3 sections

F | Appendix: Results outfitting - HVAC

Results Ducting

Data of the amount of ventilation and air-conditioning ducts is collected and per specified group of sections shown in the Figures below. A regression analysis is carried out of which the line is show in the corresponding Figures.

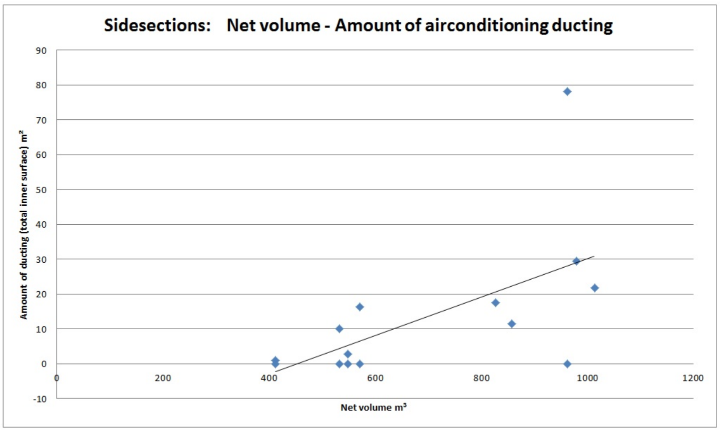


Figure F.1: Result: Data overview side sections YN 727 - ducting Airconditioning

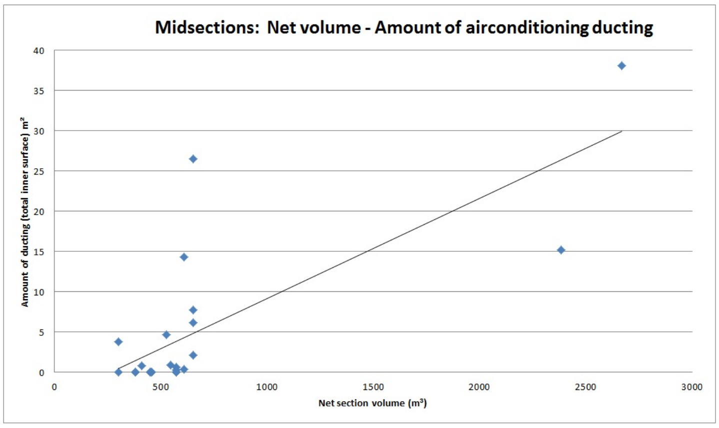


Figure F.2: Result: Data overview mid sections YN 727 - ducting Airconditioning

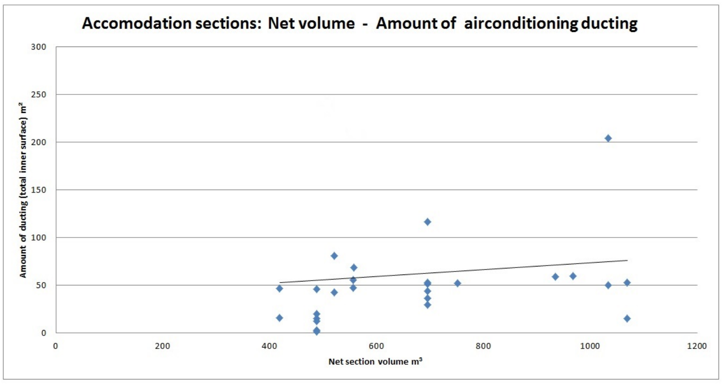


Figure F.3: Result: Data overview accomodation sections YN 727 - ducting Airconditioning

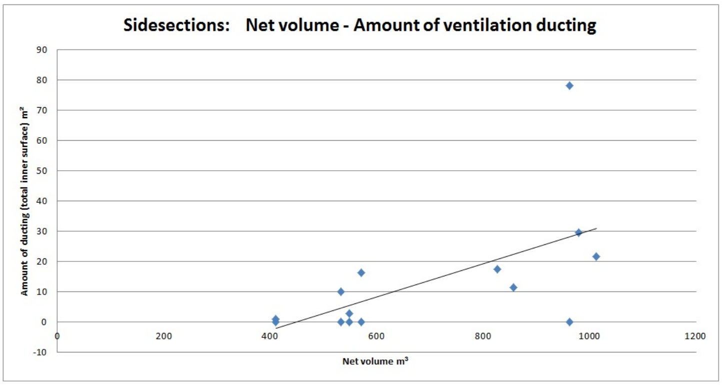


Figure F.4: Result: Data overview sidesections YN 727 - ducting Ventilation

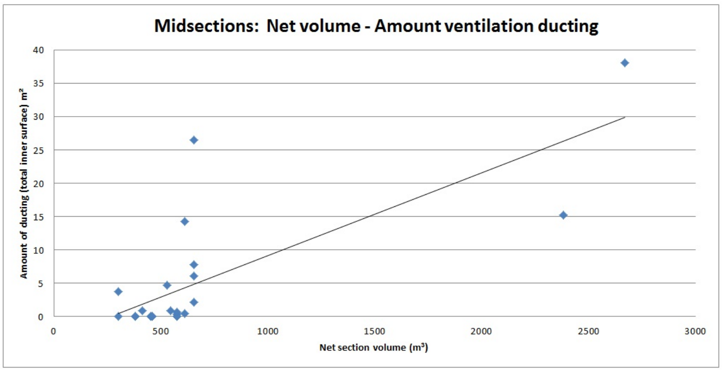


Figure F.5: Result: Data overview midsections YN 727 - ducting Ventilation

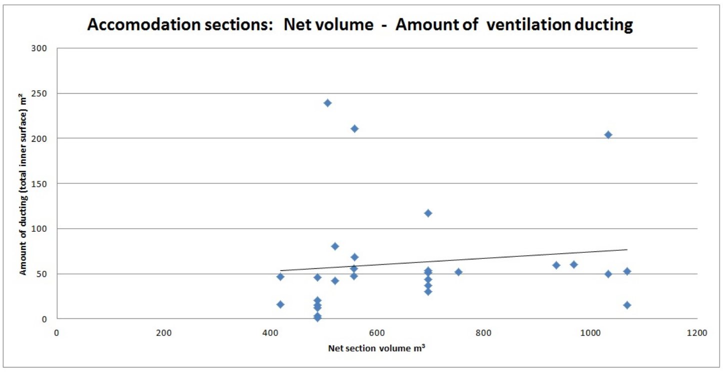


Figure F.6: Result: Data overview accomodation sections YN 727 - ducting Ventilation

Results Piping

Below, Figures are shown including the results of the research of the amount of pipe spools in sections of pipe laying vessels and hopper dredgers.

System type:		Exhaust	Heating	Ventilation/Air piping in acco	Chilling water lines
Depend on:		*Acco*	*Constant*	*Constant*	*Constant*
Factor normal	*alpha (α)*	2,63	0	0	0
	constant (β)	10,4	83,5	37,26565317	101
Max line	*alpha (α)*	0,00	0	0	0
	constant (β)	26,8	105	48	134
Min line	*alpha (α)*	0,00	0	0	0
	constant (β)	6,0	62	17	68
Difference range	Ps	21	43	31	66
Min difference (718)	%	1,18%	5,80%	5,46%	8,89%
Max difference (1269)	%	2,81%	13,78%	12,99%	21,15%
Correlation coefficient (r)		0,94	<0,80	<0,80	<0,80

Figure F.7: Step 1 - Results estimation parameters total amount of HVAC pipe spools per system - Hopper dredgers

						Validation for group			
Sectiontype	Group nr	Group tot %	Friendship	Leader?	Percentage calculated	St.dev (%)	Min difference	Max difference	St dev (ps)
1	1	0,00%	A	Yes	0,00%	0,00%	0,00%	0,00%	0
2	1	0,00%	A	No	0,00%	0,00%	0,00%	0,00%	0
3	1	0,00%	A	No	0,00%	0,00%	0,00%	0,00%	0
4	1	0,00%	A	No	0,00%	0,00%	0,00%	0,00%	0
5	2	0,00%	B	Yes	0,00%	0,00%	0,00%	0,00%	0
6	2	0,00%	B	No	0,00%	0,00%	0,00%	0,00%	0
7	2	0,00%	B	No	0,00%	0,00%	0,00%	0,00%	0
8	3	7,80%	C	Yes	0,50%	2,33%	-5,15%	6,70%	3
9	3	7,80%	C	No	0,60%	2,33%	-5,15%	6,70%	3
10	3	7,80%	D	Yes	3,17%	2,33%	-5,15%	6,70%	3
11	3	7,80%	D	No	3,53%	2,33%	-5,15%	6,70%	3
12	3	7,80%		n.a.	0,00%	2,33%	-5,15%	6,70%	3
13	4	2,05%	E	No	1,03%	1,27%	-4,11%	2,05%	2
14	4	2,05%	F	No	0,00%	1,27%	-4,11%	2,05%	2
15	4	2,05%	F	No	0,00%	1,27%	-4,11%	2,05%	2
16	4	2,05%	F	No	0,00%	1,27%	-4,11%	2,05%	2
17	4	2,05%	E	No	1,03%	1,27%	-4,11%	2,05%	2
18	5	25,35%		n.a.	10,94%	2,70%	-6,77%	5,74%	4
19	5	25,35%		n.a.	2,38%	2,70%	-6,77%	5,74%	4
20	5	25,35%		n.a.	0,00%	2,70%	-6,77%	5,74%	4
21	5	25,35%		n.a.	12,03%	2,70%	-6,77%	5,74%	4
22	6	46,63%	G	No	0,00%	5,72%	-12,38%	13,00%	9
23	6	46,63%	G	Yes	8,00%	5,72%	-12,38%	13,00%	9
24	6	46,63%		n.a.	2,91%	5,72%	-12,38%	13,00%	9
25	6	46,63%	H	No	0,00%	5,72%	-12,38%	13,00%	9
26	6	46,63%	H	No	13,60%	5,72%	-12,38%	13,00%	9
27	6	46,63%	H	No	11,00%	5,72%	-12,38%	13,00%	9
28	6	46,63%	H	No	7,43%	5,72%	-12,38%	13,00%	9
29	7	18,16%		n.a.	2,24%	3,80%	-8,65%	9,16%	6
30	7	18,16%	I	No	9,16%	3,80%	-8,65%	9,16%	6
31	7	18,16%	I	No	2,17%	3,80%	-8,65%	9,16%	6
32	7	18,16%		n.a.	4,60%	3,80%	-8,65%	9,16%	6
33	6	46,63%	H	No	3,69%	5,72%	-12,38%	13,00%	9

Figure F.8: Step 2 - Results HVAC pipe spool distribution over section types - Hopper dredgers

Section types	Pipetypes																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
2	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
3	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
4	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
5	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
6	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
7	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
8	10,53%	0,00%	0,00%	21,05%	0,00%	0,00%	26,32%	5,26%	0,00%	0,00%	0,00%	0,00%	26,32%	0,00%	0,00%	10,53%	0,00%	0,00%
9	10,53%	0,00%	0,00%	21,05%	0,00%	0,00%	26,32%	5,26%	0,00%	0,00%	0,00%	0,00%	26,32%	0,00%	0,00%	10,53%	0,00%	0,00%
10	4,44%	13,33%	13,33%	37,78%	0,00%	0,00%	0,00%	0,00%	0,00%	4,44%	0,00%	0,00%	13,33%	0,00%	0,00%	13,33%	0,00%	0,00%
11	4,44%	13,33%	13,33%	37,78%	0,00%	0,00%	0,00%	0,00%	0,00%	4,44%	0,00%	0,00%	13,33%	0,00%	0,00%	13,33%	0,00%	0,00%
12	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	50,00%	50,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
13	3,13%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	78,13%	0,00%	0,00%	18,75%	0,00%	0,00%
14	3,13%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	78,13%	0,00%	0,00%	18,75%	0,00%	0,00%
15	3,13%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	78,13%	0,00%	0,00%	18,75%	0,00%	0,00%
16	3,13%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	78,13%	0,00%	0,00%	18,75%	0,00%	0,00%
17	3,13%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	78,13%	0,00%	0,00%	18,75%	0,00%	0,00%
18	30,43%	8,70%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	60,87%	0,00%	0,00%	0,00%	0,00%	0,00%
19	13,04%	0,00%	0,00%	8,70%	0,00%	0,00%	0,00%	0,00%	0,00%	17,39%	0,00%	0,00%	26,09%	8,70%	8,70%	17,39%	0,00%	0,00%
20	22,34%	4,58%	0,84%	5,42%	0,56%	0,00%	0,00%	0,00%	0,00%	5,80%	0,00%	0,00%	44,67%	3,74%	4,30%	7,48%	0,28%	0,00%
21	23,53%	5,04%	2,52%	7,56%	1,68%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	47,06%	2,52%	4,20%	5,04%	0,84%	0,00%
22	23,91%	0,00%	0,00%	8,70%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	32,61%	2,17%	0,00%	32,61%	0,00%	0,00%
23	23,91%	0,00%	0,00%	8,70%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	32,61%	2,17%	0,00%	32,61%	0,00%	0,00%
24	15,87%	0,98%	0,00%	12,52%	0,00%	0,00%	2,74%	0,00%	0,00%	5,06%	0,00%	0,00%	29,06%	0,00%	0,00%	33,77%	0,00%	0,00%
25	15,87%	0,98%	0,00%	12,52%	0,00%	0,00%	2,74%	0,00%	0,00%	5,06%	0,00%	0,00%	29,06%	0,00%	0,00%	33,77%	0,00%	0,00%
26	11,63%	0,00%	0,00%	16,28%	0,00%	0,00%	2,33%	0,00%	0,00%	9,30%	0,00%	0,00%	32,56%	0,00%	0,00%	27,91%	0,00%	0,00%
27	26,47%	2,94%	0,00%	11,76%	0,00%	0,00%	5,88%	0,00%	0,00%	5,88%	0,00%	0,00%	11,76%	0,00%	0,00%	35,29%	0,00%	0,00%
28	9,52%	0,00%	0,00%	9,52%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	42,86%	0,00%	0,00%	38,10%	0,00%	0,00%
29	4,17%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	8,33%	8,33%	0,00%	0,00%	0,00%	66,67%	8,33%	0,00%	4,17%	0,00%	0,00%
30	45,16%	9,68%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	45,16%	0,00%	0,00%	0,00%	0,00%	0,00%
31	48,31%	1,12%	0,00%	1,12%	0,00%	0,00%	8,99%	0,00%	0,00%	2,25%	0,00%	0,00%	37,08%	1,12%	0,00%	0,00%	0,00%	0,00%
32	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	14,29%	0,00%	0,00%	0,00%	0,00%	0,00%	85,71%	0,00%	0,00%
33	13,04%	0,00%	0,00%	8,70%	0,00%	0,00%	0,00%	0,00%	0,00%	17,39%	0,00%	0,00%	26,09%	8,70%	8,70%	17,39%	0,00%	0,00%

Figure F.9: Step 4 - Results percentage of HVAC pipe type for each section type - Hopper dredger

System type:		Exhaust	Heating	Ventilation/Air piping in acco	Chilling water lines
Depend on:		*Acco*	*Constant*	*Constant*	*Constant*
Factor normal	***alpha (α)***	2,63	0	0	0
	constant (β)	10,4	334,4	60	310
Max line	***alpha (α)***	0,00	0	0	0
	constant (β)	26,8	355,9	70,73434683	386
Min line	***alpha (α)***	0,00	0	0	0
	constant (β)	6,0	312,9	39,73434683	233
Difference range	**Ps**	21	43	31	153
Min difference (727)	**%**	0,42%	2,06%	1,94%	7,38%
Max difference (7719)	**%**	0,58%	2,83%	2,66%	10,12%
Correlation coefficient (r)		0,94	<0,80	<0,80	<0,80

Figure F.10: Step 1 - Results estimation parameters total amount of HVAC pipe spools per system - Pipe laying vessel

						Validation for group		
Sectiontype	**Group nr**	**Group tot %**	**Friendship**	**Leader?**	**Percentage calculated**	**St.dev (%)**	**Min difference**	**Max difference**
1	1	4,46%	A	No	0,00%	0,00%	0,00%	0,00%
2	1	4,46%		n.a.	0,00%	0,00%	0,00%	0,00%
3	1	4,46%	A	No	0,00%	0,00%	0,00%	0,00%
4	2	19,86%	B	No	0,00%	1,57%	-2,00%	2,20%
5	2	19,86%		n.a.	0,88%	1,57%	-2,00%	2,20%
6	2	19,86%	B	No	3,26%	1,57%	-2,00%	2,20%
7	2	19,86%	C	No	0,00%	1,57%	-2,00%	2,20%
8	2	19,86%	B	No	3,46%	1,57%	-2,00%	2,20%
9	2	19,86%	C	No	2,17%	1,57%	-2,00%	2,20%
10	3	14,59%	D	No	0,25%	0,25%	-0,49%	0,25%
11	3	14,59%	E	No	0,00%	0,25%	-0,49%	0,25%
12	3	14,59%	E	No	0,00%	0,25%	-0,49%	0,25%
13	3	14,59%	D	No	0,84%	0,25%	-0,49%	0,25%
14	4	32,81%	F	No	33,37%	1,50%	-2,24%	2,61%
15	4	32,81%		n.a.	3,66%	1,50%	-2,24%	2,61%
16	4	32,81%		n.a.	0,65%	1,50%	-2,24%	2,61%
17	4	32,81%		n.a.	0,00%	1,50%	-2,24%	2,61%
18	4	32,81%		n.a.	0,00%	1,50%	-2,24%	2,61%
19	4	32,81%	F	No	6,68%	1,50%	-2,24%	2,61%
20	5	11,81%	G	No	0,00%	0,30%	-0,34%	0,38%
21	5	11,81%	G	No	0,00%	0,30%	-0,34%	0,38%
22	5	11,81%	H	No	1,56%	0,30%	-0,34%	0,38%
23	5	11,81%	H	No	0,00%	0,30%	-0,34%	0,38%
24	6	16,47%		n.a.	30,95%	3,96%	-6,37%	6,37%
25	6	16,47%	I	No	2,88%	3,96%	-6,37%	6,37%
26	6	16,47%	I	No	9,34%	3,96%	-6,37%	6,37%

Figure F.11: Step 2 - Results HVAC pipe spool distribution over section types - Pipe laying vessel

Section type	Pipetype																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
2	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
3	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
4	40,34%	12,64%	0,00%	2,38%	0,00%	0,00%	8,82%	0,00%	0,00%	0,00%	0,00%	0,00%	30,22%	4,41%	0,00%	1,19%	0,00%	0,00%
5	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	50,00%	50,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
6	57,14%	23,81%	0,00%	4,76%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	11,90%	0,00%	0,00%	2,38%	0,00%	0,00%
7	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	100,00%	0,00%	0,00%	0,00%	0,00%	0,00%
8	23,53%	1,47%	0,00%	0,00%	0,00%	0,00%	17,65%	0,00%	0,00%	0,00%	0,00%	0,00%	48,53%	8,82%	0,00%	0,00%	0,00%	0,00%
9	34,29%	0,00%	0,00%	5,71%	0,00%	0,00%	45,71%	0,00%	0,00%	5,71%	0,00%	0,00%	8,57%	0,00%	0,00%	0,00%	0,00%	0,00%
10	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	70,59%	0,00%	0,00%	29,41%	0,00%	0,00%
11	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
12	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
13	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	70,59%	0,00%	0,00%	29,41%	0,00%	0,00%
14	42,07%	1,83%	0,00%	9,45%	0,00%	0,00%	4,27%	0,00%	0,00%	3,35%	0,00%	0,00%	31,40%	0,61%	0,00%	7,01%	0,00%	0,00%
15	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	23,53%	0,00%	0,00%	5,88%	0,00%	0,00%	58,82%	0,00%	0,00%	11,76%	0,00%	0,00%
16	21,88%	0,00%	0,00%	12,50%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	59,38%	0,00%	0,00%	6,25%	0,00%	0,00%
17	33,33%	0,00%	0,00%	41,67%	0,00%	0,00%	0,00%	0,00%	0,00%	8,33%	0,00%	0,00%	0,00%	0,00%	0,00%	16,67%	0,00%	0,00%
18	18,40%	0,00%	0,00%	18,06%	0,00%	0,00%	7,84%	0,00%	0,00%	4,74%	0,00%	0,00%	39,40%	0,00%	0,00%	11,56%	0,00%	0,00%
19	28,96%	0,55%	0,00%	1,91%	0,00%	0,00%	0,00%	0,27%	0,00%	0,00%	0,00%	0,00%	57,10%	1,64%	0,55%	9,02%	0,00%	0,00%
20	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
21	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%
22	37,50%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	37,50%	25,00%	0,00%	0,00%	0,00%	0,00%
23	0,00%	0,00%	0,00%	10,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	90,00%	0,00%	0,00%	0,00%	0,00%	0,00%
24	37,28%	0,32%	0,00%	8,16%	0,00%	0,00%	4,80%	0,00%	0,00%	4,00%	0,00%	0,00%	30,56%	1,12%	0,16%	13,60%	0,00%	0,00%
25	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	48,94%	4,26%	0,00%	46,81%	0,00%	0,00%
26	24,14%	2,30%	0,00%	2,87%	0,00%	0,00%	0,00%	0,00%	0,00%	1,15%	0,00%	0,00%	51,72%	1,15%	0,00%	16,67%	0,00%	0,00%

Figure F.12: Step 4 - Results percentage of HVAC pipe type for each section type - Pipelaying vessel

Results Equipment

Below, the man-hour categories are shown for each type of room and vessel for the required installation time of HVAC equipment. Figure F.13 shows the different categories including the amount of man-hours and Figure F.14 shows the category number per type of room and vessel. Also the offset from the category value to the real value is shown in this Figure.

Categorynumber:	Manhours:
1	
2	
3	
4	
5	
6 (AC-room)	

Figure F.13: Average required amount of man-hours for installing equipment in room

Room type	Description	Pipelaying vessel	Hopper dredger	Manhours installation equipment - Pipelayer				Manhours installation equipment - Hopper dredger			
				REAL (avg)	Catergory	Mnhrs	Difference	REAL (avg)	Catergory	Mnhrs	Difference
Thusterroom		X	X				-3,15461				-3,25
Engineroom (ER)	*Deck 1*	X	X				4,1647				-1,78
	Deck 2	X	X				1,54353				1,54353
	Deck 3	X	X				-0,064				-3,064
HPU room		X	X				-0,118				1,522
Pump room	*Jet pump room*		X				0				0,976
	Gland pump room		X				0				1,066
	Dredging pump room		X				0				-2,328
Pump motor room			X				0				-2,174
Winch room		X	X				-0,278				-0,278
Switchboardroom		X	X				-0,99518				-1,678
Trafo room		X	X				4,572804				0
Pipe flushing room		X					4,464867				0
							0				0
Seperator room (FO treatment room)		X	X				1,242				1,242
AC room (central HVAC location)		X	X				-1,888				0,643767
Generator room		X	X				-2,758				-2,758
Incinerator room		X	X				-0,614				-0,614
Hydraulic room			X				0				-1,308
Steering gear room			X				0				1,036
Chemical room		X	X				1,786				1,036
Other technical space	*Large*		X				0				-4,594
	Small	X	X				0,496				1,246
							0				0
							0				0
Control room	*Engine control room (ECR)*	X	X				-3,90256				0
	ROV control room	X	X				-0,47564				0
	Other control room	X	X				-1,54292				0
Storage room	*Technical storage room*	X	X				-1,43675				1,756
	General storage room	X	X				1,756				1,756
Workshop room	*Technical workshop room*	X	X				-1,69602				1,636
	General workshop room	X	X				1,371741				-3,25
							0				0
Accomodation room within foreship	*Changing room 120.xx*	X	X				1,818465				1,786
	Office	X	X				0				0
	Galley	X	X				2,625864				3,058701
	Mess room	X	X				0,736				0,886
	Recreation room	X	X				0,886				0,886
	Cabin	X	X				0				0
	Laundry room	X	X				-2,428				-2,428
	Gym	X	X				0,886				0,886
							0				0,916
Wheelhouse		X	X				-2,33711				0
							0				0
Alleyway		X	X				1,336				0,4534
Stairs		X	X				-3,18454				1,126
Funnel		X	X				0				0
Carroussel hold		X					-1,464				0
Elevator		X	X				0				0
Hopper space			X				0				0

Figure F.14: Validation results - Overview with categories of equiment installation man-hours per room type and vessel type

G | Appendix: Results outfitting - Cable trays

A research is carried out by John S. Page in 1977 to find a method to estimate the required amount of man-hours for the installation of cable trays. The results are shown in Figure G.1 below. The method for the installation of the trays and the trays itself do not show significant changes over the last 40 years. However, the method should be verified again before using it. In this research production data of Royal IHC is finally used to determine the required amount of man-hours for the installation of a cable trays. Figure **??** shows the results of the validation of the obtained parameters using the real data of Ynr 730.

INSTALLATION OF CABLE TRAY & FITTINGS

MANHOURS PER UNITS LISTED

Tray Item Description	Unit	Width of Tray						
		6″	9″	12″	18″	24″	30″	36″
Ladder Type Cable Tray–Straight	LF.	0.25	0.30	0.33	0.35	0.40	0.45	0.55
90° Horizontal Elbows–12″ Radius	Ea.	1.25	1.25	1.50	1.90	2.50	3.00	3.50
90° Vertical Elbows–12″ Radius	Ea.	2.19	2.19	2.63	3.33	4.38	4.98	5.80
Horizontal Tees–12″ Radius	Ea.	2.30	2.30	2.75	3.50	4.60	5.25	6.10
Horizontal Crosses–12″ Radius	Ea.	3.00	3.00	3.60	4.55	6.00	6.85	7.95
Reducer	Ea.	–	–	3.00	3.50	4.00	4.50	5.00
Expansion Joint	Ea.	2.50	3.00	4.00	4.75	5.50	6.25	7.00
Connector Plates	Pr.	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Dropouts	Ea.	1.25	1.25	1.50	1.75	2.00	2.50	3.00
Blind Ends	Ea.	0.50	0.50	1.00	1.00	1.25	1.50	1.75
Tray Cover Plate	LF.	0.10	0.12	0.15	0.20	0.25	0.50	0.75
Cable Separators	Ea.	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Manhours are for installation of ladder type cable tray and fittings with 3-3/8-inch siderails and rungs on 6-inch centers all of 16 gauge steel.

Manhours include job handling, hauling, cutting, assembling, and placing.

Manhours do not include structural supports on which cable tray is installed.

Figure G.1: Results research John S. Page for the required man-hours for installation of cable trays [6]

H | Appendix: Results outfitting - Secondary steel

In this Appendix, Figures are shown that present the results of the research about the amount of secondary steel components in specific sections and the corresponding required amount of man-hours. Figure H.1 shows the results of an interview held under experiences personnel to determine the amount of man-hours required for the installation of secondary steel components. Figures H.2 and H.3 show the results of the regression analysis for hopper dredgers and pipe laying vessels. Insufficient data was available to obtain parameters for all section types. No data was available for the section types that are assigned by the symbol 'X' in Figure H.2 and H.3.

Component type	Subtype	Crane	Unit	Pers A	Pers B	Pers C	Pers D	Pers E
Foundations	Auxilary foundations (excl. Main engines)	Yes	Per piece					
	Main engine foundation	Yes						
	HVAC foundation	Yes						
	Others	Yes						
Ladder	Average Ladder	Yes	Per piece	2	1.5	2	1.5	2
Stairs	Average Stair	Yes	Per piece	1.5	1.25	1.5	1.5	1.5
Hoist beam	Hoist beam straight	Yes	Per meter					
	Hoist beam curved	Yes	Per meter					
Manholes	Average manhole	Yes?	Per piece	1.5	2	2	2	2
Markings	Hull (tanks / bulkheads)	No	Per piece	1	1	1	1	1
	Bowtruster marks	No	Per piece	1	1	1	1	1
	Manholes	No	Per piece	1	1	1	1	1
	Deck (webframes, SB/PS)	No	Per piece	1	1	1	1	1
Hand Grip	Average Handgrip	No	Per piece	0.25	0.25	0.50	0.25	0.25
Pad eyes								
Drain plugs	Average plug	No	Per piece	0.5	0.75	1	0.75	1
Gutter	Average Gutter							
Steps	Average Step	No	Per piece	1	1	0.75	1	0.75
Door	Watertight door & Splashtight door	Yes	Per piece	4	5	4	4	5
	Sliding door	Yes	Per piece	8	8	8	8	8
Hand railing	Straight	No	Per meter	1	1	1	1	1
	Curved	No	Per meter	1.5	1.5	1	1.25	1.5
Anodes		No	Per piece	0.5	0.5	1	0.5	0.5
Bollards	Average bollard	Yes	Per piece	9	10	8	10	9
Fairlead	Average Fairled	Yes	Per piece	20	22	24	20	20

Figure H.1: Results interview IHC personnel required man-hours installation secondary steel components

Section type	Count	Cor. Coeff L	Cor. Coeff B	Cor. Coeff H	Cor. Coeff Opp	Cor. Coeff Vol	Cor. Coeff Weight	alpha	constant	stdev	avg diff	Dep. Var
1	13	0,29	0,09	0,43	0,27	0,42	0,29	0,00	3,2	4,3	3,4	*Constant*
2	4	0,03	0,04	0,37	0,15	0,30	0,09	0,00	13,0	9,4	7,7	*Constant*
3	2						1,00	1,03	-43,1	0,0	0,0	*Weight*
4	14							0,00	0,0	0,0	0,0	*Constant*
5	24	0,31	0,06	0,26	0,21	0,44	0,43	0,00	34,5	14,5	11,6	*Constant*
6	1							0,00	34,1	0,0	0,0	*Constant*
7	2							0,00	6,8	0,0	0,0	*Constant*
8	6	0,48	0,88	-0,16	0,98	0,97	0,99	1,36	-46,7	9,5	8,7	*Weight*
9	X											
10	31	0,06	0,22	0,35	0,32	0,73	-0,43	0,02	-5,0	7,7	6,1	*Volume*
11	X											
12	2	-1,00	1,00	1,00	1,00	1,00	1,00	2,64	-218,9	0,0	0,0	*Weight*
13	2	-1,00			-1,00	-1,00	1,00	0,56	-31,6	0,0	0,0	*Weight*
14	X											
15	X											
16	3	-0,45	0,24	0,67	0,23	0,99	0,72	0,09	-25,6	10,1	9,1	*Volume*
17	7	-0,23	0,37		0,12	0,12	0,86	0,69	-19,6	7,9	6,7	*Weight*
18	7	0,60	-0,51	0,27	0,49	0,37	0,62	4,33	-187,2	114,9	75,6	*Weight*
19	7	0,63	-0,02	-0,02	0,49	0,46	0,88	0,34	-6,6	4,5	3,3	*Weight*
20	1							0,00	358,8	0,0	0,0	*Constant*
21	12	0,30	-0,09	-0,25	0,15	-0,17	0,18	0,00	87,6	105,8	84,5	*Constant*
22	X											
23	14	0,64	-0,53	0,38	-0,31	0,27	0,52	16,00	-116,3	31,3	27,1	*Length*
24	4	-0,97	0,76	0,97	0,75	0,77	0,41	173,50	-716,9	4,3	3,1	*Height*
25	X											
26	17	0,27	0,56	-0,13	0,54	0,31	0,40	10,76	-81,5	39,8	29,8	*Breadth*
27	9	-0,48	-0,55	0,52	-0,57	-0,05	0,83	0,48	-6,3	12,4	9,8	*Weight*
28	8	-0,17	0,56		0,18	0,18	0,15	19,57	-164,2	48,2	40,0	*Breadth*
29	9	0,78	-0,31	0,00	0,57	0,57	0,42	4,52	34,1	15,4	13,0	*Length*
30	2							0,00	96,3	0,0	0,0	*Constant*
31	3		1,00	1,00	1,00	1,00	1,00	6,31	-164,7	2,6	2,1	*Weight*
32	2							0,00	0,0	0,0	0,0	*Constant*
33	X											

Figure H.2: Results - Correlation coefficient and parameter values per section type for secondary steel man-hours hopper hredgers

Section type	Count	Cor. Coeff L	Cor. Coeff B	Cor. Coeff H	Cor. Coeff Opp	Cor. Coeff Vol	Cor. Coeff Weight	alpha	constant	stdev	avg diff	Dep. Var
1	4	0,89			0,89	0,89	0,39	0,23	8,9	8,4	6,9	*Volume*
2	2	1,00	-1,00	1,00	-1,00	1,00	-1,00	2,84	-957,8	0,0	0,0	*Volume*
3	12	0,27	0,86	-0,91	0,92	0,92	0,94	1,02	-6,6	10,3	7,9	*Weight*
4	3	-0,96	-0,24		-0,76	-0,76	-0,86	0,00	8,4	8,2	7,5	*Constant*
5	2	1,00	-1,00	1,00	1,00	1,00	1,00	0,54	-67,7	0,0	0,0	*Weight*
6	8	-0,87			-0,87	-0,87	-0,44	0,00	2,0	3,4	2,9	*Constant*
7	X											
8	15	-0,11	-0,33	0,42	-0,31	-0,21	-0,06	0,00	66,9	31,0	24,9	*Constant*
9	4	0,84	0,84	0,84	0,84	0,84	0,84	1,42	-76,7	55,3	39,5	*Weight*
10	3	0,95	0,00		0,95	0,95	0,83	0,30	-7,9	1,2	1,1	*Volume*
11	3	-0,73	0,81	0,32	-0,69	-0,02	-0,55	2,66	34,9	4,1	3,5	*Breadth*
12	1							0,00	153,5	0,0	0,0	*Constant*
13	8	-0,90	0,65	-0,54	0,59	0,59	0,70	0,91	-4,4	25,7	21,7	*Weight*
14	9	-0,91		-0,23	-0,91	-0,46	-0,24	0,00	46,2	22,1	20,3	*Constant*
15	6	0,52	0,35		0,49	0,49	0,29	78,65	-818,6	69,9	59,5	*Length*
16	2	1,00	1,00	1,00	1,00	1,00	1,00	2,41	297,3	0,0	0,0	*Weight*
17	3	0,87	-0,90		-0,93	-0,93	-0,53	19,84	-117,8	23,0	18,8	*Length*
18	2	1,00	1,00	-1,00	1,00	1,00	1,00	0,50	1,2	0,0	0,0	*Weight*
19	15	0,21	-0,05	0,09	0,05	0,34	-0,04	0,00	59,5	44,7	35,6	*Constant*
20	4	-0,99	0,91	-0,99	-0,36	-0,55	0,89	15,94	-132,9	44,6	42,8	*Breadth*
21	6	-0,07	-0,13	0,06	-0,21	-0,14	-0,39	0,00	112,9	38,7	32,1	*Constant*
22	4						0,43	0,00	21,0	9,8	8,1	*Constant*
23	6	0,85	0,16	-0,75	0,54	0,26	-0,03	38,43	-436,6	65,3	51,2	*Length*
24	37	-0,10	0,28	0,54	0,24	0,53	0,59	2,22	-10,0	73,6	40,8	*Weight*
25	5	0,00	0,53	-0,16	0,35	0,37	0,73	1,78	56,3	19,4	15,3	*Weight*
26	2	1,00	-1,00	1,00	1,00	1,00	-1,00	1,15	-525,7	0,0	0,0	*Volume*

Figure H.3: Results - Correlation coefficient and parameter values per section type for secondary steel man-hours pipe laying vessels

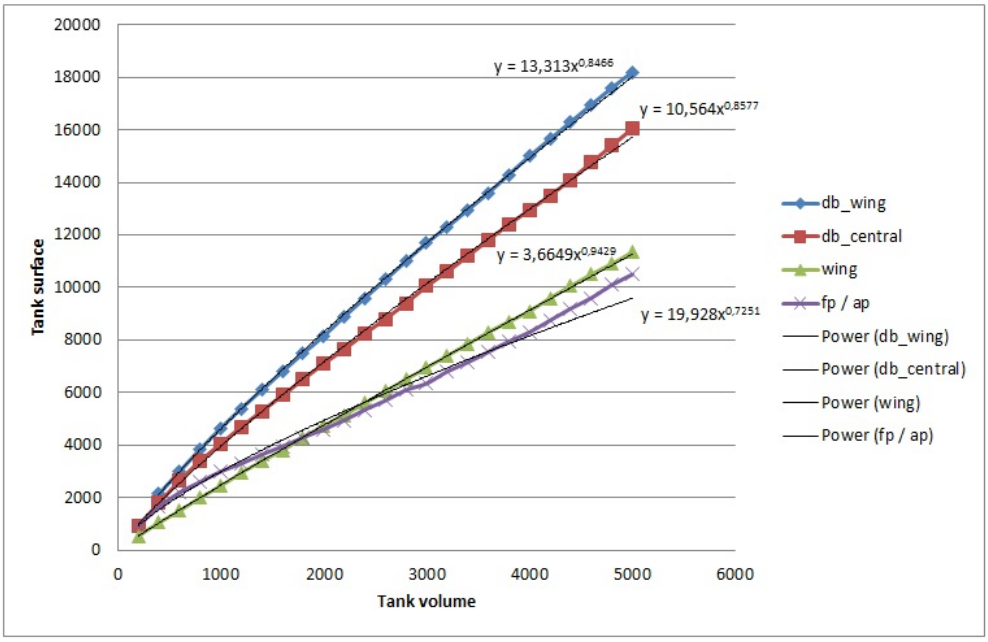
I Appendix: Results outfitting - Painting

In this Appendix, Figures are shown that present the results of the research about the amount of painting work in specific sections and the corresponding required amount of man-hours.

		Source 1			Source 2		
Activity:		parameter	unit	Note	parameter	unit	Note
Cleaning surface	-	-	-	-	0,001	mnhrs/ft²	
Spray painting exterior - Steel	1st coat	0,0022	mnhrs/ft²	B	0,0018	mnhrs/ft²	
	2nd coat	0,0025	mnhrs/ft²	B	0,0018	mnhrs/ft²	
Spray painting exterior - Steel	1st coat	0,0022	mnhrs/ft²	A	0,0018	mnhrs/ft²	
	2nd coat	0,0015	mnhrs/ft²	A	0,0018	mnhrs/ft²	
Brush field coat exterior - Steel	1st coat	0,01	mnhrs/ft²	A			
	2nd coat	0,0067	mnhrs/ft²	A			
Brush interior - metal work	1st coat	0,008	mnhrs/ft²	A			
	2nd coat	0,0088	mnhrs/ft²	A			
Roller painting	all coats				0,0036	mnhrs/ft²	D

Notes	
A	Manhours include handling, stirring, mixing and placing of paint on items. Manhours do not include scaffolding.
C	Manhours for sandblasting are those of air tool operator; for wire brushing - those of laborer. Manhours do not include scaffolding
B	Manhours include handling, stirring, mixing, filling spray gun and applying paint on surfaces. Manhours do not include scaffolding.
D	Manhours are determined for roller painting a wall with 'cut-ins', within reach of the painter incl. preparation time

Figure I.1: Productivity parameters according to Page (1977) 1 [6] and Dilworth (1990) [9]



tk_vol	db_wg	db_central	wing	fp / ap
200	-	950	550	950
400	2150	1800	1050	1650
600	3000	2650	1500	2200
800	3850	3400	2000	2600
1000	4650	4050	2450	3000
1200	5400	4700	2950	3300
1400	6100	5300	3400	3650
1600	6800	5900	3800	3950
1800	7500	6500	4300	4300
2000	8150	7100	4750	4600
2200	8900	7650	5150	4950
2400	9600	8250	5600	5350
2600	10300	8800	6050	5700
2800	11000	9400	6500	6100
3000	11700	10050	6950	6350
3200	12300	10600	7400	6800
3400	12950	11200	7850	7150
3600	13600	11800	8300	7550
3800	14300	12400	8700	7950
4000	15000	12950	9100	8300
4200	15650	13500	9600	8750
4400	16300	14100	10050	9200
4600	16950	14750	10500	9600
4800	17600	15400	10900	10100
5000	18200	16050	11350	10500

Figure I.2: Results - Research surface area tanks using tank volume

J Appendix: Results outfitting - Scaffolding

Length	Manhours required per section					
	1 or 2 section high			More than 2 section high		
	Erect	Dismantle	Total	Erect	Dismantle	Total
1 to 2 sections long	1,4	1	2,4	1,7	1,2	2,9
3 to 5 sections long	0,9	0,6	1,5	1	0,7	1,7
6 sections & more long	0,7	0,4	1,1	0,9	0,5	1,4

Figure J.1: Manhours required for erecting and dismanteling scaffolding [6]

K | Appendix: Activity Loader

This Appendix includes examples of various input sheets of the *Activity Loader*. Also a flowchart is presented which explains the structure of the code of the model.

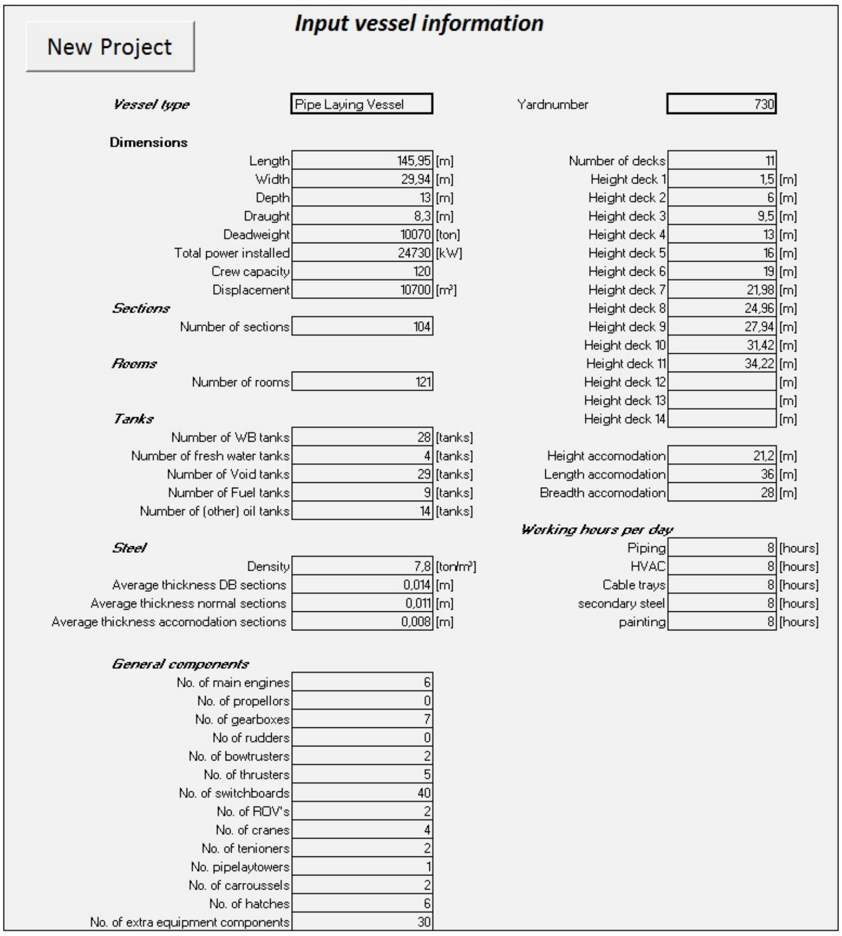
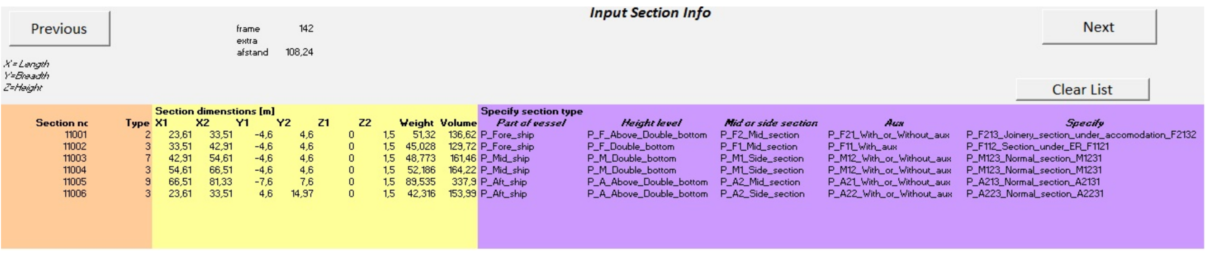


Figure K.1: Activity loader input sheet basic vessel characteristics



Section nc	Type	Section dimensions [m] X1	X2	Y1	Y2	Z1	Z2	Weight	Volume	Specify section type: Part of vessel	Height level	Mid or side section	Aux	Specify
11001	2	23,61	33,51	-4,6	4,6	0	1,5	51,32	136,62	P_Fore_ship	P_F_Above_Double_bottom	P_F2_Mid_section	P_F21_With_or_Without_aux	P_F213_Joinery_section_under_accomodation_F2132
11002	3	33,51	42,91	-4,6	4,6	0	1,5	45,028	129,72	P_Fore_ship	P_F_Double_bottom	P_F1_Mid_section	P_F11_With_aux	P_F112_Section_under_ER_F1121
11003	7	42,91	54,61	-4,6	4,6	0	1,5	48,773	161,46	P_Mid_ship	P_M_Double_bottom	P_M1_Side_section	P_M12_With_or_Without_aux	P_M123_Normal_section_M1231
11004	3	54,61	66,51	-4,6	4,6	0	1,5	52,186	164,22	P_Mid_ship	P_M_Double_bottom	P_M1_Side_section	P_M12_With_or_Without_aux	P_M123_Normal_section_M1231
11005	9	66,51	81,33	-7,6	7,6	0	1,5	89,535	337,9	P_Aft_ship	P_A_Above_Double_bottom	P_A2_Mid_section	P_A21_With_or_Without_aux	P_A213_Normal_section_A2131
11006	3	23,61	33,51	4,6	14,97	0	1,5	42,316	153,99	P_Aft_ship	P_A_Above_Double_bottom	P_A2_Side_section	P_A22_With_or_Without_aux	P_A223_Normal_section_A2231

Figure K.2: Activity loader input sheet sections

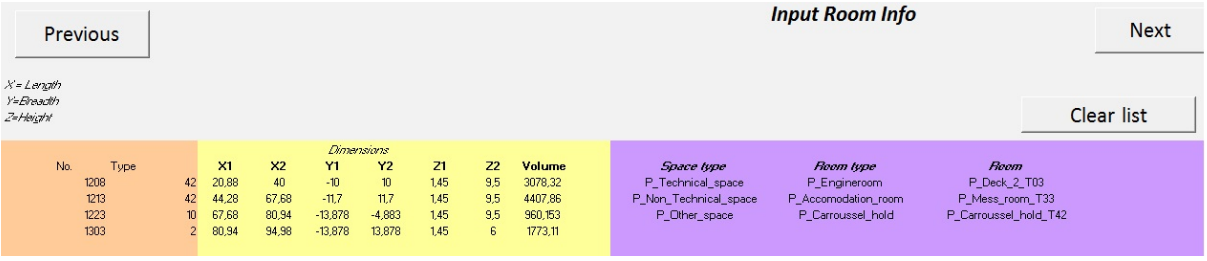


Figure K.3: Activity loader input sheet rooms

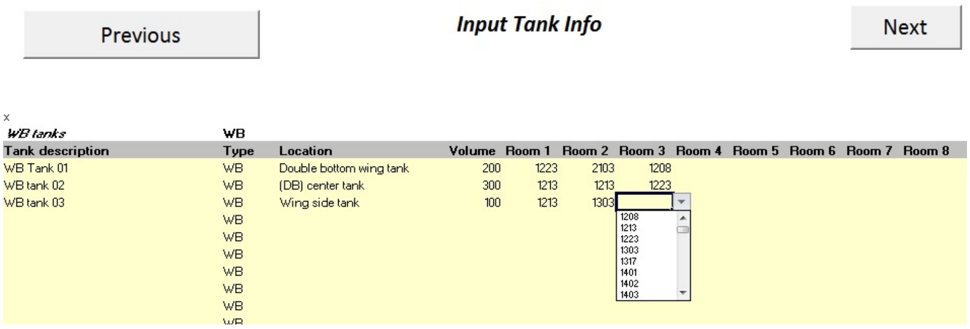


Figure K.4: Activity loader input sheet tanks

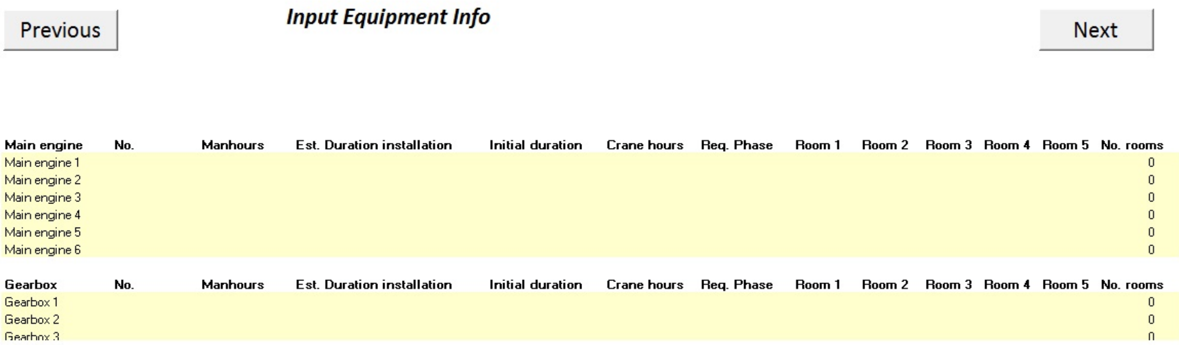


Figure K.5: Activity loader input sheet equipment

Discipline	Description	Start	End	Duration	Manhours	Phase	Constraints	Crane usage	Scaffolding
Piping	Mount spools POF	1 week before end section assembly	End Pof	POF duration	Estimation model piping	POF	-	Yes	No
HVAC	Mount AC ducts POF	1 week before end section assembly	End Pof	POF duration	HVAC duct formula’s	POF	-	No	No
HVAC	Mount Vent ducts POF	1 week before end section assembly	End Pof	POF duration	HVAC duct formula’s	POF	-	No	No
HVAC	Mount pipepsools HVAC POF	1 week before end section assembly	End Pof	POF duration	Estimation model piping	POF	-	Yes	No
Cable Trays & E-supports	Mount Cable trays POF	1 week before end section assembly	End Pof	POF duration	Cable tray formulas	POF	-	No	No
Cable Trays & E-supports	Mount supports trays POF	1 week before end section assembly	End Pof	POF duration	Tray support formulas	POF	-	No	No
Secondary steel	Mount components POF	1 week before end section assembly	End Pof	POF duration / man-hours	Secondary steel formulas	POF	-	Yes	No-
Painting	Conservation section	End POF	free	Manhours / days	Section conservation formulas	POF	-	No	Yes
Piping	Mount spools SWPO	Section on slipway	Room closed	SWPO duration	Estimation model piping	SWPO	-	Yes	Yes
HVAC	Mount AC ducts SWPO	Section on slipway	Room closed	SWPO duration	HVAC duct formula’s	SWPO	-	No	Yes
HVAC	Mount Vent ducts SWPO	Section on slipway	Room closed	SWPO duration	HVAC duct formula’s	SWPO	-	No	Yes
HVAC	Mount pipepsools HVAC SWPO	Section on slipway	Room closed	SWPO duration	Estimation model piping	SWPO	-	Yes	Yes
HVAC	Install equipment SWPO	Section on slipway	Room closed	SWPO duration / man-hours	Category per room type	SWPO	-	Yes	Yes
Cable Trays & E-supports	Mount Cable trays SWPO	Section on slipway	Room closed	SWPO duration / man-hours	Cable tray formulas	SWPO	-	No	Yes
Cable Trays & E-supports	Mount supports trays SWPO	Section on slipway	Room closed	SWPO duration / man-hours	Tray support formulas	SWPO	-	No	Yes
Secondary steel	Mount components SWPO	Section on slipway	Room closed	SWPO duration / man-hours	Secondary steel formulas	SWPO	-	Yes	No
Piping	Mount spools OF	Room closed	Start paint room	OF duration	Estimation model piping	OF	-	Yes	Yes
HVAC	Mount AC ducts OF	Room closed	Start paint room	OF duration	HVAC duct formula’s	OF	-	No	Yes
HVAC	Mount Vent ducts OF	Room closed	Start paint room	OF duration	HVAC duct formula’s	OF	-	No	Yes
HVAC	Mount pipepsools HVAC OF	Room closed	Start paint room	OF duration	Estimation model piping	OF	-	Yes	Yes
HVAC	Install equipment HVAC OF	Room closed	Start paint room	OF duration / man-hours	Category per room type	OF	-	Yes	Yes
Secondary steel	Mount components OF	Room closed	Start paint room	SWPO duration / man-hours	Secondary steel formulas	OF	-	Yes	No
Painting	Conservation room	free	deadline commissioning	Manhours / days	Room conservation formulas	OF	-	No	Yes
Painting	Conservation tank	Closing tank	Launch	Manhours / days	Tank conservation formulas	SWPO / OF	-	No	Yes
Painting	Conservation hull & accomodation	After section erection	Launchg	Manhours / days	Hull conservation formulas	OF	-	No	Yes
Painting	Conservation deck	After painting hull	launch	Manhours / days	Deck conservation formulas	OF	-	No	Yes

Overview type of activities in *Activity Loader*

L | Appendix: Planning Generator

This Appendix includes examples of various input sheets of the *Planning Generator*. Also a flowchart is presented which explains the structure of the code of the model.

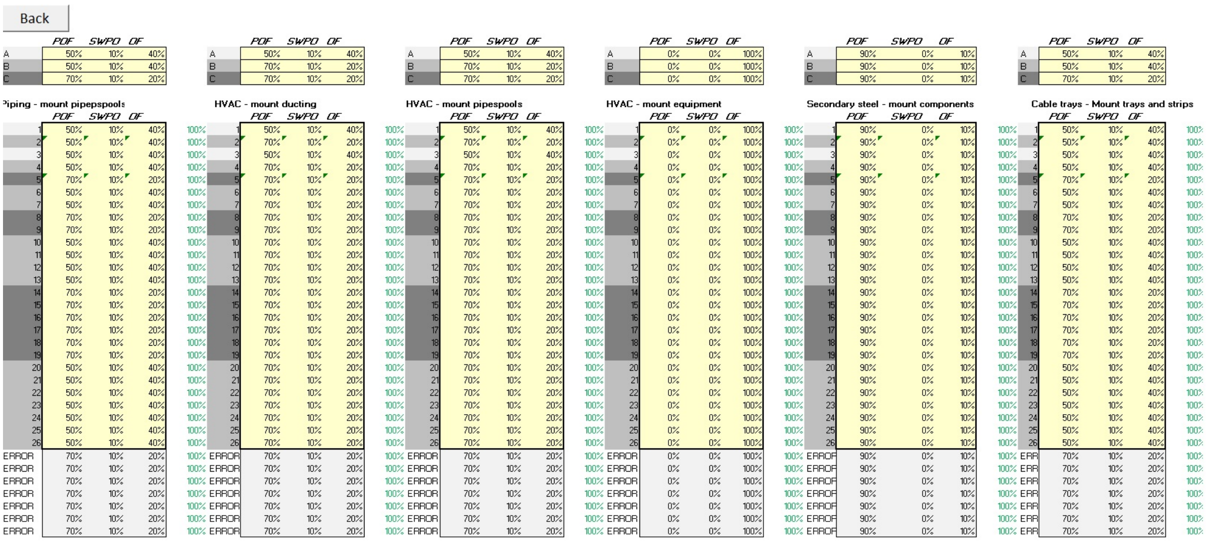
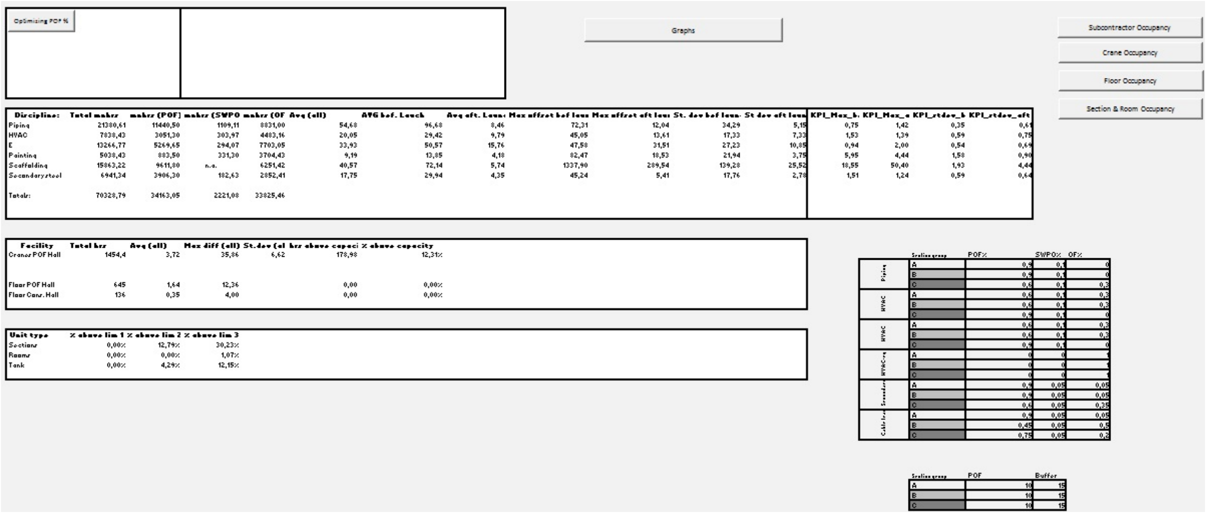


Figure L.1: Planning generator input sheet outfit percentages

	Room type		Commissioning 2 deadline
Technical spaces	Thrusterroom		Before start engines
	Engineroom (ER)	Deck 1	Before start engines
		Deck 2	Before start engines
		Deck 3	Before start engines
	HPU room		Before start engines
	Pump room	Jet pump room	Before sea trails
		Gland pump room	Before sea trails
		Dredging pump room	Before sea trails
	Pump motor room		Before sea trails
	Winch room		Before sea trails
	Switchboardroom		Before start engines
	Trafo room		Before start engines
	Pipe flushing room		Before sea trails
	Seperator room (FO treatment room)		Before start engines
	AC room (central HVAC location)		Before sea trails
	Generator room		Before sea trails
	Incinerator room		Before sea trails
	Hydraulic room		Before sea trails
	Steering gear room		Before sea trails
	Chemical room		Before sea trails
	Other technical space	Large	Before sea trails
		Small	Before sea trails
Non-Technical spaces			
	Control room	Engine control room (ECR)	Before start engines
		ROV control room	Before sea trails
		Other control room	Before sea trails
	Storage room	Technical storage room	Before sea trails
		General storage room	Before sea trails
	Workshop room	Technical workshop room	Before sea trails
		General workshop room	Before sea trails
	Accomodation room within foreship	Changing room 120.xx	Before sea trails
		Office	Before sea trails
		Galley	Before sea trails
		Mess room	Before sea trails
		Recreation room	Before sea trails
		Cabin	Before sea trails
		Laundry room	Before sea trails
		Gym	Before sea trails
	Wheelhouse		Before sea trails
Other spaces			
	Alleyway		Before sea trails
	Stairs		Before sea trails
	Funnel		Before start engines
	Carroussel hold		Before sea trails
	Elevator		Before sea trails
	Hopper space		Before sea trails

Figure L.2: Assumed milestone for deadline second commissioning phase in *Planning Generator*



Discipline:	Total mnhrs	mnhrs (POF)	mnhrs (SWPO	mnhrs (OF	Avg (all)	AVG bef. Launch	Avg aft. Laun	Max offset bef laun	Max offset aft lau	St. dev bef laun	St dev aft laun	KPI_Max_b	KPI_Max_a	KPI_stdev_b	KPI_stdev_aft
Piping	21380,61	11440,50	1109,11	8831,00	54,68	96,68	8,46	72,31	12,04	34,29	5,15	0,75	1,42	0,35	0,61
HVAC	7838,43	3051,30	303,97	4483,16	20,05	29,42	9,79	45,05	13,61	17,33	7,33	1,53	1,39	0,59	0,75
E	13266,77	5269,65	294,07	7703,05	33,93	50,57	15,76	47,58	31,51	27,23	10,85	0,94	2,00	0,54	0,69
Painting	5038,43	883,50	331,30	3704,43	9,19	13,85	4,18	82,47	18,53	21,94	3,75	5,95	4,44	1,58	0,90
Scaffolding	15863,22	9611,80	n.a.	6251,42	40,57	72,14	5,74	1337,90	289,54	139,28	25,52	18,55	50,40	1,93	4,44
Secondarysteel	6941,34	3906,30	182,63	2852,41	17,75	29,94	4,35	45,24	5,41	17,76	2,78	1,51	1,24	0,59	0,64
Totals:	70328,79	34163,05	2221,08	33825,46											

Facility	Total hrs	Avg (all)	Max diff (all)	St.dev (al	hrs above capaci	% above capacity
Cranes POF Hall	1454,4	3,72	35,86	6,62	178,98	12,31%
Floor POF Hall	645	1,64	12,36		0,00	0,00%
Floor Cons. Hall	136	0,35	4,00		0,00	0,00%

Unit type	% above lim 1	% above lim 2	% above lim 3
Sections	0,00%	12,79%	30,23%
Rooms	0,00%	0,00%	1,07%
Tank	0,00%	4,29%	12,15%

	Scaling group	POF%	SWPO%	OF%
Piping	A	0,9	0,1	0
	B	0,9	0,1	0
	C	0,6	0,1	0,3
HVAC	A	0,6	0,1	0,3
	B	0,6	0,1	0,3
	C	0,9	0,1	0
HVAC	A	0,6	0,1	0,3
	B	0,6	0,1	0,3
	C	0,9	0,1	0
HVAC-eq	A	0	0	1
	B	0	0	1
	C	0	0	1
Secondary	A	0,9	0,05	0,05
	B	0,9	0,05	0,05
	C	0,6	0,05	0,35
Cable tray	A	0,9	0,05	0,05
	B	0,45	0,05	0,5
	C	0,75	0,05	0,2

Scaling group	POF	Buffer
A	10	15
B	10	15
C	10	15

Figure L.3: Example output overview sheet *Planning Generator*

M | Appendix: Results case study

In this Appendix all results of the case study are shown.

N | Appendix: Influence erection schedule

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